

PROFESSIONAL **CMAKE**

A PRACTICAL GUIDE



CRAIG SCOTT

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PREFACE

Back around 2016, I was surprised at the lack of published material for learning how to use CMake. The official reference documentation was a useful resource for those willing to go exploring, but as a way of learning CMake in a progressive, structured manner, it was not ideal. There were some wikis and personal websites that had some useful contents, but there were also many that contained out-of-date or questionable advice and examples. There was a distinct gap, which meant those new to CMake had a hard time learning good practices, leading to many becoming overwhelmed or frustrated.

At the time, I had been writing some blog articles to do something more productive with my spare time and to deepen my own technical knowledge around software development. I frequently wrote about areas that came up in my interaction with colleagues at work or in my own development activities, and I found this to be both rewarding and useful to others. As that pattern repeated itself, the idea of writing a book was born. Fast-forward two and a half years and the result is this book.

Along the way, there was a pivotal moment I now look back on with a degree of amusement. A colleague bemoaned a particular feature that he wished CMake had. It burrowed its way into my brain and sat there for a few months until one day I decided to explore how hard it would be to add that feature myself. That culminated in the test fixtures feature that is now a part of CMake. Importantly, I was really struck by the positive experience I had making that contribution. The people, the tools and the processes in place made working on the project truly a pleasure. From there, I became more deeply involved and now fulfill the role of volunteer co-maintainer.

I have since created my own company, through which I provide consulting services based around CMake, build and release processes, C++, continuous integration, and other related areas. I didn't set out with that goal, but it is now my primary focus. I consider it a privilege to be involved in such a diverse cross-section of projects, organizations and platforms. It gives me some unique perspectives, which I can then feed back into my ongoing activities maintaining CMake. My consulting activities are also a strong driver of the updates and new material for each new edition of this book. It is my hope that you, the reader, can then benefit from these experiences, and the developments that evolve from them.

ACKNOWLEDGMENTS

It is only when you come to thank all those who have contributed to the process of getting your book released that you realize just how many people have been involved. A work like this doesn't happen without the generosity, patience, and insight of others. Nor does it succeed without being challenged, tested, and reworked. It relies on those who were kind enough to (sometimes unknowingly!) get involved in these activities as much as it does on the author. I cannot thank these people enough for their kindness and wisdom.

The CMake community wouldn't be as strong and as vibrant as it is today without the ongoing support of Kitware and its staff, past and present. I'd like to make special mention of Brad King, the CMake project leader, who through his inclusive and encouraging approach to new CMake contributors has made people like myself very welcome and feel empowered to get involved. I have personally learned much from him just by observing the way he interacts with developers and users, providing strong leadership, and fostering an environment of respect for others. It also goes without saying that the numerous contributors to CMake over the years also deserve

much praise for their efforts, often made on a purely voluntary basis. I'm humbled by the scale of contributions that have been made by so many, and by the positive impact on the world of software development.

A special mention is also much deserved for my past colleague, Mike Wake. Much of the material in the early editions of this book was thrashed out and tested in real, actively developed production projects. There were wrong turns, and many technical discussions on how to improve things from both a usability and a robustness perspective. His support in giving the space and encouragement to work through these things, and his willingness to wear some short-term (and sometimes not-so-short-term) pain were an instrumental part of distilling many processes and techniques down to what works in practice. I am also very grateful for the timely words of advice and encouragement delivered at just the right time during some of the more stressful and exhausting periods around those earlier editions.

Across the various editions, a number of people have generously agreed to review material in this book. Without these people, the book's technical accuracy and its readability would have suffered. Any remaining errors and deficiencies are my own. Fellow CMake developers Gregor Jasny and Christian Pfeiffer were valuable contributors throughout the review process for the first publication. I am truly grateful for their

suggestions and insights. Thanks also to Nils Gladitz for his input, especially at such short notice before the first publication. I'd also like to thank my past colleagues, Matt Bolger and Lachlan Hetherton, both of whom provided constructive feedback and reminded me of the importance of a fresh set of eyes before the first release.

Many of the people who have generously reviewed chapters for subsequent editions are also CMake contributors or maintainers, and I am grateful for both their time reviewing this book, and in improving CMake itself. The same can be said for readers who have also provided corrections and suggestions for improvement. I'd like to acknowledge the following people who have provided reviews, corrections, or feedback that led to updates for one or more editions after the first publication:

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Burkhard Stubert

Lukas Oyen

Caleb Huitt

Marc Chevrier

Chengfeng Xie

Mateusz Pusz

Christopher McArthur

Michael Platings

Cristian Adam

Nagy-Egri Máté Ferenc

Cristian Morales Vega

Parker Coates

Damon McDougall

Patrick Heyer

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Elias Daler

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Tristano Ajmone

Ganesh A. Hegde

Vilas Chitrakaran

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The book's cover and some supporting material on the website are the result of a better eye and understanding of graphical design than my own. To my friend and designer, V, the way you somehow managed to make sense of my random, disconnected ideas and conflicting snippets still baffles me. I don't understand how you do it, but I do like the result!

In every book's acknowledgments section, the author invariably thanks family members and spouses, and there's good reason for that. It takes a huge amount of understanding and sacrifice to tolerate your tiredness, your unavailability to do many of the things ordinary people get to do, and your unreasonable decision to devote more time to a project than to them. I truly cannot express the depth of my gratitude to my wife for the way she has managed to be so supportive and patient throughout the process of getting this book written, published and regularly updated. I am indeed a very fortunate human being.

I: GETTING STARTED

This first part of the book covers the most basic aspects of CMake. It will equip a developer who has never used CMake before with the necessary skills to be able to create, build, test, install, and package a simple executable or library. Rather than going into too much detail, these early chapters focus on getting a working project and introducing the basic commands needed to interact with it. It also establishes the importance of *targets*, one of the most fundamental concepts in CMake.

Attempting to use any tool before understanding at least the basics of what it does and how it is meant to be used is likely to result in much frustration. On the other hand, spending all one's time learning the theory about something without getting hands-on makes for a rather boring experience and often leads to an overly idealistic understanding. With that in mind, the reader is encouraged to try out the material in each chapter as they go. By the end of this part of the book, the reader should have a basic project they can use as a solid starting point for exploring the material in later chapters.

After completing this part of the book, the reader should continue on to the [Part II, “Fundamentals”](#) chapters. They go into more detail about key concepts and features that the rest of the book will rely on heavily.

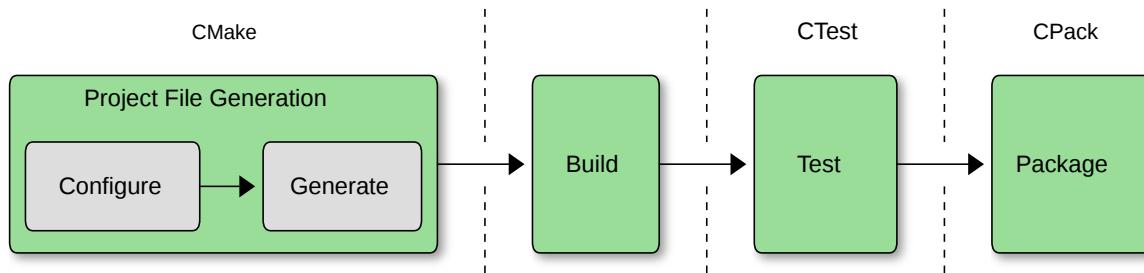
1. INTRODUCTION

Whether a seasoned developer or just starting out in a software career, one cannot avoid the process of becoming familiar with a range of tools in order to turn a project's source code into something an end user can actually use. Compilers, linkers, testing frameworks, packaging systems, and more all contribute to the complexity of deploying high quality, robust software. While some platforms have a dominant IDE environment that simplifies some aspects of this (e.g. Xcode and Visual Studio), projects that need to support multiple platforms cannot always make use of their features. Having to support multiple platforms adds more complications that can affect everything from the set of available tools through to the different capabilities available and restrictions enforced. A typical developer could be forgiven for losing at least some of their sanity trying to keep on top of the whole picture.

Fortunately, there are tools that make taming the process more manageable. CMake is one such tool, or more accurately, CMake is a suite of tools which covers everything from setting up a build right through to producing packages ready for distribution. Not only does it cover the process from start to

end, it also supports a wide range of platforms, tools, and languages.

When working with CMake, it helps to understand its view of the world. Loosely speaking, the start to end process according to CMake looks something like this:



The first stage takes a generic project description and generates platform-specific project files suitable for use with the developer's build tool of choice (make, Xcode, Visual Studio, etc.). While this setup stage is what CMake is best known for, the CMake suite of tools also includes CTest and CPack. These manage the testing and packaging stages respectively. The entire process from start to finish can be driven from CMake itself, and each stage can also be executed individually through CMake. This abstracts away platform differences, making some tasks much simpler.

The first step to getting started with CMake is ensuring it is installed on the system. Some platforms may typically come with CMake already installed (most Linux distributions have

CMake available through their package manager), but these versions are often quite old. Where possible, it is recommended that developers work with a recent CMake release. This is particularly true when developing for Apple platforms, where tools like Xcode and its SDKs change rapidly, and where app store requirements evolve over time. The official CMake packages can be downloaded and unpacked to a directory on the developer's machine without interfering with any system-wide CMake installation. Developers are encouraged to take advantage of this and remain relatively close to the most recent stable CMake release.

These days, CMake also comes with fairly extensive [reference documentation](#), which is accessible from the official CMake site. This useful resource is very helpful for looking up the various commands, options, keywords, and so on. Developers will likely want to bookmark it for quick reference. The [CMake forum](#) is also a great source of advice and is the recommended place for asking CMake-related questions where the documentation doesn't provide sufficient guidance.

2. SETTING UP A PROJECT

Without a build system, a project is just a collection of files. CMake brings some order to this, starting with a human-readable file named `CMakeLists.txt`. This file defines what can be built and how, tests that may be run, and packages to create. It is a platform-independent description of the whole project, which CMake then turns into platform-specific build tool project files. As its name suggests, it is just an ordinary text file which developers edit in their favorite text editor or development environment. The contents of this file are covered in great detail in subsequent chapters, but for now, it is enough to know that this is what controls everything that CMake will do in setting up and performing the build.

A fundamental part of CMake is the concept of a project having both a source directory and a binary directory. The source directory is where the `CMakeLists.txt` file is located, and the project's source files and all other files needed for the build are organized under that location. The source directory is frequently under version control with a tool like git, subversion, or similar.

The binary directory is where everything produced by the build is created. It is often also called the build directory. For reasons that will become clear in later chapters, CMake generally uses the term *binary* directory, but among developers, the term build directory tends to be in more common use. This book tends to prefer the latter term, since it is generally more intuitive. CMake, the chosen build tool (make, Visual Studio, etc.), CTest, and CPack will all create various files within the build directory and subdirectories below it. Executables, libraries, test output, and packages are all created within the build directory. CMake also creates a special file called `CMakeCache.txt` in the build directory to store information for reuse on later runs. Developers won't normally need to concern themselves with the `CMakeCache.txt` file, but later chapters will discuss situations where this file is relevant. The build tool's project files (Xcode or Visual Studio project files, Makefiles, etc.) are also created in the build directory, and those project files are not intended to be put under version control. The `CMakeLists.txt` files are the canonical description of the project, and the generated project files should be considered part of the build output.

When a developer commences work on a project, they must decide where they want their build directory to be in relation to their source directory. There are essentially two approaches: *in-source* and *out-of-source* builds.

2.1. In-source Builds

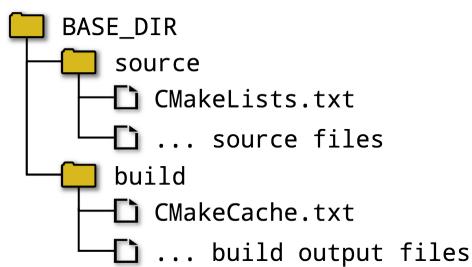
It is possible, though discouraged, for the source and build directories to be the same. This arrangement is called an *in-source* build. Developers at the beginning of their career often start out using this approach because of the perceived simplicity. A significant drawback to in-source builds is that all the build outputs are intermixed with the source files. This lack of separation causes directories to become cluttered with all sorts of files and subdirectories. This makes it harder to manage the project sources, and it runs the risk of build outputs overwriting source files. It also makes working with version control systems more difficult, since there are lots of files created by the build which the source control tool has to know to ignore, or the developer has to manually exclude during commits. Another drawback to in-source builds is that it can be non-trivial to clear out all build output and start again with a clean source tree. For these reasons, developers are discouraged from using in-source builds where possible, even for simple projects.

2.2. Out-of-source Builds

The more preferable arrangement is for the source and build directories to be different, which is called an *out-of-source* build. This keeps the sources and the build outputs completely separate from each other, thus avoiding the intermixing problems experienced with in-source builds. Out-of-source builds also have the advantage that the developer can create

multiple build directories for the same source directory. This allows builds to be set up with different sets of options, such as debug and release versions.

This book always uses out-of-source builds. It also generally follows the pattern of the source and build directories being under a common parent. The build directory will be called *build*, or some variation thereof. For example:



A variation on this is to make the build directory a subdirectory of the source directory. This offers most of the advantages of an out-of-source build, but isn't as isolated from the sources. Some continuous integration systems more or less require this structure due to how they limit access outside the source directory. IDEs also often use such an arrangement by default. If the build directory is placed under the source directory, prefer to give the build directory a name starting with `build`. This minimizes the chance of it clashing with a source directory, and it makes it easy to set up source repository ignore rules for all build directories with a simple wildcard pattern.

2.3. Generating Project Files

Once the choice of directory structure has been made, the developer runs CMake, which reads in the `CMakeLists.txt` file and creates project files in the build directory. The developer selects the type of project file to be created by choosing a particular project file *generator*. A range of different generators are supported, with the more commonly used ones listed in the table below.

Category	Generator Examples	Multi-config
Visual Studio	Visual Studio 17 2022	Yes
	Visual Studio 16 2019	
Xcode	Xcode	Yes
Ninja	Ninja	No
	Ninja Multi-Config	Yes
Makefiles	Unix Makefiles	No
	NMake Makefiles	

Some generators produce projects which support multiple configurations (Debug, Release, and so on). These allow the developer to choose between different build configurations without having to re-run CMake. This is more convenient for generators that create projects for use in IDE environments like Xcode and Visual Studio. For generators which do not support

multiple configurations, the developer has to re-run CMake to switch the build between Debug, Release, etc. These are simpler, and they often have good support in IDE environments not so closely associated with a particular compiler (CLion, Qt Creator, KDevelop, etc.).

The most basic way to run CMake is via the `cmake` command line utility. A common way to invoke that tool is to change directory to where the `CMakeLists.txt` file is located, then run `cmake` passing the `-G` option with the generator type, and the `-B` option with the build directory:

```
cmake -G "Unix Makefiles" -B build
```

The build directory will be created automatically if it doesn't exist. If the `-G` option is omitted, CMake will choose a generator based on the host platform. With CMake 3.15 or later, the `CMAKE_GENERATOR` environment variable can be used to specify a different default generator.

For all generator types, CMake will carry out a series of tests to determine how to set up the project files. This includes things like verifying that the compilers work, determining the set of supported compiler features, and various other tasks. A variety of information will be logged before CMake finishes with lines like the following upon success:

```
-- Configuring done  
-- Generating done  
-- Build files have been written to: /some/path/build
```

The above highlights that project file creation actually involves two steps: *configuring* and *generating*. During the configuring phase, CMake reads in the `CMakeLists.txt` file and builds up an internal representation of the entire project. After this is done, the generation phase creates the project files. The distinction between configuring and generating doesn't matter so much for basic CMake usage, but in later chapters, the separation of configuration and generation becomes important. This is covered in more detail in [Chapter 11, Generator Expressions](#).

When CMake has completed its run, it will have saved a `CMakeCache.txt` file in the build directory. CMake uses this file to save details so that if it is run again, it can re-use information computed the first time and speed up the project generation. As covered in later chapters, it also allows developer options to be saved between runs. A GUI application, `cmake-gui`, is available as an alternative to running the `cmake` command line tool. Discussion of that GUI application is deferred to [Chapter 6, Variables](#) where its usefulness is clearer.

2.4. Running The Build Tool

At this point, with project files now available, the developer can use their selected build tool in the way to which they are

accustomed. The build directory will contain the necessary project files, which can be loaded into an IDE and read by command line tools. Alternatively, `cmake` can invoke the build tool on the developer's behalf:

```
cmake --build /pathTo/build --config Debug --target MyApp
```

This works even for project types the developer may be more accustomed to using through an IDE like Xcode or Visual Studio. The `--build` option points to the build directory used by the CMake project generation step. For multi-configuration generators, the `--config` option specifies which configuration to build, whereas single-configuration generators will ignore the `--config` option and rely instead on information provided when the CMake project generation step was performed. Specifying the build configuration is covered in depth in [Chapter 15, Build Type](#). The `--target` option can be used to tell the build tool what to build. If no `--target` option is provided, the default target will be built instead. With CMake 3.15 or later, multiple targets can be listed after the `--target` option, separated by spaces.

While developers will typically invoke their selected build tool directly in day-to-day development, invoking it via the `cmake` command as shown above can be more useful in scripts driving an automated build. Using this approach, a simple scripted build might look something like this:

```
cmake -G "Unix Makefiles" -B build  
cmake --build build --config Release --target MyApp
```

If the developer wishes to experiment with different generators, the argument given to the `cmake -G` option is the only thing that needs to be changed. The correct build tool will be automatically invoked. The build tool doesn't even have to be on the user's PATH for `cmake --build` to work, although it may need to be for the initial configuration step when `cmake` is first invoked.

2.5. Recommended Practices

Even when first starting out using CMake, it is advisable to make a habit of keeping the build directory completely separate from the source tree. A good way to experience the benefits of such an arrangement is to set up two or more different builds for the same source directory. One build could be configured with Debug settings, the other for a Release build. Another option is to use different project generators for the different build directories, such as Unix Makefiles and Xcode. This can help to catch any unintended dependencies on a particular build tool, or to check for differing compiler settings between generator types.

It can be tempting to focus on using one particular type of project generator in the early stages of a project, especially if the developer is not accustomed to writing cross-platform

software. But projects frequently grow beyond their initial scope, and it is relatively common to need to support additional platforms and generator types later. Periodically checking the build with a different project generator than the one a developer usually uses can save considerable future pain by discouraging generator-specific code where it isn't required. This has the added benefit of making the project well-placed to take advantage of any new generator types in the future. A good strategy is to ensure the project builds with the default generator type on each platform of interest, plus one other generator type.

Ninja is an excellent choice for the CMake generator. It has the broadest platform support of all the generators, and it creates very efficient builds. Developers should get familiar with its use, as it is becoming somewhat of a de facto standard for CMake projects.

If the project is being scripted, invoke the build tool using `cmake --build` instead of invoking the build tool directly. This allows the script to easily switch between generator types without having to modify the build command.

3. A MINIMAL PROJECT

All CMake projects start with a file called `CMakeLists.txt`, which is required to be at the top of the source tree. Think of it as the CMake project file, defining everything about the build, from sources and targets through to testing, packaging, and other custom tasks. It can be as simple as a few lines, or it can be quite complex and pull in more files from other directories. `CMakeLists.txt` is just an ordinary text file and is usually edited directly, just like any other source file in the project.

Continuing the analogy with sources, CMake defines its own language which has many things a programmer would be familiar with, such as variables, functions, macros, conditional logic, looping, code comments, and so on. These various concepts and features are covered in [Part II, “Fundamentals”](#), but for now, the goal is just to get a simple build working as a starting point. The following is a minimal, well-formed `CMakeLists.txt` file that defines a basic executable.

```
cmake_minimum_required(VERSION 3.2)
project(MyApp)
add_executable(MyExe main.cpp)
```

Each line in the above example executes a built-in CMake *command*. In CMake, commands are similar to other languages' function calls, except that while they support arguments, they do not return values directly (but a later chapter shows how to pass values back to the caller in other ways). Arguments are separated from each other by spaces and may be split across multiple lines:

```
add_executable(MyExe  
    main.cpp  
    src1.cpp  
    src2.cpp  
)
```

Command names are also case-insensitive, so the following are all equivalent:

```
add_executable(MyExe main.cpp)  
ADD_EXECUTABLE(MyExe main.cpp)  
Add_Executable(MyExe main.cpp)
```

Typical style varies, but the accepted convention these days is to use all lowercase for command names. This is also the convention followed by the CMake documentation for built-in commands.

3.1. Managing CMake Versions

CMake is continually updated and extended to add support for new tools, platforms, and features. The developers behind CMake are very careful to maintain backwards compatibility

with each new release, so when users update to a newer version of CMake, projects should continue to build as they did before. Sometimes, a particular CMake behavior needs to change, or more stringent checks and warnings may be introduced in newer versions. Rather than requiring all projects to immediately deal with this, CMake provides *policy* mechanisms which allow the project to say “Behave like CMake version X.Y.Z”. This allows CMake to fix bugs internally and introduce new features, but still maintain the expected behavior of any particular past release.

The primary way a project specifies details about its expected CMake version behavior is with the `cmake_minimum_required()` command. This should always be the first line of the `CMakeLists.txt` file. It ensures that the project’s requirements are checked and established before anything else. This command does two things:

- It specifies the minimum version of CMake the project needs. If the `CMakeLists.txt` file is processed with a CMake version older than the one specified, it will halt immediately with an error. This ensures that a particular minimum set of CMake functionality is available before proceeding.
- It enforces policy settings to match CMake behavior to the specified version.

Using this command is so important that CMake 3.26 and later will issue a warning if the top level `CMakeLists.txt` file does not call `cmake_minimum_required()` before calling `project()`. CMake needs to know how to set up the policy behavior for all subsequent processing. For most projects, it is enough to treat `cmake_minimum_required()` as simply specifying the minimum required CMake version, as its name suggests. The fact that it also implies CMake should behave the same as that particular version can be considered a useful side benefit. [Chapter 13, Policies](#) discusses policy settings in more detail and explains how to tailor this behavior as needed.

The typical form of the `cmake_minimum_required()` command is straightforward:

```
cmake_minimum_required(VERSION major.minor[.patch[.tweak]])
```

The `VERSION` keyword must always be present, and the version details provided must have at least the `major.minor` part. In most projects, specifying the patch and tweak parts is not necessary, since new features typically only appear in minor version updates (this is the official CMake behavior from version 3.0 onward). Only if a specific bug fix is needed should a project specify a patch part. Furthermore, since no CMake release in the 3.x series has used a tweak number, projects should not need to specify one either.

Developers should think carefully about what minimum CMake version their project should require. Version 3.5 is the absolute oldest any new project should consider. Anything older will trigger deprecation warnings if the developer uses the latest CMake version on the project. If working with fast-moving platforms such as iOS, quite recent versions of CMake may be needed to support the latest OS and Xcode releases.

As a general rule of thumb, choose the most recent CMake version that won't present significant problems for those building the project. The greatest difficulty is typically experienced by projects that need to support older platforms where the system-provided version of CMake may be quite old. For such cases, if at all possible, developers should consider installing a more recent release rather than restricting themselves to very old CMake versions. On the other hand, if the project will itself be a dependency for other projects, then choosing a more recent CMake version may present a hurdle for adoption. In such cases, it may be beneficial to instead require the oldest CMake version that still provides the minimum CMake features needed, but make use of features from later CMake versions if available ([Chapter 13, Policies](#) presents techniques for achieving this). This will avoid forcing other projects to require a more recent version than their target environment typically allows or provides. Dependent projects can always require a more recent version if they so wish, but they cannot require an older one. The main disadvantage of

using the oldest workable version is that it may result in more deprecation warnings, since newer CMake versions will warn about older behaviors to encourage maintainers to update their project.

3.2. The project() Command

Every CMake project should contain a `project()` command, and it should appear after `cmake_minimum_required()` has been called. The command with its most common options has the following form:

```
project(projectName
    [VERSION major[.minor[.patch[.tweak]]]]
    [LANGUAGES languageName ...]
)
```

The `projectName` is required and may only contain letters, numbers, underscores (`_`) and hyphens (`-`), although typically only letters and perhaps underscores are used in practice. Since spaces are not permitted, the project name does not have to be surrounded by quotes. This name is used for the top level of a project with some project generators (Xcode and Visual Studio). It is also used in various other parts of the project, such as to act as defaults for packaging and documentation metadata, and to provide project-specific variables. The name is the only mandatory argument for the `project()` command.

The optional VERSION details are only supported in CMake 3.0 and later. Like the projectName, the version details are used by CMake to populate some variables and as default package metadata, but other than that, the version details don't have any other significance. Nonetheless, a good habit to establish is to define the project's version here so that other parts of the project can refer to it. [Chapter 22, Specifying Version Details](#) covers this in depth and explains how to refer to this version information later in the CMakeLists.txt file.

The optional LANGUAGES argument defines the programming languages that should be enabled for the project. Supported values include C, CXX, Fortran, ASM, CUDA, and others, depending on the CMake version. If specifying multiple languages, separate each with a space. In some special situations, projects may want to indicate that no languages are used, which can be done using LANGUAGES NONE. Techniques introduced in later chapters take advantage of this particular form. If no LANGUAGES option is provided, CMake will default to C and CXX. CMake versions prior to 3.0 do not support the LANGUAGES keyword, but languages can still be specified after the project name using the older form of the command like so:

```
project(MyProj C CXX)
```

New projects are encouraged to specify a minimum CMake version of at least 3.0 and use the new form with the LANGUAGES

keyword instead.

The `project()` command does much more than populate a few variables. One of its important responsibilities is to check the compilers for each enabled language and ensure they are able to compile and link successfully. Problems with the compiler and linker setup are then caught very early. Once these checks have passed, CMake sets up a number of variables and properties which control the build for the enabled languages.

[Chapter 24, Toolchains And Cross Compiling](#) discusses this area in much greater detail, including the various ways to influence toolchain selection and configuration. [Chapter 8, Using Subdirectories](#) also discusses additional considerations and requirements that affect the use of the `project()` command.

When the compiler and linker checks performed by CMake are successful, their results are cached so that they do not have to be repeated in later CMake runs. These cached details are stored in the `CMakeCache.txt` file in the build directory. Additional details about the checks can be found in subdirectories within the build area, but developers would typically only need to look there if working with a new or unusual compiler, or when setting up toolchain files for cross-compiling.

3.3. Building A Basic Executable

To complete the minimal example, the `add_executable()` command tells CMake to create an executable from a set of source files. The basic form of this command is:

```
add_executable(targetName source1 [source2 ...])
```

This creates an executable which can be referred to within the CMake project as `targetName`. This name may contain letters, numbers, underscores, and hyphens. When the project is built, an executable will be created in the build directory with a platform-dependent name. The default name for the executable is based on the target name. Consider the following simple example command:

```
add_executable(MyApp main.cpp)
```

By default, the name of the executable would be `MyApp.exe` on Windows and `MyApp` on Unix-based platforms like macOS, Linux, and others. The executable name can be customized with target properties, a CMake feature introduced in [Chapter 10, Properties](#). Multiple executables can also be defined within the one `CMakeLists.txt` file by calling `add_executable()` multiple times with different target names. If the same target name is used in more than one `add_executable()` command, CMake will fail and highlight the error.

3.4. Commenting

Before leaving this chapter, it is useful to demonstrate how to add comments to a `CMakeLists.txt` file. Comments are used extensively throughout this book, and developers are encouraged to also get into the habit of commenting their projects just as they would for ordinary source code.

CMake follows commenting conventions similar to Unix shell scripts. Any line beginning with a `#` character is treated as a comment. Except within a quoted string, anything after a `#` on a line within a `CMakeLists.txt` file is also treated as a comment.

CMake 3.0 also added support for lua-style block comments. The start of the block comment has the form `#[==[` where there can be any number of `=` characters between the square brackets, including none. Everything up until a matching `]==]` is treated as a comment, where the number of `=` characters must match the number at the start of the comment. This can be a useful way to temporarily comment out a block of code.

The following shows a few comment examples and brings together the concepts introduced in this chapter:

```
cmake_minimum_required(VERSION 3.2)

# We don't use the C++ compiler, so don't let project()
# test for it in case the platform doesn't have one
project(MyApp VERSION 4.7.2 LANGUAGES C)

# Primary tool for this project
add_executable(MainTool
    main.c
```

```
    debug.c  # Optimized away for release builds
)

# Helpful diagnostic tool for development and testing
add_executable(TestTool testTool.c)

# These tools are not ready yet, disable them
#[=[
add_executable(NewTool1 tool1.c)
add_executable(NewTool2
    tool2.c
    extras.c
)
]=]
```

3.5. Recommended Practices

Ensure every CMake project has a `cmake_minimum_required()` command as the first line of its top level `CMakeLists.txt` file. When deciding the minimum required version number to specify, keep in mind that later versions will give more freedom in using newer CMake features. It will also mean the project is likely to be better placed to adapt to new platform or operating system releases, which inevitably introduce new things for build systems to deal with. Conversely, if the project is intended to be built and distributed as part of the operating system (common for Linux), the minimum CMake version is likely to be dictated by the version of CMake provided by that same distribution.

It is good to force thinking about project version numbers early and start incorporating version numbering into the `project()`

command as soon as possible. It can be difficult to overcome the inertia of existing processes and change how version numbers are handled later in the life of a project. Consider popular practices such as [Semantic Versioning](#) when deciding on a versioning strategy.

4. BUILDING SIMPLE TARGETS

As shown in the previous chapter, defining a simple executable in CMake is relatively straightforward. The simple example given previously required defining a target name for the executable and listing the source files to be compiled:

```
add_executable(MyApp main.cpp)
```

This assumes the developer wants a basic console executable to be built. But CMake also allows the developer to define other types of executables, such as app bundles on Apple platforms, and Windows GUI applications. This chapter discusses additional options which can be given to `add_executable()` to specify these details.

In addition to executables, developers also frequently need to build and link libraries. CMake supports a few different kinds of libraries, including static, shared, modules, and frameworks. CMake also offers very powerful features for managing dependencies between targets and how libraries are linked. This whole area of libraries and how to work with them in CMake forms the bulk of this chapter. The concepts covered

here are used extensively throughout this book. Some very basic use of variables and properties are also given to provide a flavor for how these CMake features relate to libraries and targets in general.

4.1. Executables

The more complete form of the basic `add_executable()` command is as follows:

```
add_executable(targetName [WIN32] [MACOSX_BUNDLE]
               [EXCLUDE_FROM_ALL]
               source1 [source2 ...]
)
```

The only differences to the form shown previously are the new optional keywords.

WIN32

When building the executable on a Windows platform, this option instructs CMake to build the executable as a Windows GUI application. In practice, this means it will be created with a `WinMain()` entry point instead of just `main()`, and it will be linked with the `/SUBSYSTEM:WINDOWS` option. On all other platforms, the `WIN32` option is ignored.

MACOSX_BUNDLE

When present, this option directs CMake to build an app bundle when building on an Apple platform. Contrary to

what the option name suggests, it applies not just to macOS, but also to other Apple platforms like iOS. The exact effects of this option vary somewhat between platforms. For example, on macOS, the app bundle layout has a very specific directory structure, whereas on iOS, the directory structure is flattened. CMake will also generate a basic Info.plist file for bundles. These and other details are covered in more detail in [Section 25.2, “Application Bundles”](#). On non-Apple platforms, the MACOSX_BUNDLE keyword is ignored.

EXCLUDE_FROM_ALL

Sometimes, a project defines a number of targets, but by default only some of them should be built. When no target is specified at build time, the default ALL target is built. Depending on the CMake generator used, the name may be slightly different, such as ALL_BUILD for Xcode, or all when using one of the Makefiles or Ninja generators. If an executable is defined with the EXCLUDE_FROM_ALL option, it will not be included in that default ALL target. The executable will then only be built if it is explicitly requested by the build command, or if it is a dependency for another target that is part of the default ALL build. A common situation where it can be useful to exclude a target from ALL is where the executable is a developer tool that is only needed occasionally.

In addition to the above, there are other forms of the `add_executable()` command which produce a kind of reference to an existing executable or target rather than defining a new one to be built. These alias executables are covered in detail in [Chapter 19, Target Types](#).

```
# Main GUI app, built as part of the default "ALL" target
add_executable(MyApp WIN32 MACOSX_BUNDLE
    main.cpp
    widgets.cpp
)

# Helpful command-line tools, not built by default
add_executable(checker checker.cpp EXCLUDE_FROM_ALL)
add_executable(reporter reporter.cpp EXCLUDE_FROM_ALL)
```

The following command will only build `MyApp`:

```
cmake --build /path/to/build
```

A helper tool can be built on-demand like so:

```
cmake --build /path/to/build --target checker
```

4.2. Defining Libraries

Creating simple executables is a fundamental need of any build system. For many larger projects, the ability to create and work with libraries is also essential to keep the project manageable. CMake supports building a variety of different kinds of libraries, taking care of many of the platform differences, but

still supporting the native idiosyncrasies of each. Library targets are defined using the `add_library()` command, of which there are a number of forms. The most basic of these is the following:

```
add_library(targetName [STATIC | SHARED | MODULE]
            [EXCLUDE_FROM_ALL]
            source1 [source2 ...]
        )
```

This form is analogous to how `add_executable()` is used to define a simple executable. The `targetName` is used within the `CMakeLists.txt` file to refer to the library, with the name of the built library on the file system being derived from this name by default. The `EXCLUDE_FROM_ALL` keyword has exactly the same effect as it does for `add_executable()`, namely to prevent the library from being included in the default `ALL` target. The type of library to be built is specified by one of the remaining three keywords `STATIC`, `SHARED`, or `MODULE`.

STATIC

This specifies a static library or archive. On Windows, the default library name would be `targetName.lib`, while on Unix-like platforms, it would typically be `libtargetName.a`.

SHARED

This specifies a shared or dynamically linked library. On Windows, the default library name would be `targetName.dll`,

on Apple platforms it would be `libtargetName.dylib`, and on other Unix-like platforms it would typically be `libtargetName.so`. On Apple platforms, shared libraries can also be marked as frameworks, a topic covered in [Section 25.3, “Frameworks”](#).

MODULE

Specifies a library that is somewhat like a shared library, but is intended to be loaded dynamically at run-time rather than being linked directly to a library or executable. These are typically plugins or optional components the user may choose to have loaded or not. On Windows platforms, no import library is created for the DLL.

It is possible to omit the keyword defining what type of library to build. Unless the project specifically requires a particular type of library, the preferred practice is to not specify it and leave the choice up to the developer when building the project. In such cases, the library will be either STATIC or SHARED, with the choice determined by the value of a CMake variable called `BUILD_SHARED_LIBS`. If `BUILD_SHARED_LIBS` has been set to `true`, the library target will be a shared library, otherwise it will be static. Working with variables is covered in detail in [Chapter 6, Variables](#), but for now, one way to set this variable is by including a `-D` option on the `cmake` command line like so:

```
cmake -DBUILD_SHARED_LIBS=YES -B /path/to/build
```

It could be set in the `CMakeLists.txt` file instead with the following placed before any `add_library()` commands, but that would then require developers to modify it if they wanted to change it (i.e. it would be less flexible):

```
set(BUILD_SHARED_LIBS YES)
```

Just as for executables, library targets can also be defined to refer to some existing binary or target rather than being built by the project. Another type of pseudo-library is also supported for collecting together object files without going as far as creating a static library. These are all discussed in detail in [Chapter 19, Target Types](#).

4.3. Linking Targets

When considering the targets that make up a project, developers are typically used to thinking in terms of library A needing library B, so A is linked to B. This is the traditional way of looking at library handling, where the idea of one library needing another is very simplistic. In reality, there are a few different types of dependency relationships that can exist between libraries:

PRIVATE

Private dependencies specify that library A uses library B in its own internal implementation. Anything else that links to

library A doesn't need to know about B because it is an internal implementation detail of A.

PUBLIC

Public dependencies specify that not only does library A use library B internally, it also uses B in its interface. This means that A cannot be used without B, so anything that uses A will also have a direct dependency on B. An example of this would be a function defined in library A which has at least one parameter of a type defined and implemented in library B, so code cannot call the function from A without providing a parameter whose type comes from B.

INTERFACE

Interface dependencies specify that in order to use library A, parts of library B must also be used. This differs from a public dependency in that library A doesn't require B internally, it only uses B in its interface. An example of where this is useful is when working with library targets defined using the INTERFACE form of `add_library()`, such as when using a target to represent a header-only library's dependencies (see [Section 19.2.4, “Interface Libraries”](#)).

CMake captures this richer set of dependency relationships with its `target_link_libraries()` command, not just the simplistic idea of needing to link. The general form of the command is:

```
target_link_libraries(targetName
    <PRIVATE|PUBLIC|INTERFACE> item1 [item2 ...]
    [<PRIVATE|PUBLIC|INTERFACE> item3 [item4 ...]]...
)
```

This allows projects to precisely define how one library depends on others. CMake then takes care of managing the dependencies throughout the chain of libraries linked in this fashion. For example:

```
add_library(Collector src1.cpp)
add_library(Algo src2.cpp)
add_library(Engine src3.cpp)
add_library(Ui src4.cpp)
add_executable(MyApp main.cpp)

target_link_libraries(Collector
    PUBLIC Ui
    PRIVATE Algo Engine
)
target_link_libraries(MyApp PRIVATE Collector)
```

In the above, the `Ui` library is linked to the `Collector` library as `PUBLIC`, so even though `MyApp` only directly links to `Collector`, `MyApp` will also be linked to `Ui` because of that `PUBLIC` relationship. On the other hand, the `Algo` and `Engine` libraries are linked to `Collector` as `PRIVATE`, so `MyApp` will not be directly linked to them. [Section 16.2.1, “Linking Libraries”](#) and [Section 23.2, “Linking Static Libraries”](#) discuss additional behaviors for static libraries which may result in further linking to satisfy dependency relationships, including cyclic dependencies.

Later chapters present a few other `target_...()` commands which further enhance the dependency information carried between targets. These allow header search paths, compiler definitions, and other compiler and linker options to also carry through from one target to another when they are connected by `target_link_libraries()`. These features were added progressively from CMake 2.8.11 through to 3.2, and they lead to considerably simpler and more robust `CMakeLists.txt` files.

Later chapters also discuss the use of more complex source directory hierarchies. In such cases, if using CMake 3.12 or earlier, the `targetName` used with `target_link_libraries()` must have been defined by an `add_executable()` or `add_library()` command in the same directory from which `target_link_libraries()` is being called (this restriction was removed in CMake 3.13).

4.4. Linking Non-targets

In the preceding section, all the items being linked to were existing CMake targets, but the `target_link_libraries()` command is more flexible than that. In addition to CMake targets, the following things can also be specified as items in a `target_link_libraries()` command:

Full path to a library file

CMake will add the library file to the linker command. If the library file changes, CMake will detect that change and re-link the target. With CMake 3.3 and later, the linker command always uses the full path given. Prior to version 3.3, there were some situations where CMake may ask the linker to search for the library instead, replacing a path like `/usr/lib/libfoo.so` with something like `-lfoo`. The reasoning behind the pre-3.3 behavior is non-trivial and largely historical. A more complete discussion can be found in the CMake documentation for the `CMP0060` policy.

Plain library name

If just the name of the library is given with no path, the linker command will search for that library (e.g. `foo` becomes `-lfoo` or `foo.lib`, depending on the platform). This is sometimes used for libraries provided by the system, but there are cases where that may be undesirable (see [Section 18.1, “Require Targets For Linking”](#)).

Link flag

As a special case, items starting with a hyphen other than `-l` or `-framework` will be treated as flags to be added to the linker command. Projects should avoid using this feature and instead use the dedicated support for adding linker options (see [Section 16.1.2, “Linker Flags”](#) and [Section 16.2.2, “Linker Options”](#)).

4.5. Old-style CMake

For historical reasons, any link item specified in `target_link_libraries()` may be preceded by one of the keywords `debug`, `optimized`, or `general`. The effect of these keywords is to further refine when the item following it should be included based on whether the build is configured as a debug build (see [Chapter 15, Build Type](#)). If an item is preceded by the `debug` keyword, then it will only be added if the build is a debug build. If an item is preceded by the `optimized` keyword, it will only be added if the build is not a debug build. The `general` keyword specifies that the item should be added for all build configurations, which is the default behavior anyway if no keyword is used. The `debug`, `optimized` and `general` keywords should be avoided for new projects, as there are clearer, more flexible, and more robust ways to achieve the same thing with today's CMake features.

The `target_link_libraries()` command also has a few other forms, some of which have been part of CMake from well before version 2.8.11. These forms are discussed here for the benefit of understanding older CMake projects, but their use is generally discouraged for new projects. The full form shown previously with `PRIVATE`, `PUBLIC`, and `INTERFACE` sections should be preferred, as it expresses the nature of dependencies with more accuracy.

```
target_link_libraries(targetName item [item...])
```

The above form is generally equivalent to the items being defined as PUBLIC, but in certain situations, they may instead be treated as PRIVATE. If a project defines a chain of library dependencies with a mix of old and new command forms, CMake will halt with an error unless very old policy settings are used ([Chapter 13, Policies](#) discusses the general feature, policy CMP0023 controls this specific behavior).

Another supported but deprecated form is the following:

```
target_link_libraries(targetName
    LINK_INTERFACE_LIBRARIES item [item...]
)
```

This is a precursor to the INTERFACE keyword of the newer form covered above, but its use is discouraged by the CMake documentation. Its behavior can affect different target properties, with the policy settings controlling that behavior. This is a potential source of confusion for developers, which can be avoided by using the newer INTERFACE form instead.

```
target_link_libraries(targetName
    <LINK_PRIVATE|LINK_PUBLIC> lib [lib...]
    [<LINK_PRIVATE|LINK_PUBLIC> lib [lib...]]
)
```

Similar to the previous old-style form, this one is a precursor to the PRIVATE and PUBLIC keyword versions of the newer form. Again, the old-style form has the same confusion over which

target properties it affects, and the PRIVATE/PUBLIC keyword form should be preferred for new projects.

4.6. Recommended Practices

Target names need not be related to the project name. While they are sometimes the same, the two things are separate concepts. Changing one shouldn't imply that the other must also change. Project and target names should rarely change anyway, since doing so would break any downstream consumer that relied on the existing names. Therefore, set the project name directly rather than via a variable. Choose a target name according to what the target does rather than the project it is part of. Assume the project will eventually need to define more than one target. These practices reinforce better habits, which will be important when working on more complex, multi-target projects.

It is common to see tutorials and examples define a variable for the project name, and then reuse that variable for the name of an executable or library target. Another common variation uses the PROJECT_NAME variable, which is set automatically by the project() command. Both practices should be avoided.

```
# BAD: Don't use a variable to set the project name,  
# set it directly  
set(projectName MyExample)  
project(${projectName})
```

```
# BAD: Don't set the target name from the project name  
add_executable(${ projectName } ...)
```

```
# GOOD: Set the project name directly  
project(MyProj)
```

```
# BAD: Don't set the target name from the project name  
add_executable(${ PROJECT_NAME } ...)
```

```
# GOOD: Set the project name directly  
project(MyProj)
```

```
# GOOD: Target name is independent of the project name  
add_executable(MyThing ...)
```

When naming targets for libraries, resist the temptation to start or end the name with `lib`. On just about all platforms except Windows, a leading `lib` will be prefixed automatically when constructing the actual library name to make it conform to the platform's usual convention. If the target name already begins with `lib`, the library file names end up with the form `liblibsomething....`, which people often assume to be a mistake.

Avoid specifying the `STATIC` or `SHARED` keyword for a library until it is known to be needed. This allows greater flexibility in choosing between static or dynamic libraries as an overall project-wide strategy. The `BUILD_SHARED_LIBS` variable can be used to change the default in one place instead of having to modify every call to `add_library()`.

Always specify PRIVATE, PUBLIC, or INTERFACE keywords when calling the target_link_libraries() command rather than following the old-style CMake syntax which assumed everything was PUBLIC. As a project grows in complexity, these three keywords have a stronger impact on how inter-target dependencies are handled. Using them from the beginning of a project also forces developers to think about the dependencies between targets, which can help to highlight structural problems within the project much earlier.

5. BASIC TESTING AND DEPLOYMENT

CMake provides a variety of features for testing a project, installing it, and producing packages. The features associated with each of these activities can be overwhelming, in large part because the activities themselves are complex. The sheer number of different things done by various platforms, testing tools, and packaging systems is often underappreciated. CMake aims to simplify that complexity by presenting a more consistent interface and set of controls, while still providing access to low-level features where needed. As a result, understanding a few basics is generally enough to start exploring each of these topics and obtain useful results.

5.1. Testing

CMake provides a separate command-line tool called `ctest`. It can be thought of as a test scheduling and reporting tool, offering close integration with CMake for defining tests in a convenient and flexible way. Typically, CMake will generate the

input file necessary for `ctest` based on details provided by the project.

The following minimal example shows how to define a project with a couple of simple test cases:

```
cmake_minimum_required(VERSION 3.19)
project(MyProj VERSION 4.7.2)

enable_testing()

add_executable(testSomething testSomething.cpp)

add_test(
    NAME SomethingWorks
    COMMAND testSomething
)
add_test(
    NAME ExternalTool
    COMMAND /path/to/tool someArg moreArg
)
```

The `enable_testing()` call is needed to instruct CMake to produce an input file for `ctest`. It should generally be called just after `project()`.

The `add_test()` command is how a project can define a test case. It supports a couple of different forms, but the one shown above with `NAME` and `COMMAND` keywords is recommended.

The argument following `NAME` should generally contain only letters, numbers, hyphens, and underscores. Other characters may be supported if using CMake 3.19 or later, but projects

should avoid anything complicated and stick with these basic characters in most cases.

The COMMAND can be any arbitrary command that could be run from a shell or command prompt. As a special case, it can also be the name of an executable target defined by the project. CMake will then translate that target name into the location of the binary built for that target. In the above example, the SomethingWorks test will run the executable built for the testSomething CMake target. The project doesn't have to care where the build will create the binary in the file system, CMake will provide that information to ctest automatically.

By default, a test is deemed to pass if it returns an exit code of 0. Much more detailed and flexible criteria can be defined, which is covered in [Section 27.3, “Pass / Fail Criteria And Other Result Types”](#), but a simple check of the exit code is often sufficient.

The following sequence of steps will configure, build, and test a project. Any CMake generator could be used, but this example uses Ninja. It configures the build to use the Debug configuration, and ctest will detect that automatically.

```
cmake -G Ninja -B build -DCMAKE_BUILD_TYPE=Debug  
cd build  
cmake --build .  
ctest
```

Some generators are multi-configuration, like Xcode, Visual Studio, and Ninja Multi-Config. When using such generators, the configuration to build and test needs to be provided at build and test time:

```
cmake -G "Ninja Multi-Config" -B build
cd build
cmake --build . --config Debug
ctest --build-config Debug
```

For convenience, `-C` can be used instead of the longer `--build-config` with the `ctest` command.

If there are many tests, and they take non-trivial time to run, they can be executed in parallel:

```
ctest --parallel 16
```

The shorter `-j` option can also be used instead of `--parallel`. The number after the keyword specifies how many tests can run at the same time. In more advanced scenarios, a test can be allocated more than one CPU, which is discussed in [Section 28.3, “Parallel Execution”](#).

The default output from `ctest` is fairly concise. Output from passing and failing tests will be hidden, with only the results being shown. Full output can be obtained with the `-V` or `--verbose` option, or just the output of failing tests with `--output-on-failure`.

As a convenience, CMake also defines a test build target, which runs `ctest` with a default set of options. These default settings run all tests and provide only limited control over the test output and the way tests are run (CMake 3.17 and later does support specifying additional options through the `CMAKE_CTEST_ARGUMENTS` variable). The test build target can be useful as a way to run tests in IDEs that don't provide a dedicated feature for running `ctest` tests. But generally, developers are better off learning to run `ctest` directly to take advantage of the many options it supports.

CMake and `ctest` offer much more functionality than discussed above. [Part IV, “Testing And Analysis”](#) includes a number of chapters that walk through many of the powerful and flexible features available.

5.2. Installing

While things built by a project can often be used directly from the build directory, that's often just a stepping stone on the way to deploying the project. Deployment can take different forms, but a common element to most of them is an install step. During installation, files are copied from the build directory (and possibly the source directory) to the install location. Files may be transformed in some way before or after the copy.

CMake provides direct support for installing different types of artifacts. The `install()` command provides the majority of that

functionality, and it has a number of different forms. The following minimal example uses the `install(TARGETS)` form to install a few CMake targets.

```
cmake_minimum_required(VERSION 3.14)
project(MyProj VERSION 4.7.2)

add_executable(MyApp ...)
add_library(AlgoRuntime SHARED ...)
add_library(AlgoSDK STATIC ...)

# This concise form requires CMake 3.14 or later
install(TARGETS MyApp AlgoRuntime AlgoSDK)
```

The above example takes advantage of features added in CMake 3.14. When no destinations are given to tell CMake where to install the targets, CMake will use default locations that correspond to the convention used on most Unix systems. The same layout also typically works fine on Windows, so it can generally be used everywhere except for application bundles on Apple platforms, which have their own unique directory structure (discussed in detail in [Section 25.2.1, “Bundle Structure”](#) and [Section 25.3.1, “Framework Structure”](#)). CMake’s default layout will install executables to a `bin` subdirectory below the base install location, libraries in a `lib` subdirectory, and headers in an `include` subdirectory. On Windows, DLL libraries would be installed to `bin` rather than `lib`.

If using CMake 3.13 or earlier, no default destinations are provided, and the project must specify them explicitly. The

equivalent `install()` command to the previous example would then look like this:

```
install(TARGETS MyApp AlgoRuntime AlgoSDK
        RUNTIME DESTINATION bin
        LIBRARY DESTINATION lib
        ARCHIVE DESTINATION lib
)
```

[Section 35.2, “Installing Project Targets”](#) goes into detail about what `RUNTIME`, `LIBRARY`, and `ARCHIVE` mean, along with a range of other types of installable entities associated with a target. It also discusses the handling of symbolic links created for shared libraries when they have version details associated with them, which is a separate topic covered in [Section 23.3, “Shared Library Versioning”](#).

Files and directories can also be installed. The following demonstrates how header files have traditionally been installed until more recent CMake versions:

```
install(FILES things.h algo.h DESTINATION include/myproj)
install(DIRECTORY headers/myproj DESTINATION include)
```

The `install(FILES)` form requires each file to be listed individually. This is useful when only some files within a directory should be installed. The `install(DIRECTORY)` form recursively copies the specified directory to the destination. To copy the *contents* of the directory rather than the directory itself, append a trailing `/` to the directory name. For example, if

the only thing in the headers directory was a `myproj` subdirectory, the following command would be equivalent to the one above:

```
install(DIRECTORY headers/ DESTINATION include)
```

With CMake 3.23 or later, a more powerful, more convenient way of handling headers is to use *file sets*. A file set can associate headers with a target, and the headers can be installed along with the target in an `install(TARGETS)` call. No separate `install(FILES)` or `install(DIRECTORY)` call is needed. In addition, a file set provides information about whether a header is private or public, and also about the header search paths a consumer of the target must use.

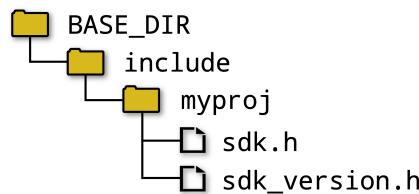
File sets are defined by the `target_sources()` command. [Section 16.2.7, “File Sets”](#), [Section 32.6, “File Sets Header Verification”](#), and [Section 35.5.1, “File Sets”](#) discuss the topic in detail, but for now, the following example shows how a public headers file set might be defined and installed:

```
add_library(AlgoSDK ...)

target_sources(AlgoSDK
  PUBLIC
    FILE_SET api
    TYPE HEADERS
    BASE_DIRS headers
    FILES
      headers/myproj/sdk.h
      headers/myproj/sdk_version.h
)
```

```
install(TARGETS AlgoSDK FILE_SET api)
```

As mentioned earlier, CMake 3.14 and later will use `include` as a default destination for headers when no destination is provided. And when file sets are installed as part of a target, the relative structure below the file set's `BASE_DIRS` will be preserved. Thus, the directory structure of the installed headers resulting from the above example would be:



When installing libraries and headers for other projects to build against, it is recommended to provide a set of CMake-specific config package files as well. These files give the consuming project a CMake target they can link against, and that target will include header search path details to be applied to the consumer. The `install(EXPORT)` sub-command is typically used to produce some of these config package files. This more complex topic is discussed in [Section 35.3, “Installing Exports”](#) and [Section 35.9, “Writing A Config Package File”](#). The consumer imports the package with a command called `find_package()`, which is covered in detail in [Section 34.4, “Finding Packages”](#).

The following sequence of commands shows how to configure, build, and install a project:

```
cmake -G Ninja -B build -DCMAKE_BUILD_TYPE=Debug  
cd build  
cmake --build .  
cmake --install . --prefix /path/to/somewhere
```

These steps are very similar to those given earlier for the example in [Section 5.1, “Testing”](#), except the last command is different. The `cmake --install <buildDir>` form is available with CMake 3.15 or later. The `--prefix <installDir>` option specifies the base install location to install the project to. If `--prefix` is not given, the install location is taken from a platform-dependent value set during the configure step. See the discussion of `CMAKE_INSTALL_PREFIX` in [Section 35.1.2, “Base Install Location”](#) for further details on that aspect.

As was the case for testing, multi-configuration generators are also supported for installs too. The configuration must be specified as part of the build and install steps:

```
cmake -G "Ninja Multi-Config" -B build  
cd build  
cmake --build . --config Debug  
cmake --install . --config Debug --prefix /path/to/somewhere
```

CMake also provides an `install` build target, which can be used to install the project with default options. It isn’t as flexible as running `cmake --install`, but it is supported for all CMake

releases, not just CMake 3.15 or later. The `cmake --install` command accepts a few other options not shown above (see [Section 35.10, “Executing An Install”](#)), whereas the `install` build target has limited customizability.

Once a project grows beyond a single application or library, installing everything in a single package may no longer be appropriate. The project may want to split up the installation into separate *components*. CMake has extensive support for this, but it is not a simple topic. Splitting up a project into multiple components affects not just what is installed, but also raises questions like "What dependencies exist between the components?", and "How should components map to separate packages, or installable units within a packaged product?". Components are discussed throughout [Chapter 35, *Installing*](#), and [Section 36.2, “Components”](#) focuses specifically on the packaging aspects.

5.3. Packaging

Installing a project built from sources was once a widespread way for users to install software. However, many projects can't provide source files for the user to build themselves. These days, users also tend to expect pre-built packages instead.

CMake provides the `cpack` tool, which can produce binary packages in a variety of formats. These include simple archives like `.zip`, `.tar.gz`, and `.7z` packages for platform-specific

packaging systems like RPM, DEB, MSI, and even standalone graphical installers. These are all based on installing a project using the information provided through `install()` commands, and others. Internally, `cpack` effectively does one or more `cmake --install` commands with `--prefix` set to a temporary staging area. The contents of that staging area are then used to create a package in the relevant format.

Basic packaging is implemented by setting some relevant CMake variables, then including a CMake module called `CPack`, which writes out an input file for the `cpack` tool. CMake modules are introduced in [Chapter 12, *Modules*](#), CMake variables in [Chapter 6, *Variables*](#), and [Chapter 36, *Packaging*](#) covers packaging in detail. For now, the following minimal example shows how to put these things together in a fairly simple way:

```
cmake_minimum_required(VERSION 3.14)
project(MyProj VERSION 4.7.2)

add_executable(MyApp ...)
add_library(AlgoRuntime SHARED ...)
add_library(AlgoSDK STATIC ...)

install(TARGETS MyApp AlgoRuntime AlgoSDK)

# These are project-specific
set(CPACK_PACKAGE_NAME MyProj)
set(CPACK_PACKAGE_VENDOR MyCompany)
set(CPACK_PACKAGE_DESCRIPTION_SUMMARY "An example project")

# These lines tend to be the same for every project
set(CPACK_PACKAGE_INSTALL_DIRECTORY ${CPACK_PACKAGE_NAME})
set(CPACK_VERBATIM_VARIABLES TRUE)
```

```
# This is what writes out the input file for cpack
include(CPack)
```

The various `set(...)` lines in the above example demonstrate setting CMake variables. The values only need to be surrounded in quotes if they contain spaces. A real project would set more variables than these, but the above is enough to get started producing a working package. [Section 36.1, “Packaging Basics”](#) provides more complete guidance on a minimum set of variables a project should set for production-grade packages.

Note the `VERSION` keyword in the `project()` call. It is a convenient way of providing a default value for the package version when using CMake 3.12 or later. As noted back in [Section 3.2, “The `project\(\)` Command”](#), it can also be used in other ways by the project, such as embedding the version number in source files compiled for the project (covered in [Chapter 22, *Specifying Version Details*](#)).

The following familiar set of steps demonstrates how to configure, build, and package a project:

```
cmake -G Ninja -B build -DCMAKE_BUILD_TYPE=Release
cd build
cmake --build .
cpack -G "ZIP;WIX"
```

Once again, only the last line is significantly different to earlier examples (the above also configures for Release rather than

Debug, since that's more typical for pre-built packages). The `cpack -G` option specifies the package formats to generate. When more than one format is given, they must be separated by a semicolon. The list of supported formats varies by platform and can be obtained by running `cpack --help`.

As expected, multi-configuration generators are supported, and the configuration must be specified when building and when packaging:

```
cmake -G "Ninja Multi-Config" -B build
cd build
cmake --build . --config Release
cpack -G "ZIP;WIX" -C Release
```

Continuing the familiar pattern, CMake provides a package build target, which runs `cpack` with the options specified by the project. Again, customizability is very limited when building the package target instead of running `cpack` directly. When using the package build target, a default set of package generators will be used, but that default set is unlikely to be appropriate. The project can override the default set by setting the `CPACK_GENERATOR` variable before calling `include(CPack)`. The list of generators will typically be different for each major platform, so some conditional logic is likely to be needed (see [Chapter 7, *Flow Control*](#)). The following example taken from [Section 36.1, “Packaging Basics”](#) provides a good starting point.

```
if(WIN32)
    set(CPACK_GENERATOR ZIP WIX)
elseif(APPLE)
    set(CPACK_GENERATOR TGZ productbuild)
elseif(CMAKE_SYSTEM_NAME STREQUAL "Linux")
    set(CPACK_GENERATOR TGZ RPM)
else()
    set(CPACK_GENERATOR TGZ)
endif()
```

The `cpack -G` option overrides any list set by the project with the `CPACK_GENERATOR` variable, so the command line still has full control.

5.4. Recommended Practices

Get familiar with the `ctest` and `cpack` command line tools. These support various options which are not available when building the corresponding test and package targets. The `ctest` tool in particular has many useful options that are instrumental in day-to-day development when running tests.

When using a multi-configuration generator like Xcode, Visual Studio, or Ninja Multi-Config, beware of the inconsistencies in how the build configuration is specified across the different command-line tools. When building with `cmake --build`, the `--config` option specifies the build configuration, but `ctest` and `cpack` use `-C` instead. Be especially careful with `cpack`, which confusingly also supports a `--config` option that has nothing to do with the build configuration.

When developing the project and modifying its `install()` commands, doing test installs to a temporary staging area is a useful technique. Use commands like `cmake --install` with the `--prefix` option pointing at the staging area to confirm the installed contents match the expected set of files. The temporary staging area should first be wiped to ensure no contents from any previous test install are left behind.

Avoid doing direct installs from the build tree to permanent or system-wide locations. Consider producing a binary package and installing that instead as two separate steps. Installing directly from a build directory may require administrative privileges, and some aspects of doing an install may modify the contents of the build directory and change file or directory ownership. This can cause hard-to-trace build errors later when the build runs under the non-administrative account, but is unable to modify things it normally would be able to.

If the project can set its minimum CMake version to 3.23 or higher, invest some time learning about CMake file sets (see [Section 16.2.7, “File Sets”](#) and [Section 35.5.1, “File Sets”](#)). Put all the project’s header files in file sets, and use separate PRIVATE and PUBLIC file sets to clearly define which ones are meant to be installed, and which ones are not. This will also simplify the handling of header search paths, both when building the project, and when it is installed.

II: FUNDAMENTALS

This part of the book follows a logical progression through CMake's more fundamental features and concepts. It is structured to enable the reader to immediately experiment, and to do increasingly useful things with each chapter. The goal is to incrementally build up the base knowledge needed to use CMake effectively, with an emphasis on being able to put that knowledge into practice right away.

The chapters also establish good habits, teaching sound methods that scale to large projects and more complex scenarios. The later parts of the book assume a good grasp of all the fundamental material covered here.

Those who have already been using CMake for some time may find the earlier chapters in this part of the book relatively familiar. However, the material also includes hard-won knowledge from real world projects and interaction with the CMake community. Even experienced users should find at least the *Recommended Practices* section at the end of each chapter to be a useful read.

The last chapter in this part of the book, [Chapter 16, Compiler And Linker Essentials](#), is one of the most important. It draws heavily on the chapters before it, covering fundamental commands and concepts that are at the heart of every CMake project.

6. VARIABLES

The preceding chapters showed how to define basic targets and produce build outputs. On its own, this is already useful, but CMake comes with a whole host of other features which bring great flexibility and convenience. This chapter covers one of the most fundamental parts of CMake, namely the use of variables.

6.1. Variable Basics

Like any computing language, variables are a cornerstone of getting things done in CMake. The most basic way of defining a variable is with the `set()` command. A normal variable can be defined in a `CMakeLists.txt` file as follows:

```
set(varName value... [PARENT_SCOPE])
```

The name of the variable, `varName`, can contain letters, numbers, and underscores, with letters being case-sensitive. The name may also contain the characters `./-+` but these are rarely seen in practice. Other characters are also possible via indirect means, but again, they are not typically seen in normal use.

In CMake, a variable has a particular scope, much like how variables in other languages have scope limited to a particular function, file, etc. A variable cannot be read or modified outside its own scope. Compared to other languages, variable scope is a little more flexible in CMake, but for now, consider the scope of a variable as being the file it is defined in. [Section 6.4, “Scope Blocks”](#) discusses how to define a local scope and pass information back up to enclosing scopes. [Chapter 8, Using Subdirectories](#) and [Chapter 9, Functions And Macros](#) introduce further situations where local scopes arise.

CMake treats all variables as strings. In various contexts, variables may be interpreted as a different type, but ultimately, they are just strings. When setting a variable’s value, CMake doesn’t require those values to be quoted unless the value contains spaces. If multiple values are given, the values will be joined together with a semicolon separating each value. The resultant string is how CMake represents lists. The following demonstrates the behavior:

```
set(myVar a b c)      # myVar = "a;b;c"  
set(myVar a;b;c)      # myVar = "a;b;c"  
set(myVar "a b c")    # myVar = "a b c"  
set(myVar a b;c)      # myVar = "a;b;c"  
set(myVar a "b c")    # myVar = "a;b c"
```

The value of a variable is obtained with `${myVar}`, which can be used anywhere a string or variable is expected. CMake is particularly flexible in that it is also possible to use this form

recursively, or to specify the name of another variable to set. CMake also doesn't require variables to be defined before using them. Using an undefined variable results in an empty string being substituted, similar to Unix shell script behavior. By default, no warning is issued for use of an undefined variable, but the `--warn-uninitialized` option can be given to the `cmake` command to enable such warnings. Using undefined variables is common practice though, and it is not necessarily a symptom of a problem. The usefulness of the `--warn-uninitialized` option may therefore be limited.

```
set(foo ab)          # foo    = "ab"
set(bar ${foo}cd)    # bar    = "abcd"
set(baz ${foo} cd)   # baz    = "ab;cd"
set(myVar ba)        # myVar = "ba"
set(big "${${myVar}r}ef") # big    = "${bar}ef" = "abcdef"
set(${foo} xyz)      # ab    = "xyz"
set(bar ${notSetVar}) # bar    = ""
```

Strings are not restricted to being a single line, they can contain embedded newline characters. They can also contain quotes, which require escaping with backslashes.

```
set(myVar "goes here")
set(multiLine "First line ${myVar}
Second line with a \"quoted\" word")
```

If using CMake 3.0 or later, an alternative to quotes is to use the lua-inspired bracket syntax where the start of the content is marked by [= [and the end with]=]. Any number of = characters can appear between the square brackets, including

none at all, but the same number of = characters must be used at the start and the end. If the opening brackets are immediately followed by a newline character, that first newline is ignored, but subsequent newlines are not. Furthermore, no further transformation of the bracketed content is performed (i.e. no variable substitution or escaping).

```
# Simple multi-line content with bracket syntax,
# no = needed between the square bracket markers
set(multiLine [[
First line
Second line
]])

# Bracket syntax prevents unwanted substitution
set(shellScript [=[
#!/bin/bash

[[ -n "${USER}" ]] && echo "Have USER"
]=])

# Equivalent code without bracket syntax
set(shellScript
"#!/bin/bash

[[ -n \"\$${USER}\\" ]] && echo \"Have USER\"
")
```

As the above example shows, bracket syntax is particularly well suited to defining content like Unix shell scripts. Such content uses the \${...} syntax for its own purpose and frequently contains quotes, but using bracket syntax means these things do not have to be escaped, unlike the traditional quoting style of defining CMake content. The flexibility to use any number of =

characters between the [and] markers also means embedded square brackets do not get misinterpreted as markers. [Chapter 21, Working With Files](#) includes further examples which highlight situations where bracket syntax can be a better alternative.

A variable can be unset either by calling `unset()` or by calling `set()` with no value for the named variable. The following are equivalent, with no error or warning if `myVar` does not already exist:

```
set(myVar)
unset(myVar)
```

In addition to variables defined by the project for its own use, the behavior of many of CMake's commands can be influenced by the value of specific variables at the time the command is called. This is a common pattern used by CMake to tailor command behavior, or to modify defaults so they don't have to be repeated for every command, target definition, etc. The CMake reference documentation for each command typically lists any variables that can affect the command's behavior. Later chapters of this book also highlight a number of useful variables and the way they affect or give information about the build.

6.2. Environment Variables

CMake also allows the value of environment variables to be retrieved and set using a modified form of the CMake variable notation. The value of an environment variable is obtained using the special form `$ENV{varName}`, which can be used almost anywhere a regular `${varName}` form can be used. Setting an environment variable can be done in a similar way to a CMake variable, except with `ENV{varName}` instead of just `varName` as the variable to set. For example:

```
set(ENV{PATH} "$ENV{PATH}:/opt/myDir")
```

Note that setting an environment variable like this only affects the currently running CMake instance. As soon as the CMake run is finished, the change to the environment variable is lost. In particular, the change to the environment variable will not be visible at build time. Therefore, setting environment variables within the `CMakeLists.txt` file like this is rarely useful.

6.3. Cache Variables

In addition to normal variables discussed in [Section 6.1, “Variable Basics”](#), CMake also supports *cache* variables. Unlike normal variables which have a lifetime limited to the processing of the `CMakeLists.txt` file, cache variables are stored in the special file called `CMakeCache.txt` in the build directory, and they persist between CMake runs. Once set, cache variables remain set until something explicitly removes them from the cache.

One of the primary uses of cache variables is as a customization point for developers. Rather than hard-coding the value in the CMakeLists.txt file as a normal variable, a cache variable can be used so that the developer can override the value without having to edit the CMakeLists.txt file. Cache variables can be set on the cmake command line or modified by interactive GUI tools without having to change anything in the project itself. Using these customization points, the developer can turn different parts of the build on or off, set paths to external packages, use different flags for compilers and linkers, and so on. Later chapters cover these and other uses of cache variables.

6.3.1. Getting And Setting Cache Variables

The value of a cache variable is retrieved in exactly the same way as a normal variable (i.e. with the \${myVar} form). The set() command is also used to set a cache variable, but additional arguments are required and the behavior is more involved:

```
set(varName value... CACHE type "docstring" [FORCE])
```

When the CACHE keyword is present, the set() command will apply to a cache variable named varName instead of a normal variable. An important difference between normal and cache variables is that the set() command will only overwrite a cache variable if the FORCE keyword is present. Compare this to normal variables, where the set() command will always overwrite a pre-existing value. When used to define cache

variables without the `FORCE` keyword, the `set()` command conceptually acts more like `set-if-not-set`. If a non-cache variable of the same `varName` already exists, the behavior is more complex. The results depend on certain policy settings, which are discussed further below.

Cache variables have more information attached to them than a normal variable, including a nominal type and a documentation string. Both must be provided when setting a cache variable.

The `docstring` does not affect how CMake treats the variable. It is used only by GUI tools to provide things like a tooltip or one-line description for the cache variable. The `docstring` should be short and consist of plain text with no HTML markup. It can be an empty string.

CMake will always treat a variable as a string during processing. The type is used mostly to improve the user experience in GUI tools, with some important exceptions discussed later in this section. The type must be one of the following:

BOOL

The cache variable is a boolean true or false value. GUI tools use a checkbox or similar to represent the variable. The underlying string value held by the variable will conform to one of the ways CMake represents booleans as strings

(ON/OFF, TRUE/FALSE, 1/0, etc. - see [Section 7.1.1, “Basic Expressions”](#) for full details).

FILEPATH

The cache variable represents a path to a file on disk. GUI tools present a file dialog to the user for modifying the variable’s value.

PATH

Like FILEPATH, but GUI tools present a dialog that selects a directory rather than a file.

STRING

The variable is treated as an arbitrary string. By default, GUI tools use a single-line text edit widget for manipulating the value of the variable. Projects may use cache variable properties to provide a pre-defined set of values for GUI tools to present as a combobox or similar instead (see [Section 10.6, “Cache Variable Properties”](#)).

INTERNAL

The variable is not intended to be made available to the user. Internal cache variables are sometimes used to persistently record internal information by the project, such as caching the result of an intensive query or computation. GUI tools do not show INTERNAL variables. INTERNAL also implies FORCE.

Setting a boolean cache variable is such a common need that CMake provides a separate command for it. Rather than the somewhat verbose `set()` command, developers can use `option()` instead:

```
option(optVar helpString [initialValue])
```

If `initialValue` is omitted, the default value `OFF` will be used. If provided, the `initialValue` must conform to one of the boolean values accepted by the `set()` command. For reference, the above can be thought of as more or less equivalent to:

```
set(optVar initialValue CACHE BOOL helpString)
```

Compared to `set()`, the `option()` command more clearly expresses the behavior for boolean cache variables, so it would generally be the preferred command to use. Be aware though that the effect of the two commands can be different in certain situations. Examples of this are given further below.

A point that is often not well understood is that normal and cache variables are two separate things. It is possible to have a normal variable and a cache variable with the same name, but holding different values. In such cases, CMake will retrieve the normal variable's value rather than the cache variable when using `${myVar}`. Put another way, normal variables take precedence over cache variables.

The exception to this is that when setting a cache variable's value, any normal variable of the same name may be removed from the current scope. Newer CMake versions don't do this (when permitted by policy settings), but with older CMake versions, the same-named non-cache variable will be removed in any of the following scenarios:

- The cache variable did not exist before the call to `set()` or `option()`.
- The cache variable existed before the call to `set()` or `option()`, but it did not have a defined type (see [Section 6.3.2, “Setting Cache Values On The Command Line”](#) for how this can occur).
- The `FORCE` or `INTERNAL` option was used in the call to `set()`.

In the first two cases above, this means it is possible to get different behavior between the first and subsequent CMake runs. In the first run, the cache variable won't exist or won't have a defined type, but in subsequent runs it will. Therefore, in the first run, a normal variable would be hidden, but in subsequent runs, it would not. An example should help illustrate the problem:

```
# CMP0077 and CMP0126 policies are assumed to be set to OLD
# (see discussion following the example for details)

set(myVar foo)                      # Local myVar
set(result ${myVar})                  # result = foo
set(myVar bar CACHE STRING "")      # Cache myVar
```

```
set(result ${myVar}) # First run:      result = bar
                      # Subsequent runs: result = foo

set(myVar fred)
set(result ${myVar}) # result = fred
```

In CMake 3.13, the behavior of `option()` was changed such that if a normal variable already exists with the same name, the command does nothing. This newer behavior is typically what developers intuitively expect. A similar change was made for the `set()` command in CMake 3.21, but note the following differences in the new behavior for both commands:

- For `set()`, the cache variable is still set if it didn't exist previously, but for `option()` it is not.
- If `INTERNAL` or `FORCE` is used with `set()`, the cache variable will always be set or updated.

Developers should be mindful of these inconsistencies and the different CMake versions that provide the new behaviors. Policies `CMP0077` and `CMP0126` control the actual behavior (see [Chapter 13, Policies](#) for an understanding of how these can be manipulated). Projects that set their minimum CMake version to 3.21 or higher in their call to `cmake_minimum_required()` will use the new, more intuitive behaviors by default.

The interaction between cache and non-cache variables can also lead to other potentially unexpected behavior. Consider the following three commands:

```
unset(foo)
set(foo)
set(foo "")
```

One might be tempted to think that the evaluation of `${foo}` would always give an empty string after any of these three cases, but only the last is guaranteed to do so. Both `unset(foo)` and `set(foo)` remove a non-cache variable from the current scope. If there is also a *cache* variable called `foo`, that cache variable is left alone and `${foo}` would provide the value of that cache variable. In this sense, `unset(foo)` and `set(foo)` both effectively unmask the `foo` cache variable, if one exists. On the other hand, `set(foo "")` doesn't remove a non-cache variable, it explicitly sets it to an empty value. `${foo}` will then evaluate to an empty string regardless of whether there is also a cache variable called `foo`. Therefore, setting a variable to an empty string rather than removing it is likely to be the more robust way of achieving the developer's intention.

For those rare situations where a project may need to get the value of a cache variable and ignore any non-cache variable of the same name, CMake 3.13 added documentation for the `$CACHE{someVar}` form. Projects should not generally make use of this other than for temporary debugging, since it breaks the long-established expectation that normal variables will override values set in the cache.

6.3.2. Setting Cache Values On The Command Line

CMake allows cache variables to be manipulated directly via command line options passed to `cmake`. The primary workhorse is the `-D` option, which is used to define the value of a cache variable.

```
cmake -D myVar:type=someValue ...
```

`someValue` will replace any previous value of the `myVar` cache variable. The behavior is essentially as though the variable was being assigned using the `set()` command with the `CACHE` and `FORCE` options. The command line option only needs to be given once, since it is stored in the cache for later runs and therefore does not need to be provided every time `cmake` is run. Multiple `-D` options can be provided to set more than one variable at a time on the `cmake` command line.

When defining cache variables this way, they do not have to be set within the `CMakeLists.txt` file (i.e. no corresponding `set()` command is required). Cache variables defined on the command line have an empty docstring. The type can also be omitted, in which case the variable will have an undefined type, or more accurately, it is given a special type that is similar to `INTERNAL` but which CMake interprets to mean undefined. The

following shows various examples of setting cache variables via the command line.

```
cmake -D foo:BOOL=ON -D bar:STRING=high ...
cmake -D "msg:STRING=This contains spaces" ...
cmake -D hideMe=mysteryValue ...
cmake -D helpers:FILEPATH=subdir/helpers.txt ...
cmake -D helpDir:PATH=/opt/helpThings ...
```

Note how the entire value given with the `-D` option should be quoted if setting a cache variable with a value containing spaces.

There is a special case for handling values initially declared without a type on the `cmake` command line. If the project's `CMakeLists.txt` file then tries to set the same cache variable and specifies a type of `FILEPATH` or `PATH`, and if the value of that cache variable is a relative path, CMake will treat it as being relative to the directory from which `cmake` was invoked and automatically convert it to an absolute path. This is not particularly robust, since `cmake` could be invoked from any directory. Therefore, developers are advised to always include a type if specifying a variable on the `cmake` command line for a variable that represents some kind of path. It is a good habit to always specify the type of the variable on the command line in general anyway so that it is likely to be shown in GUI applications in the most appropriate form. It will also prevent one of the surprising behavior scenarios mentioned in the previous section.

It is also possible to remove variables from the cache with the `-U` option, which can be repeated as necessary to remove more than one variable. Note that the `-U` option supports `*` and `?` wildcards, but care needs to be taken to avoid deleting more than was intended and leaving the cache in an unbuildable state. In general, it is recommended to only remove specific entries without wildcards unless it is absolutely certain the wildcards used are safe.

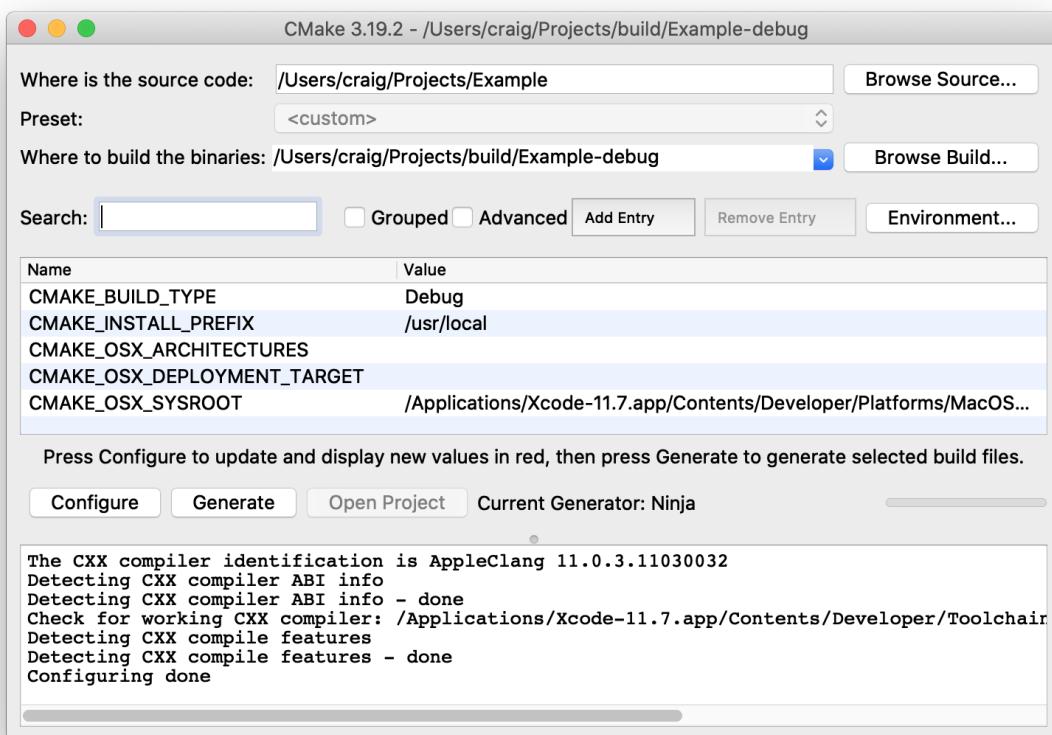
```
cmake -U 'help*' -U foo ...
```

6.3.3. CMake GUI Tools

Setting cache variables via the command line is an essential part of automated build scripts and anything else driving CMake via the `cmake` command. But for everyday development, the GUI tools provided by CMake often present a better user experience. CMake provides two equivalent GUI tools, `cmake-gui` and `ccmake`, which allow developers to manipulate cache variables interactively. `cmake-gui` is a fully functional GUI application supported on all major desktop platforms. `ccmake` uses a curses-based interface which can be used in text-only environments, such as over a ssh connection. `cmake-gui` is included in the official CMake release packages for all platforms, while `ccmake` is included for all platforms except Windows. If using system-provided packages on Linux rather

than the official releases, note that many distributions split `cmake-gui` out into its own package.

The `cmake-gui` user interface is shown in the figure below. The top section allows the project's source and build directories to be defined. The middle section is where the cache variables can be viewed and edited. At the bottom are the Configure and Generate buttons, followed by a log area that shows the output from those operations.



The source directory must be set to the directory containing the `CMakeLists.txt` file at the top of the project's source tree. The

build directory is where CMake will generate all build output (recommended directory layouts were discussed in [Chapter 2, Setting Up A Project](#)). For new projects, both must be set, but for existing projects, setting the build directory will also update the source directory, since the source location is stored in the build directory's cache.

CMake's two-stage setup process was introduced in [Section 2.3, “Generating Project Files”](#). In the first stage, the `CMakeLists.txt` file is read and a representation of the project is built up in memory. This is called the *configure* stage. If the configure stage is successful, the *generate* stage can then be executed to create the build tool's project files in the build directory. When running `cmake` from the command line, both stages are executed automatically, but in the GUI application, they are triggered separately with the Configure and Generate buttons.

Each time the configure step is initiated, the cache variables shown in the middle of the UI are updated. Any new cache variables added by the last configure step will be highlighted in red. When a project is first loaded, all variables are considered new, so they are all shown highlighted in red. Good practice is to re-run the configure stage until no variables are highlighted. This ensures robust behavior for more complex projects where enabling some options may add further options which could require another configure pass.

Once all cache variables are shown without red highlighting, the generate stage can be run. The example in the previous screenshot shows typical log output after the configure stage has been run and no new cache variables were added.

Hovering the mouse over any cache variable will show a tooltip containing the docstring for that variable. New cache variables can also be added with the Add Entry button, which is equivalent to issuing a `set()` command with an empty docstring. Cache variables can be removed with the Remove Entry button, although CMake will most likely recreate that variable on the next run.

Clicking on a variable allows its value to be edited in a widget tailored to the variable type. Booleans are shown as a checkbox, files and paths have a browse filesystem button, and strings are usually presented as a text line edit. As a special case, cache variables of type `STRING` can be given a set of values to show in a combobox in CMake GUI instead of showing a simple text entry widget. This is achieved by setting a cache variable's `STRINGS` property (covered in detail in [Section 10.6, “Cache Variable Properties”](#), but shown here for convenience):

```
set(TRAFFIC_LIGHT Green CACHE STRING "Status of something")
set_property(CACHE TRAFFIC_LIGHT PROPERTY STRINGS
    Red Orange Green
)
```

In the above, the TRAFFIC_LIGHT cache variable will initially have the value Green. When the user attempts to modify TRAFFIC_LIGHT in cmake-gui, they will be given a combobox containing the three values Red, Orange, and Green instead of a simple line edit widget which would otherwise have allowed them to enter any arbitrary text. Note that setting the STRINGS property on the variable doesn't prevent that variable from having other values assigned to it, it only affects the widget used by cmake-gui when editing it. The variable can still be given other values via set() commands in the CMakeLists.txt file or by other means such as manually editing the CMakeCache.txt file.

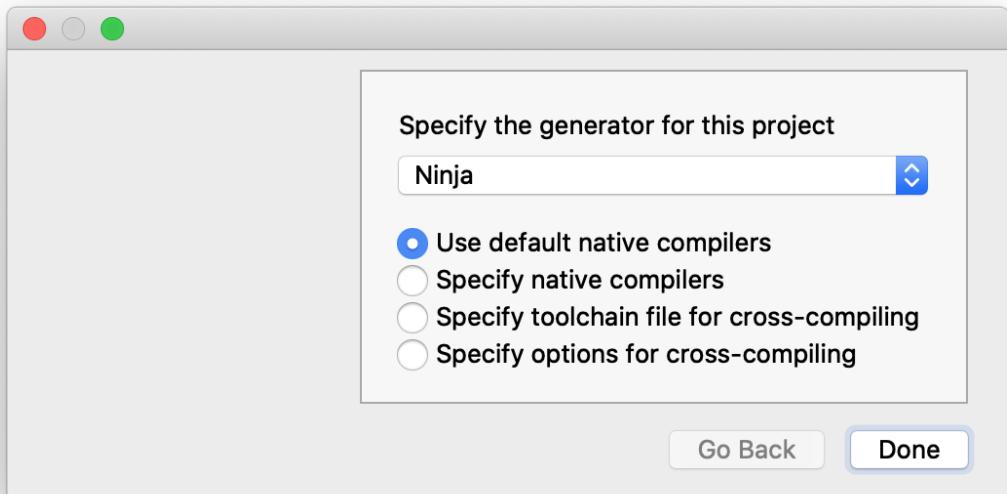
Cache variables can also have a property marking them as advanced or not. This too only affects the way the variable is displayed in cmake-gui, it does not in any way affect how CMake uses the variable during processing. By default, cmake-gui only shows non-advanced variables, which typically presents just the main variables a developer would be interested in viewing or modifying. Enabling the Advanced option shows all cache variables except those marked INTERNAL. The only way to see INTERNAL variables is to edit the CMakeCache.txt file with a text editor, since they are not intended to be manipulated directly by developers. Variables can be marked as advanced with the mark_as_advanced() command within the CMakeLists.txt file:

```
mark_as_advanced([CLEAR|FORCE] var1 [var2...])
```

The `CLEAR` keyword ensures the variables are not marked as advanced, while the `FORCE` keyword ensures the variables are marked advanced. Without either keyword, the variables will only be marked as advanced if they don't already have an advanced/non-advanced state set.

In the CMake GUI tool, selecting the Grouped option can make viewing advanced variables easier by grouping variables together based on the start of the variable name up to the first underscore. Another way to filter the list of variables shown is to enter text in the Search area, which results in only showing variables with the specified text in their name or value.

When the configure stage is run for the first time on a new project, the developer is presented with a dialog similar to that shown in the next screenshot:



This dialog is where the CMake generator and toolchain are specified. The choice of generator is usually up to the developer's personal preference, with available options provided in the combobox. Depending on the project, the choice of generator may be more restricted than what the combobox options allow, such as if the project relies on generator-specific functionality. A common example of this is a project that requires the Xcode generator due to the Apple platform's unique features, such as code signing and support for iOS, tvOS, watchOS, and visionOS. Once a generator has been selected for a project, it cannot be changed without deleting the cache and starting again, which can be done from the File menu if required.

For the toolchain options presented, each one requires progressively more information from the developer. Using the default native compilers is the usual choice for ordinary desktop development, and selecting that option requires no further details. If more control is required, developers can instead override the native compilers, with the paths to the compilers being given in a follow-up dialog. If a separate toolchain file is available, that can be used to customize not just the compilers, but also the target environment, compiler flags, and various other things. Using a toolchain file is typical when cross-compiling, which is covered in detail in [Chapter 24, Toolchains And Cross Compiling](#). Lastly, for ultimate control, developers can specify the full set of options for cross-compiling, but this is not recommended for normal use. A toolchain file can provide the same information, but has the advantage that it can be re-used as needed.

The `ccmake` tool offers most of the same functionality as the `cmake-gui` application, but it does so through a text-based interface:

The screenshot shows a terminal window titled "Example-debug — ccmake . — 98x15". The window displays configuration variables for a CMake project. On the left, a list of variables is shown: CMAKE_BUILD_TYPE, CMAKE_INSTALL_PREFIX, CMAKE OSX ARCHITECTURES, CMAKE OSX DEPLOYMENT_TARGET, and CMAKE OSX SYSROOT. The "CMAKE OSX ARCHITECTURES" variable is highlighted in blue. On the right, the value for "Debug" is set to "/usr/local", and the full path "/Applications/Xcode-11.7.app/Contents/Developer/Platforms/MacOS" is displayed. A status bar at the bottom indicates "CMAKE OSX ARCHITECTURES: Build architectures for OSX" and lists keyboard shortcuts for editing entries (e.g., [enter] Edit an entry, [d] Delete an entry, etc.). It also shows "CMake Version 3.19.2".

Rather than selecting the source and build directories like with `cmake-gui`, the source or build directory has to be specified on the `ccmake` command line, just like for the `cmake` command.

A minor drawback of the `ccmake` interface is that there is no ability to filter the variables shown. The methods for editing a variable are also not as rich as with `cmake-gui`. Nevertheless, the `ccmake` tool is a useful alternative when the full `cmake-gui` application is not practical or not available, such as over a terminal connection that cannot support UI forwarding.

6.4. Scope Blocks

As mentioned in [Section 6.1, “Variable Basics”](#), a variable has a scope. Cache variables have global scope, so they are always accessible. In the material presented so far, a non-cache variable’s scope is the `CMakeLists.txt` file in which the variable is defined. This is often called the *directory scope*.

Subdirectories and functions inherit variables from their parent scope (covered in [Section 8.1.2, “Scope”](#) and [Section 9.4, “Returning Values”](#) respectively).

With CMake 3.25 or later, the `block()` and `endblock()` commands can be used to define a local variable scope. Upon entering the block, it receives a copy of all the variables defined in the surrounding scope at that point in time. Any changes to variables in the block are performed on the block’s copies, leaving the surrounding scope’s variables unchanged. Upon leaving the block, all variables that were copied into the block or that were created in the block are discarded. This can be a useful way of isolating a particular set of commands from the main logic.

```
set(x 1)

block()
    set(x 2)  # Shadows outer "x"
    set(y 3)  # Local, not visible outside the block
endblock()

# Here, x still equals 1, y is not defined
```

A block may not always want to be completely isolated from its caller. It may want to selectively modify some variables in the surrounding scope. The `PARENT_SCOPE` of the `set()` and `unset()` commands can be used to modify a variable in the enclosing scope instead of the current scope:

```
set(x 1)
set(y 3)
block()
    set(x 2 PARENT_SCOPE)
    unset(y PARENT_SCOPE)
    # x still has the value 1 here
    # y still exists and has the value 3
endblock()
# x has the value 2 here and y is no longer defined
```

When `PARENT_SCOPE` is used, the variable being set or unset is the one in the parent scope, not the one in the current scope. Importantly, it does *not* mean to set or unset the variable in both the parent *and* the current scope. This can make `PARENT_SCOPE` awkward to use, since it often means repeating the same command for the two different scopes when a change needs to affect both. The `block()` command supports a `PROPAGATE` keyword which can be used to provide that behavior in a more robust and concise way. When control flow leaves the block, the value of every variable listed after the `PROPAGATE` keyword is propagated from the block to its surrounding scope. If a propagated variable is unset inside the block, it is unset in the surrounding scope upon leaving the block.

```
set(x 1)
set(z 5)
block(PROPAGATE x z)
    set(x 2)  # Gets propagated back out to the outer "x"
    set(y 3)  # Local, not visible outside the block
    unset(z)  # Unsets the outer "z" too
endblock()
# Here, x equals 2, y and z are undefined
```

The `block()` command can be used to control more than just variable scopes. The command's full signature is specified as:

```
block([SCOPE_FOR [VARIABLES] [POLICIES]] [PROPAGATE var...])
```

The `SCOPE_FOR` keyword can be used to specify what kind of scope(s) the `block` should create. When `SCOPE_FOR` is omitted, `block()` creates a new local scope for both variables and policies (see [Section 13.4, “Policy Scope”](#) for discussion of the latter). The following has the same effect as the previous example, but it only creates a variable scope, leaving the policy scope unchanged:

```
set(x 1)
set(z 5)
block(SCOPE_FOR VARIABLES PROPAGATE x z)
    set(x 2)  # Gets propagated back out to the outer "x"
    set(y 3)  # Local, not visible outside the block
    unset(z)  # Unsets the outer "z" too
endblock()
# Here, x equals 2, y and z are undefined
```

While `SCOPE_FOR VARIABLES` is likely to be what the project needs most of the time, it will often be harmless to allow a new policy scope to be created as well. Using `block()` rather than `block(SCOPE_FOR VARIABLES)` may be slightly less efficient, but may still be preferred for its simplicity.

See [Section 7.2.3, “Interrupting Loops”](#), [Section 8.4, “Ending Processing Early”](#) and [Section 9.4, “Returning Values”](#) for how

the `block()` command interacts with other control flow structures.

6.5. Printing Variable Values

As projects get more complicated or when investigating unexpected behavior, it can be useful to print out diagnostic messages and variable values during a CMake run. This is generally achieved using the `message()` command, which is covered in detail in [Chapter 14, Debugging And Diagnostics](#). For now, it is enough to know that in its simplest form, all the `message()` command does is print its arguments to CMake's output. It adds no separator between arguments if more than one argument is given, and a newline is automatically appended to the end of the message. Newlines can also be explicitly included using the common `\n` notation. A variable's value can be included in the message by using the usual `${myVar}` notation.

```
set(myVar HiThere)

message("The value of myVar = ${myVar}\nAnd this "
       "appears on the next line")
```

This will give the following output:

```
The value of myVar = HiThere
And this appears on the next line
```

6.6. String Handling

As project complexity grows, in many cases so too does the need to implement more involved logic for how variables are managed. A core tool CMake provides for this is the `string()` command, which provides a wide range of useful string handling functionality. This command enables projects to perform find and replace operations, regular expression matching, upper/lower case transformations, strip whitespace, and a variety of other tasks.

The first argument to `string()` defines the operation to be performed, and the rest of the arguments depend on the operation being requested. These arguments will generally require at least one input string, and since CMake commands cannot return a value, an output variable for the result of the operation. In the examples below, this output variable will generally be named `outVar`.

The following examples give a flavor of what the `string()` command can be used for. Consult the official CMake documentation for the full list of supported operations and `string()` command signatures.

```
# FIND input stringToFind outVar
string(FIND abcdefabcdef def fwdIndex)
string(FIND abcdefabcdef def revIndex REVERSE)
string(FIND abcdefabcdef XXX noIndex)

message("fwdIndex = ${fwdIndex}\n"
```

```
"revIndex = ${revIndex}\n"
"noIndex  = ${noIndex}")
```

```
fwdIndex = 3
revIndex = 9
noIndex  = -1
```

```
# REPLACE matchString replaceWith outVar input...
string(REPLACE def XXXXX result abcdefabcdef)

message("result = ${result}")
```

```
result = abcXXXXXabcXXXXX
```

For `string(REPLACE)`, multiple input strings can be given. In such cases, the input strings are joined together without any separator between them before searching for substitutions. This can sometimes lead to unexpected matches, so it is generally advisable to provide only one input string in most cases.

```
string(REGEX MATCH    "[de]" matchOne abcdefabcdef)
string(REGEX MATCHALL "[de]" matchAll abcdefabcdef)
string(REGEX REPLACE   "([de]+)" "X\\$1Y" replaced abcdefabcdef)

message("matchOne = ${matchOne}\n"
        "matchAll = ${matchAll}\n"
        "replaced = ${replaced}")
```

```
matchOne = d
matchAll = d;e;d;e
replaced = abcXdeYfabcXdeYf
```

The REGEX subcommands also support multiple input strings being provided, but the same advice as for REPLACE also applies. It is safer to pass just a single input string to avoid surprises with string boundaries.

The REGEX REPLACE operation is especially powerful. It supports substituting captured text, using \1 for the first (...) in the regular expression, \2 for the second (...), and so on. Note that the \ itself has to be escaped to prevent CMake from treating it as escaping the character after it, so the replacement string in the above example is X\\1Y, not X\1Y.

```
# SUBSTRING input index length outVar
# A length of -1 means to the end of the string.
string(SUBSTRING abcdefabcdef 4 2 result1)
string(SUBSTRING abcdefabcdef 4 -1 result2)

message("result1 = ${result1}\n"
       "result2 = ${result2}")
```

```
result1 = ef
result2 = efabcdef
```

```
string(LENGTH aBcDe length)
string(TOLOWER aBcDe lower)
string(TOUPPER aBcDe upper)
string(STRIPI " aBcDe " stripped)

message("length    = ${length}\n"
       "lower     = ${lower}\n"
       "upper     = ${upper}\n"
       "stripped = '${stripped}'")
```

```
length    = 5
lower     = abcde
upper     = ABCDE
stripped = 'aBcDe'
```

In the case of LENGTH, the command counts bytes rather than characters. For strings containing multibyte characters, this means the reported length will be different to the number of characters.

6.7. Lists

Lists are used heavily in CMake. Ultimately, lists are just a string with list items separated by semicolons (with one exception, see [Section 6.7.1, “Problems With Unbalanced Square Brackets”](#)).

This can make it less convenient to manipulate individual list items. CMake provides the list() command to facilitate such tasks. Just as for the string() command, list() expects the operation to perform as its first argument. The second argument is always the list to operate on, and it must be a variable name. Passing a raw list like a;b;c as the second argument is not permitted. The rest of this section provides examples of the more commonly used list subcommands.

```
set(myList a b c)      # Creates the list "a;b;c"

# Last argument names the variable to store the result in
list(LENGTH myList len)
list(GET myList 2 1 letters)
list(FIND myList c index)    ①
list(JOIN myList "***" joined)
```

```
message("length = ${len}\n"
       "letters = ${letters}\n"
       "index   = ${index}\n"
       "joined  = ${joined}")
```

- ① It is often easier and more concise to use if(something IN_LIST myList) rather than list(FIND) (see [Section 7.1.5, “Existence Tests”](#)).

```
length = 3
letters = c;b
index   = 2
joined  = a***b***c
```

```
set(myList a b c)

# These operations all modify the list directly in-place

list(INSERT myList 2 X Y Z)
message("myList (INSERT) = ${myList}")

list(APPEND myList d e f)
message("myList (APPEND) = ${myList}")

# CMake 3.15 or later required
list(PREPEND myList P Q R)
message("myList (PREPEND) = ${myList}")
```

```
myList (INSERT) = a;b;X;Y;Z;c
myList (APPEND) = a;b;X;Y;Z;c;d;e;f
myList (PREPEND) = P;Q;R;a;b;X;Y;Z;c;d;e;f
```

```
set(myList a b c d e f g a b c d e f g)

# These operations all modify the list directly in-place.

list(REMOVE_ITEM      myList d) # removes all "d" items
list(REMOVE_AT        myList 1) # removes first "b"
```

```
list(REMOVE_DUPLICATES myList)

message("After removals = ${myList}")
```

```
After removals = a;c;e;f;g;b
```

```
set(myList a b c d e f g)

# These operations all modify the list directly in-place.
# CMake 3.15 or later is also required.
```

```
list(POP_BACK myList last secondLast)
message("myList (POP_BACK) = ${myList}\n"
       "last           = ${last}\n"
       "secondLast     = ${secondLast}")
```

```
list(POP_FRONT myList first second)
message("myList (POP_FRONT) = ${myList}\n"
       "first          = ${first}\n"
       "second         = ${second}")
```

```
myList (POP_BACK) = a;b;c;d;e
last             = g
secondLast       = f
myList (POP_FRONT) = c;d;e
first            = a
second           = b
```

For POP_BACK and POP_FRONT, when no output variables are given, a single item is popped from the back or front and discarded. If one or more output variable names are given, popped items will be stored in those variables, with the number of items popped equal to the number of variable names provided.

For all list operations that take an index as an argument, a negative index indicates that counting starts from the end of the list. When used this way, the last item in the list has index -1, the second last -2, and so on.

```
set(myList a b c d e f)

list(INSERT myList -2 X Y Z)
message("myList = ${myList}")
```

```
myList = a;b;c;d;X;Y;Z;e;f
```

6.7.1. Problems With Unbalanced Square Brackets

There is one exception to the way CMake usually treats semicolons as list separators. For historical reasons, if a list item contains an opening square bracket [, it must also have a matching closing square bracket]. CMake will consider any semicolon between these square brackets to be part of the list item instead of as a list separator. If one tries to construct a list with unbalanced square brackets, the list won't be interpreted as expected. The following demonstrates the behavior:

```
set(noBrackets "a_a" "b_b")
set(withBrackets "a[a" "b]b")

list(LENGTH noBrackets lenNo)
list(LENGTH withBrackets lenWith)

list(GET noBrackets 0 firstNo)
list(GET withBrackets 0 firstWith)
```

```
message("No brackets: "
       "Length=${lenNo} --> First_element=${firstNo}"
)
message("With brackets: "
       "Length=${lenWith} --> First_element=${firstWith}"
)
```

The output from the above would be:

```
No brackets: Length=2 --> First_element=a_a
With brackets: Length=1 --> First_element=a[a;b]b
```

[Section 9.8.3, “Special Cases For Argument Expansion”](#) covers further aspects of this peculiarity.

6.8. Math

One other common form of variable manipulation is math computation. CMake provides the `math()` command for performing basic mathematical evaluation:

```
math(EXPR outVar mathExpr [OUTPUT_FORMAT format])
```

The first argument must be the keyword `EXPR`, while `mathExpr` defines the expression to be evaluated and the result will be stored in `outVar`. The expression may use any of the following operators, all of which have the same meaning as they would in C code: `+` `-` `*` `/` `%` `|` `&` `^` `~` `<<` `>>`. Parentheses are also supported and have their usual mathematical meaning. Variables can be referenced in the `mathExpr` with the usual

`${myVar}` notation. If using CMake 3.13 or later, the `OUTPUT_FORMAT` keyword can be given to control how the result is stored in `outVar`. The format should be either `DECIMAL`, which is the default behavior, or `HEXADECIMAL`.

```
set(x 3)
set(y 7)
math(EXPR zDec "(${x}+${y}) * 2")
message("decimal = ${zDec}")

# Requires CMake 3.13 or later for HEXADECIMAL
math(EXPR zHex "(${x}+${y}) * 2" OUTPUT_FORMAT HEXADECIMAL)
message("hexadecimal = ${zHex}")
```

```
decimal = 20
hexadecimal = 0x14
```

6.9. Recommended Practices

Where the development environment allows it, the CMake GUI tool is a useful way to quickly and easily understand the build options for a project and to modify them as needed during development. A little bit of time spent getting familiar with it will simplify working with more complex projects later. It also gives developers a good base to work from should they need to experiment with things like compiler settings, since these are easily found and modified within the GUI environment.

Prefer to provide cache variables for controlling whether to enable optional parts of the build instead of encoding the logic in build scripts outside of CMake. This makes it trivial to turn

them on and off in the CMake GUI and other tools which understand how to work with the CMake cache (a growing number of IDE environments are acquiring this capability).

Avoid relying on environment variables being defined, apart from perhaps the ubiquitous PATH or similar operating system level variables. The build should be predictable, reliable, and easy to set up. If it relies on environment variables being set for things to work correctly, this can be a point of frustration for new developers as they wrestle to get their build environment prepared. Furthermore, the environment at the time CMake is run can change compared to when the build itself is invoked. Therefore, prefer to pass information directly to CMake through cache variables instead wherever possible. One exception to this is environment variables set by CI (continuous integration) tools. Projects may want to use those if they need special behavior only when building within that controlled scenario.

Try to establish a variable naming convention early. For cache variables, consider grouping related variables under a common prefix followed by an underscore. This takes advantage of how CMake GUI groups variables based on the same prefix automatically. Also consider that the project may one day become a subpart of some larger project, so names beginning with the project name or something closely associated with the project may be desirable.

Try to avoid defining non-cache variables in the project which have the same name as cache variables. The interaction between the two types of variables can be unexpected for developers new to CMake. Later chapters also highlight other common errors and misuses of regular variables that share the same name as cache variables.

CMake provides a large number of predefined variables that provide details about the system or influence certain aspects of CMake's behavior. Some of these variables are heavily used by projects, such as those that are only defined when building for a particular platform (WIN32, APPLE, UNIX, and so on). It is recommended for developers to occasionally make a quick scan through the CMake documentation page listing the predefined variables to become familiar with what is available.

7. FLOW CONTROL

Most CMake projects will need to apply some steps only in certain circumstances. They may want to use certain compiler flags only with a particular compiler, or when building for a particular platform. In other cases, the project may need to iterate over a set of values, or to keep repeating some set of steps until a certain condition is met. These examples of flow control are well-supported by CMake in ways which should be familiar to most software developers. The `if()` command provides the expected if-then-else behavior, and looping is provided through the `foreach()` and `while()` commands. All three commands provide the traditional behavior as implemented by most programming languages, but they also have added features specific to CMake.

7.1. The `if()` Command

The modern form of the `if()` command is as follows (multiple `elseif()` clauses can be provided):

```
if(expression1)
    # commands ...
elseif(expression2)
```

```
# commands ...
else()
# commands ...
endif()
```

Very early versions of CMake required expression1 to be repeated as an argument to the `else()` and `endif()` clauses, but this has not been required since CMake 2.8.0. While it is still not unusual to encounter projects and example code using that older form, it is discouraged for new projects, since it can be more confusing to read. New projects should leave the `else()` and `endif()` arguments empty, as shown above.

The expressions in `if()` and `elseif()` commands can take a variety of different forms. CMake offers the traditional boolean logic, as well as various other conditions like file system tests, version comparisons, and testing for the existence of things.

7.1.1. Basic Expressions

The most basic of all expressions is a single constant value:

```
if(value)
```

CMake's logic for what it considers true and false is a little more involved than most programming languages. There are a number of aspects that are unique to CMake, and some behavior can be quite surprising. For a single unquoted value, the rules are as follows:

- If value is a quoted or unquoted constant with value ON, YES, TRUE, or Y, it is treated as true. The test is case-insensitive.
- If value is a quoted or unquoted constant with value OFF, NO, FALSE, N, IGNORE, NOTFOUND, an empty string, or a string that ends in -NOTFOUND, it is treated as false. Again, the test is case-insensitive.
- If value is a (possibly floating-point) number, it will be converted to a bool following usual C rules, although values other than 0 or 1 are seldom used in this context.
- If none of the above cases apply, it will be treated as a variable name (or possibly as a string) and evaluated further as described below.

In the following examples, only the `if(...)` part of the command is shown for illustration purposes, the corresponding body and `endif()` is omitted:

```
# Examples of quoted and unquoted constants
if(YES)
if("True")
if(0)
if(TRUE)

# These are also treated as unquoted constants because the
# variable evaluation occurs before if() sees the values
set(A YES)
set(B 0)
if(${A}) # Evaluates to true
if(${B}) # Evaluates to false

# Does not match any of the true or false constants, so
```

```
# proceed to testing as a variable name in the fall-through
# case below
if(someLetters)

# Quoted value that doesn't match any of the true or false
# constants, so again fall through to testing as a variable
# name or string
if("someLetters")
```

The CMake documentation refers to the fall through case as the following form:

```
if(<variable|string>)
```

What this means in practice is the if-expression is either:

- An unquoted name of a (possibly undefined) variable.
- A quoted string.

When an unquoted variable name is used, the variable's value is compared against the false constants. If none of those match the value, the result of the expression is true. An undefined variable will evaluate to an empty string, which matches one of the false constants and will therefore yield a result of false.

```
# Common pattern, often used with variables defined
# by commands such as option(enableSomething ...)
if(enableSomething)
    #
endif()
```

Note that environment variables do not count as variables in this discussion. A statement like `if(ENV{some_var})` will always

evaluate to false, regardless of whether an environment variable called `some_var` exists or not.

When the if-expression is a quoted string, the behavior is more involved:

- A quoted string that doesn't match any of the defined true constants always evaluates to false in CMake 3.1 or later, regardless of the string's value (but this can be overridden with policy setting `CMP0054`, see [Chapter 13, Policies](#)).
- Before CMake 3.1, if the value of the string matched the name of an existing variable, then the quoted string is effectively replaced by that variable name (unquoted) and the test is then repeated.

Both of the above can be a surprise to developers, but at least the CMake 3.1 behavior is always predictable. The pre-3.1 behavior would occasionally lead to unexpected string substitutions when the string value happened to match a variable name, possibly one defined somewhere quite far from that part of the project. The potential confusion around quoted values means it is generally advisable to avoid using quoted arguments with the `if(something)` form. There are usually better comparison expressions that handle strings more robustly, which are covered in [Section 7.1.3, “Comparison Tests”](#) further below.

7.1.2. Logic Operators

CMake supports the usual AND, OR, and NOT logical operators, as well as parentheses to control order of precedence.

```
# Logical operators
if(NOT expression)
if(expression1 AND expression2)
if(expression1 OR expression2)

# Example with parentheses
if(NOT (expression1 AND (expression2 OR expression3)))
```

Following usual conventions, expressions inside parentheses are evaluated first, beginning with the innermost parentheses.

7.1.3. Comparison Tests

CMake separates comparison tests into distinct categories: *numeric*, *string*, *version numbers* and *path*, but the syntax forms all follow the same pattern:

```
if(value1 OPERATOR value2)
```

The two operands, `value1` and `value2`, can be either variable names or (possibly quoted) values. If a value is the same as the name of a defined variable, it will be treated as a variable. Otherwise, it is treated as a string or value directly. Once again though, quoted values have ambiguous behavior similar to that in basic unary expressions. Prior to CMake 3.1, a quoted string with a value that matched a variable name would be replaced

by that variable's value. The behavior of CMake 3.1 and later uses the quoted value without substitution, which is what developers intuitively expect.

All the comparison categories support the same set of operations, but the OPERATOR names are different for each category. The following table summarizes the supported operators:

Numeric	String	Version numbers	Path
LESS	STRLESS	VERSION_LESS	
GREATER	STRGREATER	VERSION_GREATER	
EQUAL	STREQUAL	VERSION_EQUAL	PATH_EQUAL ²
LESS_EQUAL ¹	STRLESS_EQUAL ¹	VERSION_LESS_EQUAL ¹	
GREATER_EQUAL ¹	STRGREATER_EQUAL ¹	VERSION_GREATER_EQUAL ¹	

¹ Only available with CMake 3.7 and later.

² Only available with CMake 3.24 and later.

Numeric comparison works as one would expect by comparing the value of the left against the right. But note that CMake does not typically raise an error if either operand is not a number, and its behavior does not fully conform to the official documentation when values contain more than just digits.

Depending on the mix of digits and non-digits, the result of the expression may be true or false.

```
# Valid numeric expressions, all evaluating as true
if(2 GREATER 1)
if("23" EQUAL 23)
set(val 42)
if(${val} EQUAL 42)
if("${val}" EQUAL 42)

# Invalid expression that evaluates as true with at
# least some CMake versions. Do not rely on this behavior.
if("23a" EQUAL 23)
```

Version number comparisons are somewhat like an enhanced form of numerical comparisons. Version numbers are assumed to be in the form `major[.minor[.patch[.tweak]]]`, where each component is expected to be a non-negative integer. When comparing two version numbers, the `major` part is compared first. Only if the `major` components are equal will the `minor` parts be compared (if present), and so on. A missing component is treated as zero. In all the following examples, the expression evaluates to true:

```
if(1.2 VERSION_EQUAL 1.2.0)
if(1.2 VERSION_LESS 1.2.3)
if(1.2.3 VERSION_GREATER 1.2 )
if(2.0.1 VERSION_GREATER 1.9.7)
if(1.8.2 VERSION_LESS 2 )
```

The version number comparisons have the same robustness caveats as numeric comparisons. Each version component is

expected to be an integer, but the comparison result is essentially undefined if this restriction does not hold.

For strings, values are compared lexicographically. But the arguments to string comparison functions can be either a variable name or a string, and once again this can create confusion. The following example demonstrates a common trap:

```
# No variable named "a" is defined, so it is treated as
# a string with value "a"
if(a STREQUAL "there")
    message("We do not get here")
elseif(a STREQUAL "")
    message("We do not get here either")
endif()

set(a there)

# Now there is a variable named "a", so its value is used.
if(a STREQUAL "there")
    message("We DO get here")
endif()
```

The following guidelines can be used to avoid any surprising behavior:

- Always ensure policy CMP0054 is set to NEW (see [Chapter 13, Policies](#)). This prevents quoted values from being treated as anything other than a string.
- Only use an unquoted argument if it is guaranteed that a variable by that name exists.

The PATH_EQUAL operator is much like a special case of STREQUAL. The operands are assumed to be paths in CMake's native path form (forward slashes for directory separators). A key difference for PATH_EQUAL is that it uses a component-wise comparison. Multiple consecutive directory separators are collapsed to a single separator, which is the primary practical difference to STREQUAL. The following example from the official CMake documentation demonstrates the difference:

```
if ("/a//b/c" PATH_EQUAL "/a/b/c")
    # We DO get here...
endif()

if ("/a//b/c" STREQUAL "/a/b/c")
    # We do NOT get here...
endif()
```

In addition to the operator forms above, a string can also be tested against a regular expression:

```
if(value MATCHES regex)
```

The value again follows the variable-or-string rules defined above and is compared against the regex regular expression. If the value matches, the expression evaluates to true. While the CMake documentation doesn't define the supported regular expression syntax for if() commands, it does define it elsewhere for other commands (see the string() command documentation). Essentially, CMake supports basic regular expression syntax only.

Parentheses can be used to capture parts of the matched value. The command will set variables with names of the form CMAKE_MATCH_<n> where <n> is the group to match. The entire matched string is stored in group 0.

```
if("Hi from ${who}" MATCHES "Hi from (Fred|Barney).*")
  message("${CMAKE_MATCH_1} says hello")
endif()
```

7.1.4. File System Tests

CMake also includes a set of tests which can be used to query the file system:

```
if(EXISTS pathToFileOrDir)
if(IS_READABLE pathToFileOrDir)      # CMake 3.29 or later
if(IS_WRITABLE pathToFileOrDir)      # CMake 3.29 or later
if(IS_EXECUTABLE pathToFileOrDir)    # CMake 3.29 or later
if(IS_DIRECTORY pathToDir)
if(IS_SYMLINK fileName)
if(IS_ABSOLUTE path)
if(file1 IS_NEWER_THAN file2)
```

Unlike most other if() expressions, none of the above operators perform any variable/string substitution without \${}, regardless of any quoting.

The IS_DIRECTORY, IS_SYMLINK, and IS_ABSOLUTE operators should be self-explanatory. Perhaps not so intuitively, the EXISTS operator checks more than just the existence of its argument. It also requires the named file or directory to be readable, although this behavior may change in a future version of

CMake. In most cases, the newer IS_READABLE, IS_WRITABLE, or IS_EXECUTABLE operator would better express the real condition that should be checked. Therefore, only use EXISTS if the project needs to support CMake 3.28 or older, or if it is not important whether the named file or directory can be read, written, or executed.

Unfortunately, IS_NEWER_THAN is an inaccurate name for what that operator does. It also returns true if both files have the *same* timestamp, not just if the timestamp of file1 is newer than that of file2. This is especially important on file systems that only have timestamps with a one-second resolution, such as the HFS+ file system on macOS 10.12 and earlier. On such systems, scenarios where files have the same timestamp are common, even when those files are created by separate commands. Another less intuitive behavior is that it also returns true if *either* file is missing. Furthermore, if either file is not specified as an absolute path, the behavior is undefined. Therefore, to obtain the desired condition, it will often be necessary to use IS_NEWER_THAN in a negated way.

Consider a scenario where secondFile is generated from firstFile. If firstFile is updated or secondFile is missing, then secondFile needs to be recreated. If firstFile does not exist, it should be a fatal error. Such logic would need to be expressed like so:

```
set(firstFile "/full/path/to/somewhere")
set(secondFile "/full/path/to/another/file")

if(NOT EXISTS ${firstFile})
    message(FATAL_ERROR "${firstFile} is missing")
elseif(NOT EXISTS ${secondFile} OR
      NOT ${secondFile} IS_NEWER_THAN ${firstFile})
    # ... commands to recreate secondFile
endif()
```

One might naively think that the condition could be expressed like this instead:

```
# WARNING: Very likely to be wrong
if(${firstFile} IS_NEWER_THAN ${secondFile})
    # ... commands to recreate secondFile
endif()
```

Although the words might express the desired condition, it doesn't do what it appears to because it also returns true if the two files have the same timestamp. If the operation to recreate secondFile is fast and the file system only has second timestamp resolution, it is very likely that secondFile would be recreated every time CMake is run. If build steps depend on secondFile, the build would also end up rebuilding those things after every CMake run.

7.1.5. Existence Tests

The last category of `if()` expressions support testing whether various CMake entities exist. They can be particularly useful in larger, more complex projects where some parts might or might

not be present or be enabled. While their usage may initially seem straightforward, there are some more subtle aspects to be aware of, which are discussed below.

```
if(DEFINED name)
if(COMMAND name)
if(POLICY name)
if(TARGET name)
if(TEST name)           # Available since CMake 3.4
if(value IN_LIST listVar) # Available since CMake 3.3
```

All but the last of the above will return true if an entity of the specified name exists at the point where the `if()` command is issued.

DEFINED

Returns true if a variable of the specified name exists. The value of the variable is irrelevant, only its existence is tested. The variable can be a regular CMake variable, or it can be a cache variable. From CMake 3.14, it is possible to check for a cache variable only using the `CACHE{name}` form. All CMake versions also support testing for the existence of an environment variable using the `ENV{name}` form, even though this was only officially documented as supported from CMake 3.13.

```
# Checks for a CMake variable (regular or cache)
if(DEFINED SOMEVAR)

# Checks for a CMake cache variable
if(DEFINED CACHE{SOMEVAR})
```

```
# Checks for an environment variable  
if(DEFINED ENV{SOMEVAR})
```

COMMAND

Tests whether a CMake command, function, or macro with the specified name exists. This can be useful for checking whether something is defined before trying to use it. For CMake-provided commands, prefer to test the CMake version instead, but for project-supplied functions and macros (see [Chapter 9, Functions And Macros](#)), this can be an appropriate check. It is especially useful if a command is provided as a technology preview in a third party package. For such cases, version-based logic wouldn't be appropriate, since the command might disappear in a future version.

```
# The "specialNewThing" is provided as a tech preview, but  
# it might not yet be officially supported.  
if(COMMAND specialNewThing)  
    specialNewThing(...)  
else()  
    # Fall back to doing things another way...  
endif()
```

POLICY

Tests whether a particular policy is known to CMake. Policy names are usually of the form CMPxxxx, where xxxx is a four-digit number. See [Chapter 13, Policies](#) for details on this topic. This test is frequently used to only enable a specific

policy if it is supported without having to enable all policies up to a specific CMake version.

```
# Use new FetchContent behavior if supported
if(POLICY CMP0168)
    cmake_policy(SET CMP0168 NEW)
endif()
```

TARGET

Returns true if a CMake target of the specified name has been defined by one of the commands `add_executable()`, `add_library()`, or `add_custom_target()`. The target could have been defined in any directory, as long as it is known at the point where the `if()` test is performed. This test is particularly useful in complex project hierarchies that pull in other external projects, and where those projects may share common dependent subprojects. It is frequently used in negative form to check if a target is already defined before trying to create that target.

```
if(NOT TARGET something)
    add_custom_target(something ...)
endif()
```

TEST

Returns true if a CMake test with the specified name has been previously defined by the `add_test()` command (covered in detail in [Chapter 27, Testing Fundamentals](#)). The

TEST operator can only be used if policy CMP0064 is NEW (see [Chapter 13, Policies](#)).

IN_LIST

The IN_LIST form returns true if listVar contains the specified value, where value follows the usual variable-or-string rules. listVar must be the name of a list variable, it cannot be a string.

```
# Correct
set(things A B C)
if("B" IN_LIST things)
  ...
endif()

# WRONG: Right hand side must be the name of a variable
if("B" IN_LIST "A;B;C")
  ...
endif()

# Equivalent but more verbose alternative
list(FIND things "B" index)
if(NOT index EQUAL -1)
  ...
endif()
```

Also note that IN_LIST can only be used if policy CMP0057 is NEW (see [Chapter 13, Policies](#)). Use the alternative logic based on list(FIND) as shown above if the NEW behavior of CMP0057 cannot be assumed.

7.1.6. Common Examples

A few misuses of `if()` are so common, they deserve special mention. Many of these use the wrong predefined CMake variables in their logic, especially variables relating to the compiler or target platform. For example, consider a project which has two C++ source files, one for building with Visual Studio compilers or those compatible with them (e.g. Intel), and another for building with all other compilers. Such logic is frequently implemented like so:

```
if(WIN32)
    set(platformImpl source_win.cpp)
else()
    set(platformImpl source_generic.cpp)
endif()
```

While this will likely work for the majority of projects, it doesn't actually express the right constraint. Consider a project built on Windows but using the MinGW compiler. For such cases, `source_generic.cpp` may be the more appropriate source file. The above could be more accurately implemented as follows:

```
if(MSVC)
    set(platformImpl source_msvc.cpp)
else()
    set(platformImpl source_generic.cpp)
endif()
```

Another example involves conditional behavior based on the CMake generator being used. In particular, CMake offers additional features when building with the Xcode generator which no other generators support. Projects sometimes make

the assumption that building for macOS means the Xcode generator will be used, but this doesn't have to be the case (and often isn't). The following incorrect logic is sometimes used:

```
if(APPLE)
    # Some Xcode-specific settings here...
else()
    # Things for other platforms here...
endif()
```

Again, this may seem to do the right thing, but if a developer tries to use a different generator (e.g. Ninja or Unix Makefiles) on macOS, the logic fails. Testing the platform with the expression APPLE doesn't express the right condition, the CMake generator should be tested instead:

```
if(CMAKE_GENERATOR STREQUAL "Xcode")
    # Some Xcode-specific settings here...
else()
    # Things for other CMake generators here...
endif()
```

The above examples are both cases of testing the platform instead of the entity the constraint actually relates to. This is understandable, since the platform is one of the simplest things to understand and test. But using it instead of the more accurate constraint can unnecessarily limit the generator choices available to developers, or it may result in the wrong behavior entirely.

Another common example, this time used appropriately, is the conditional inclusion of a target based on whether a particular CMake option has been set.

```
option(BUILD_MYLIB "Enable building the MyLib target")
if(BUILD_MYLIB)
    add_library(MyLib src1.cpp src2.cpp)
endif()
```

More complex projects often use the above pattern to conditionally include subdirectories or perform a variety of other tasks based on a CMake option or cache variable. Developers can then turn that option on or off, or set the variable to non-default values without having to edit the CMakeLists.txt file directly. This is especially useful for scripted builds driven by continuous integration systems, etc. which may want to enable or disable certain parts of the build.

7.2. Looping

Another common need in many CMake projects is to perform some action on a list of items or for a range of values. Alternatively, some action may need to be performed repeatedly until a particular condition is met. These needs are well covered by CMake, offering the traditional behavior with some additions to make working with CMake features a little easier.

7.2.1. foreach()

CMake provides the `foreach()` command to enable projects to iterate over a set of items or values. There are a few different forms of `foreach()`, the most basic of which is:

```
foreach(loopVar arg1 arg2 ...)
# ...
endforeach()
```

In the above form, for each `argN` value, `loopVar` is set to that argument and the loop body is executed. No variable/string test is performed, the arguments are used exactly as the values are specified. Rather than listing out each item explicitly, the arguments can also be specified by one or more list variables using the more general form of the command:

```
foreach(loopVar IN [LISTS listVar1 ...] [ITEMS item1 ...])
# ...
endforeach()
```

In this more general form, individual arguments can still be specified using the `ITEMS` keyword, but the `LISTS` keyword allows one or more list variables to be specified. Either `ITEMS` or `LISTS` (or both) must be provided when using this more general form. When both are provided, the `ITEMS` must appear after the `LISTS`. It is permitted for the `listVarN` list variables to hold an empty list. An example with its output should help clarify this more general form's usage.

```
set(list1 A B)
set(list2)
```

```
set(foo WillNotBeShown)

foreach(loopVar IN LISTS list1 list2 ITEMS foo bar)
    message("Iteration for: ${loopVar}")
endforeach()
```

```
Iteration for: A
Iteration for: B
Iteration for: foo
Iteration for: bar
```

CMake 3.17 added a more specialized form for looping over multiple lists at once:

```
foreach(loopVar... IN ZIP_LISTS listVar...)
    #
endforeach()
```

If only one `loopVar` is given, then the command will set variables of the form `loopVar_N` at each iteration, where `N` corresponds to the `listVarN` variable. Numbering starts from 0. If there is one `loopVar` for each `listVar`, then the command maps them one-to-one instead of creating `loopVar_N` variables. The following example demonstrates the two cases:

```
set(list0 A B)
set(list1 one two)

foreach(var0 var1 IN ZIP_LISTS list0 list1)
    message("Vars: ${var0} ${var1}")
endforeach()

foreach(var IN ZIP_LISTS list0 list1)
    message("Vars: ${var_0} ${var_1}")
endforeach()
```

Both `foreach()` loops will print the same output:

```
Vars: A one  
Vars: B two
```

The lists to be "zipped" in this way do not have to be the same length. The associated iteration variable will be undefined when iteration moves past the end of the shorter list. Taking the value of an undefined variable results in an empty string. The next example demonstrates the behavior:

```
set(long A B C)  
set(short justOne)  
  
foreach(varLong varShort IN ZIP_LISTS long short)  
    message("Vars: ${varLong} ${varShort}")  
endforeach()
```

```
Vars: A justOne  
Vars: B  
Vars: C
```

The `foreach()` command also supports the more C-like iteration over a range of numerical values:

```
foreach(loopVar RANGE start stop [step])
```

When using the `RANGE` form of `foreach()`, the loop is executed with `loopVar` set to each value in the range `start` to `stop` (inclusive). If the `step` option is provided, then this value is

added to the previous one after each iteration and the loop stops when the result of that is greater than stop. The RANGE form also accepts just one argument like so:

```
foreach(loopVar RANGE value)
```

This is equivalent to `foreach(loopVar RANGE 0 value)`, which means the loop body will execute $(value + 1)$ times. This is unfortunate, since the more intuitive expectation is probably that the loop body executes `value` times. For this reason, it is likely to be clearer to avoid using this second RANGE form and explicitly specify both the start and stop values instead.

Similar to the situation for the `if()` and `endif()` commands, in very early versions of CMake (i.e. prior to 2.8.0), all forms of the `foreach()` command required that the `loopVar` also be specified as an argument to `endforeach()`. Again, this harms readability and offers little benefit, so specifying the `loopVar` with `endforeach()` is discouraged for new projects.

7.2.2. `while()`

The other looping command offered by CMake is `while()`:

```
while(condition)
# ...
endwhile()
```

The condition is tested and if it evaluates to true (following the same rules as the expression in `if()` statements), then the loop body is executed. This is repeated until condition evaluates to false or the loop is exited early (see next section). Again, in CMake versions prior to 2.8.0, the condition had to be repeated in the `endwhile()` command, but this is no longer necessary and is actively discouraged for new projects.

7.2.3. Interrupting Loops

Both `while()` and `foreach()` loops support the ability to exit the loop early with `break()` or to skip to the start of the next iteration with `continue()`. These commands behave just like their similarly named C language counterparts and both operate only on the innermost enclosing loop. The following example illustrates the behavior.

```
foreach(outerVar IN ITEMS a b c)
    set(s "")

foreach(innerVar IN ITEMS 1 2 3)
    list(APPEND s "${outerVar}${innerVar}")

    # Stop inner loop once string s gets long
    string(LENGTH "${s}" length)
    if(length GREATER 5)
        break()      ①
    endif()

    # Do no more processing if outerVar is "b"
    if(outerVar STREQUAL "b")
        continue()  ②
    endif()
```

```
    message("Processing ${outerVar}-${innerVar}")
endforeach()

    message("Accumulated list: ${s}")
endforeach()
```

- ① Ends the `innerVar` foreach loop early.
- ② Ends the current `innerVar` *iteration* and moves on to the next `innerVar` item.

The output from the above example would be:

```
Processing a-1
Processing a-2
Accumulated list: a1;a2;a3
Accumulated list: b1;b2;b3
Processing c-1
Processing c-2
Accumulated list: c1;c2;c3
```

The `break()` and `continue()` commands are also permitted within a block defined by the `block()` and `endblock()` commands (see [Section 6.4, “Scope Blocks”](#)). Leaving a block via `break()` or `continue()` ends that block’s local scope. The following contrived example demonstrates the behavior:

```
set(log "Value: ")
set(values one two skipMe three stopHere four)
set(didSkip FALSE)

while(NOT values STREQUAL "")
    list(POP_FRONT values next)

    # Modifications to "log" will be discarded
    block(PROPAGATE didSkip)
        string(APPEND log "${next}")
```

```

if(next MATCHES "skip")
    set(didSkip TRUE)
    continue()
elseif(next MATCHES "stop")
    break()
elseif(next MATCHES "t")
    string(APPEND log ", has t")
endif()
message("${log}")
endblock()

endwhile()

message("Did skip: ${didSkip}")
message("Remaining values: ${values}")

```

```

Value: one
Value: two, has t
Value: three, has t
Did skip: TRUE
Remaining values: four

```

With CMake 3.29 and later, CMake provides another command which has an effect similar to the standard C `exit()` function, but it is only available in CMake script mode. Discussion of that topic can be found in [Section 20.5, “Platform Independent Commands”](#).

7.3. Recommended Practices

Minimize opportunities for strings to be unintentionally interpreted as variables in `if()`, `foreach()`, and `while()` commands. Avoid unary expressions with quotes, prefer to use a string comparison operation instead. Strongly prefer to set a

minimum CMake version of at least 3.1 and ensure policy CMP0054 is set to NEW (see [Chapter 13, Policies](#)). This will disable the old behavior that allows implicit conversion of quoted string values to variable names.

When regular expression matching in `if(xxx MATCHES regex)` commands and the group capture variables are needed, store the `CMAKE_MATCH_<n>` match results in ordinary variables as soon as possible. These variables will be overwritten by the next command that does any sort of regular expression operation.

Prefer to use looping commands which avoid ambiguous or misleading code. If using the RANGE form of `foreach()`, always specify both the start and end values. If iterating over items, consider using the IN LISTS or IN ITEMS forms to communicate more clearly what is being done rather than using the older `foreach(loopVar item1 item2 ...)` form.

8. USING SUBDIRECTORIES

Keeping everything in one directory is fine for simple projects, but most real world projects split their files across multiple directories. It is common to find different file types or individual modules grouped under their own directories, or for files belonging to logical functional groupings to be in their own part of the project's directory hierarchy. While the directory structure may be driven by how developers think of the project, the way the project is structured also impacts the build system.

Two fundamental CMake commands in any multi-directory project are `add_subdirectory()` and `include()`. These commands bring content from another file or directory into the build, allowing the build logic to be distributed across the directory hierarchy rather than forcing everything to be defined at the top-most level. This offers a number of advantages:

- Build logic is *localized*, meaning that characteristics of the build can be defined in the directory where they have the most relevance.
- Builds can be composed of subcomponents which are defined independently of the top level project consuming them. This

is especially important if a project makes use of things like git submodules or embeds third party source trees.

- Because directories can be self-contained, it becomes relatively trivial to turn parts of the build on or off simply by choosing whether to add that directory.

`add_subdirectory()` and `include()` have quite different characteristics, so it is important to understand the strengths and weaknesses of both.

8.1. `add_subdirectory()`

The `add_subdirectory()` command allows a project to bring another directory into the build. That directory must have its own `CMakeLists.txt` file, which will be processed at the point where `add_subdirectory()` is called. A corresponding directory will be created in the project's build tree.

```
add_subdirectory(sourceDir [binaryDir]
    [EXCLUDE_FROM_ALL]
    [SYSTEM] # Requires CMake 3.25 or later
)
```

The `sourceDir` does not have to be a subdirectory within the source tree, although it usually is. Any directory can be added, with `sourceDir` being specified as either an absolute or relative path, the latter being relative to the current *source* directory. Absolute paths are typically only needed when adding directories that are outside the main source tree.

Normally, the `binaryDir` does not need to be specified. When omitted, CMake creates a directory in the build tree with the same name as the `sourceDir`. If `sourceDir` contains any path components, these will be mirrored in the `binaryDir` created by CMake. Alternatively, the `binaryDir` can be explicitly specified as either an absolute or relative path, with the latter being evaluated relative to the current *binary* directory (discussed in more detail shortly). If `sourceDir` is a path outside the source tree, CMake requires the `binaryDir` to be specified, since a corresponding relative path can no longer be constructed automatically.

The optional `EXCLUDE_FROM_ALL` keyword is intended to control whether targets defined in the subdirectory being added should be included in the project's `ALL` target by default. Unfortunately, for some CMake versions and project generators, it doesn't always act as expected, and can even result in broken builds. The `SYSTEM` keyword would not normally be used directly by projects and is discussed in [Section 16.8.2, “System Header Search Paths”](#).

8.1.1. Source And Binary Directory Variables

Sometimes a developer needs to know the location of the build directory corresponding to the current source directory, such as when copying files needed at run time, or to perform a custom build task. With `add_subdirectory()`, both the source and the

build trees' directory structures can be arbitrarily complex. There could even be multiple build trees being used with the same source tree. The developer therefore needs some assistance from CMake to determine the directories of interest. To that end, CMake provides a number of variables which keep track of the source and binary directories for the `CMakeLists.txt` file currently being processed. The following read-only variables are updated automatically as each file is processed by CMake. They always contain absolute paths.

`CMAKE_SOURCE_DIR`

The top-most directory of the *source* tree, where the top-most `CMakeLists.txt` file resides. This variable never changes its value.

`CMAKE_BINARY_DIR`

The top-most directory of the *build* tree. This variable never changes its value.

`CMAKE_CURRENT_SOURCE_DIR`

The directory of the `CMakeLists.txt` file currently being processed by CMake. It is updated each time a new file is processed as a result of an `add_subdirectory()` call and is restored back again when processing of that directory is complete.

`CMAKE_CURRENT_BINARY_DIR`

The build directory corresponding to the `CMakeLists.txt` file currently being processed by CMake. It changes for every call to `add_subdirectory()` and is restored again when `add_subdirectory()` returns.

An example should help demonstrate the behavior:

Top level CMakeLists.txt

```
cmake_minimum_required(VERSION 3.0)
project(MyApp)

message("top: CMAKE_SOURCE_DIR      = ${CMAKE_SOURCE_DIR}")
message("top: CMAKE_BINARY_DIR       = ${CMAKE_BINARY_DIR}")
message("top: CMAKE_CURRENT_SOURCE_DIR = ${CMAKE_CURRENT_SOURCE_DIR}")
message("top: CMAKE_CURRENT_BINARY_DIR = ${CMAKE_CURRENT_BINARY_DIR}")

add_subdirectory(mysub)

message("top: CMAKE_CURRENT_SOURCE_DIR = ${CMAKE_CURRENT_SOURCE_DIR}")
message("top: CMAKE_CURRENT_BINARY_DIR = ${CMAKE_CURRENT_BINARY_DIR}")
```

mysub/CMakeLists.txt

```
message("mysub: CMAKE_SOURCE_DIR      = ${CMAKE_SOURCE_DIR}")
message("mysub: CMAKE_BINARY_DIR       = ${CMAKE_BINARY_DIR}")
message("mysub: CMAKE_CURRENT_SOURCE_DIR = ${CMAKE_CURRENT_SOURCE_DIR}")
message("mysub: CMAKE_CURRENT_BINARY_DIR = ${CMAKE_CURRENT_BINARY_DIR}")
```

For the above example, if the top level `CMakeLists.txt` file was in the directory `/somewhere/src` and the build directory was `/somewhere/build`, the following output would be generated:

```
top: CMAKE_SOURCE_DIR      = /somewhere/src
top: CMAKE_BINARY_DIR       = /somewhere/build
top: CMAKE_CURRENT_SOURCE_DIR = /somewhere/src
```

```
top: CMAKE_CURRENT_BINARY_DIR = /somewhere/build
mysub: CMAKE_SOURCE_DIR          = /somewhere/src
mysub: CMAKE_BINARY_DIR          = /somewhere/build
mysub: CMAKE_CURRENT_SOURCE_DIR  = /somewhere/src/mysub
mysub: CMAKE_CURRENT_BINARY_DIR  = /somewhere/build/mysub
top:  CMAKE_CURRENT_SOURCE_DIR   = /somewhere/src
top:  CMAKE_CURRENT_BINARY_DIR   = /somewhere/build
```

8.1.2. Scope

In [Section 6.4, “Scope Blocks”](#), the concept of *scope* was discussed. One of the effects of calling `add_subdirectory()` is that CMake creates a new scope for processing that subdirectory’s `CMakeLists.txt` file. That new scope acts like a child of the calling scope, in a similar way to how the `block()` command creates a local child scope. The effects are very similar:

- All variables defined in the calling scope are copied into the subdirectory’s child scope upon entry.
- Any new variable created in the subdirectory’s child scope will not be visible to the calling scope.
- Any change to a variable in the subdirectory’s child scope is local to that child scope.
- Unsetting a variable in the subdirectory’s child scope does not unset it in the calling scope.

CMakeLists.txt

```
set(myVar foo)

message("Parent (before): myVar    = ${myVar}")
message("Parent (before): childVar = ${childVar}")
```

```
add_subdirectory(subdir)

message("Parent (after): myVar      = ${myVar}")
message("Parent (after): childVar = ${childVar}")
```

subdir/CMakeLists.txt

```
message("Child (before): myVar      = ${myVar}")
message("Child (before): childVar = ${childVar}")

set(myVar bar)
set(childVar fuzz)

message("Child (after): myVar      = ${myVar}")
message("Child (after): childVar = ${childVar}")
```

This produces the following output:

```
Parent (before): myVar      = foo      ①
Parent (before): childVar =           ②
Child  (before): myVar      = foo      ③
Child  (before): childVar =           ④
Child  (after):  myVar      = bar      ⑤
Child  (after):  childVar = fuzz     ⑥
Parent (after):  myVar      = foo      ⑦
Parent (after):  childVar =           ⑧
```

- ① `myVar` is defined at the parent level.
- ② `childVar` is not defined at the parent level, so it evaluates to an empty string.
- ③ `myVar` is still visible in the child scope.
- ④ `childVar` is still undefined in the child scope before it is set.
- ⑤ `myVar` is modified in the child scope.
- ⑥ `childVar` is set in the child scope.
- ⑦ When processing returns to the parent scope, `myVar` still has the value from before the call to `add_subdirectory()`. The modification to `myVar` in the child scope is not

visible to the parent.

- ⑧ childVar was defined in the child scope, so it is not visible to the parent and evaluates to an empty string.

The above behavior of scoping for variables highlights one of the important characteristics of `add_subdirectory()`. It allows the added directory to change whatever variables it wants without affecting variables in the calling scope. This helps keep the calling scope isolated from potentially unwanted changes.

As discussed in [Section 6.4, “Scope Blocks”](#), the `PARENT_SCOPE` keyword can be used with the `set()` or `unset()` commands to change or unset a variable in a parent scope instead of the current scope. This works the same way for a child scope created by `add_subdirectory()`:

CMakeLists.txt

```
set(myVar foo)
message("Parent (before): myVar = ${myVar}")
add_subdirectory(subdir)
message("Parent (after): myVar = ${myVar}")
```

subdir/CMakeLists.txt

```
message("Child (before): myVar = ${myVar}")
set(myVar bar PARENT_SCOPE)
message("Child (after): myVar = ${myVar}")
```

This produces the following output:

```
Parent (before): myVar = foo
Child (before): myVar = foo
Child (after):  myVar = foo  ①
```

```
Parent (after): myVar = bar ②
```

- ① The `myVar` in the child scope is not affected by the `set()` call because the `PARENT_SCOPE` keyword tells CMake to modify the parent's `myVar`, not the local one.
- ② The parent's `myVar` has been modified by the `set()` call in the child scope.

Because the use of `PARENT_SCOPE` prevents any local variable of the same name from being modified by the command, it can be less misleading if the local scope does not reuse the same variable name as one from the parent. In the above example, a clearer set of commands would be:

subdir/CMakeLists.txt

```
set(localVar bar)
set(myVar ${localVar} PARENT_SCOPE)
```

The above is a trivial example, but for real world projects, there may be many commands which contribute to building up the value of `localVar` before finally setting the parent's `myVar` variable.

It's not just variables that are affected by scope. Policies and some properties also have similar behavior to variables in this regard. In the case of policies, each `add_subdirectory()` call creates a new scope in which policy changes can be made without affecting the policy settings of the parent. Similarly, there are directory properties which can be set in the child directory's `CMakeLists.txt` file which will have no effect on the parent's directory properties. Both of these are covered in more

detail in their own respective chapters: [Chapter 13, Policies](#) and [Chapter 10, Properties](#).

8.1.3. When To Call project()

A question that sometimes arises is whether to call `project()` in the `CMakeLists.txt` files of subdirectories. In most cases, it is not necessary or desirable to do so, but it is permitted. The only place where `project()` must be called is the top-most `CMakeLists.txt` file. Upon reading the top level `CMakeLists.txt` file, CMake scans that file's contents looking for a call to `project()`. If no such call is found, CMake will issue a warning and insert an internal call to `project()` with the default C and C++ languages enabled. Projects should never rely on this mechanism, they should always explicitly call `project()` themselves. Note that it is not enough to call `project()` through a wrapper function or via a file read in via `add_subdirectory()` or `include()`. The top level `CMakeLists.txt` file must call `project()` *directly*.

Calling `project()` in subdirectories typically does no harm, but it may result in CMake having to generate extra files. For the most part, these extra `project()` calls and generated files are just noise, but in some cases they can be useful. When using a Visual Studio project generator, each `project()` command results in the creation of an associated solution file. Normally, the developer would load the solution file corresponding to the

top-most `project()` call (that solution file will be at the top of the build directory). This top level solution file contains all the targets in the project. The solution files generated for any `project()` calls within subdirectories will contain a more trimmed down view, containing just the targets from that directory scope and below, plus any other targets from the rest of the build that they depend on. Developers can load these sub-solutions instead of the top level one for a more trimmed-down view of the project, allowing them to focus on a smaller subset of the set of targets. For very large projects with many targets, this can be especially useful.

The Xcode generator behaves in a similar way, creating an Xcode project for each `project()` call. These Xcode projects can be loaded for a similar trimmed down view, but unlike for Visual Studio generators, they do not include the logic for building targets from outside of that directory scope or below. The developer is responsible for ensuring that anything required from outside of that trimmed down view has been built already. In practice, this means the top level project likely needs to be loaded and built first before switching to the trimmed down Xcode project.

8.2. `include()`

The other method CMake provides for pulling in content from other directories is the `include()` command. It has the following

two closely related forms:

```
include(fileName  
    [OPTIONAL] [RESULT_VARIABLE myVar] [NO_POLICY_SCOPE]  
)  
include(module  
    [OPTIONAL] [RESULT_VARIABLE myVar] [NO_POLICY_SCOPE]  
)
```

The first form is somewhat analogous to `add_subdirectory()`, but there are important differences:

- `include()` expects the name of a file to read in, whereas `add_subdirectory()` expects a directory and will look for a `CMakeLists.txt` file within that directory. The file name passed to `include()` typically has the extension `.cmake`, but it can be anything.
- `include()` does not introduce a new variable scope, whereas `add_subdirectory()` does.
- Both commands introduce a new policy scope by default, but the `include()` command can be told not to do so with the `NO_POLICY_SCOPE` option (`add_subdirectory()` has no such option). See [Chapter 13, Policies](#) for further details on policy scope handling.
- The value of the `CMAKE_CURRENT_SOURCE_DIR` and `CMAKE_CURRENT_BINARY_DIR` variables do not change when processing the file named by `include()`, whereas they do

change for `add_subdirectory()`. This is discussed in more detail shortly.

The second form of the `include()` command serves an entirely different purpose. It is used to load the named *module*, a topic covered in depth in [Chapter 12, Modules](#). All but the first of the above points also hold true for this second form.

Since the value of `CMAKE_CURRENT_SOURCE_DIR` does not change when `include()` is called, it may seem difficult for the included file to work out the directory in which it resides. `CMAKE_CURRENT_SOURCE_DIR` will contain the location of the file from where `include()` was called, not the directory containing the included file. Furthermore, unlike `add_subdirectory()` where the `fileName` will always be `CMakeLists.txt`, the name of the file can be anything when using `include()`. Therefore, it can be difficult for the included file to determine its own name or location. To address situations like these, CMake provides an additional set of variables:

`CMAKE_CURRENT_LIST_DIR`

Analogous to `CMAKE_CURRENT_SOURCE_DIR`, except it *will* be updated when processing the included file. This is the variable to use where the directory of the current file being processed is required, no matter how it has been added to the build. It will always hold an absolute path.

CMAKE_CURRENT_LIST_FILE

Always gives the name of the file currently being processed. It always holds an absolute path to the file, not just the file name.

CMAKE_CURRENT_LIST_LINE

Holds the line number of the file currently being processed. This variable is rarely needed, but may prove useful in some debugging scenarios.

Note that the above three variables work for *any* file being processed by CMake, not just those pulled in by an `include()` command. They have the same values as described above even for a `CMakeLists.txt` file pulled in via `add_subdirectory()`, in which case `CMAKE_CURRENT_LIST_DIR` would have the same value as `CMAKE_CURRENT_SOURCE_DIR`. The following example demonstrates the behavior:

CMakeLists.txt

```
add_subdirectory(subdir)
message("")
include(subdir/CMakeLists.txt)
```

subdir/CMakeLists.txt

```
message("CMAKE_CURRENT_SOURCE_DIR = ${CMAKE_CURRENT_SOURCE_DIR}")
message("CMAKE_CURRENT_BINARY_DIR = ${CMAKE_CURRENT_BINARY_DIR}")
message("CMAKE_CURRENT_LIST_DIR   = ${CMAKE_CURRENT_LIST_DIR}")
message("CMAKE_CURRENT_LIST_FILE  = ${CMAKE_CURRENT_LIST_FILE}")
message("CMAKE_CURRENT_LIST_LINE  = ${CMAKE_CURRENT_LIST_LINE}")
```

This produces output like the following:

```
CMAKE_CURRENT_SOURCE_DIR = /somewhere/src/subdir
CMAKE_CURRENT_BINARY_DIR = /somewhere/build subdir
CMAKE_CURRENT_LIST_DIR   = /somewhere/src/subdir
CMAKE_CURRENT_LIST_FILE  = /somewhere/src/subdir/CMakeLists.txt
CMAKE_CURRENT_LIST_LINE  = 5

CMAKE_CURRENT_SOURCE_DIR = /somewhere/src
CMAKE_CURRENT_BINARY_DIR = /somewhere/build
CMAKE_CURRENT_LIST_DIR   = /somewhere/src/subdir
CMAKE_CURRENT_LIST_FILE  = /somewhere/src/subdir/CMakeLists.txt
CMAKE_CURRENT_LIST_LINE  = 5
```

The above example also highlights another interesting characteristic of the `include()` command. It can be used to include content from a file that has already been included in the build previously. If different subdirectories of a large, complex project both want to make use of CMake code in some file in a common area of the project, they may both `include()` that file independently.

8.3. Project-relative Variables

As will be seen in later chapters, various scenarios require paths relative to a location in the source or build directory. Consider one such example where a project needs a path to a file that resides in its top level source directory. From [Section 8.1.1, “Source And Binary Directory Variables”](#), `CMAKE_SOURCE_DIR` seems to be a natural fit, allowing a path like `${CMAKE_SOURCE_DIR}/someFile` to be used. But consider what

happens if that project is later incorporated into another parent project by bringing it into the parent build via `add_subdirectory()`. It could be used as a git submodule, or fetched on demand using techniques like those discussed in [Chapter 39, *FetchContent*](#). What used to be the top of the original project's source tree is now a subdirectory within the parent project's source tree. `CMAKE_SOURCE_DIR` now points to the top of the *parent* project, so the file path will be pointing to the wrong directory. A similar trap exists for `CMAKE_BINARY_DIR`.

The above scenario is encountered surprisingly often in online tutorials and older projects, but it can easily be avoided. The `project()` command sets some variables that provide a much more robust way of defining paths relative to locations in the directory hierarchy. The following variables will be available after `project()` has been called at least once:

PROJECT_SOURCE_DIR

The source directory of the most recent call to `project()` in the current scope or any parent scope. The project name (the first argument given to the `project()` command) is not relevant.

PROJECT_BINARY_DIR

The build directory corresponding to the source directory defined by `PROJECT_SOURCE_DIR`.

projectName_SOURCE_DIR

The source directory of the most recent call to `project(projectName)` in the current scope or any parent scope. This is tied to a specific project name and therefore to a particular call to `project()`.

`projectName_BINARY_DIR`

The build directory corresponding to the source directory defined by `projectName_SOURCE_DIR`.

The following example demonstrates how these variables can be used (the ..._BINARY_DIR variables follow a similar pattern to the ..._SOURCE_DIR variables shown).

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.0)
project(topLevel)

message("Top level:")
message(" PROJECT_SOURCE_DIR = ${PROJECT_SOURCE_DIR}")
message(" topLevel_SOURCE_DIR = ${topLevel_SOURCE_DIR}")
add_subdirectory(child)
```

child/CMakeLists.txt

```
message("Child:")
message(" PROJECT_SOURCE_DIR (before) = ${PROJECT_SOURCE_DIR}")

project(child)

message(" PROJECT_SOURCE_DIR (after)   = ${PROJECT_SOURCE_DIR}")
message(" child_SOURCE_DIR           = ${child_SOURCE_DIR}")

add_subdirectory(grandchild)
```

child/grandchild/CMakeLists.txt

```
message("Grandchild:")
message(" PROJECT_SOURCE_DIR = ${PROJECT_SOURCE_DIR}")
message(" child_SOURCE_DIR    = ${child_SOURCE_DIR}")
message(" topLevel_SOURCE_DIR = ${topLevel_SOURCE_DIR}")
```

Running `cmake` on the top level of this project hierarchy would give output similar to the following:

```
Top level:
PROJECT_SOURCE_DIR  = /somewhere/src
topLevel_SOURCE_DIR = /somewhere/src
Child:
PROJECT_SOURCE_DIR (before) = /somewhere/src
PROJECT_SOURCE_DIR (after)  = /somewhere/src/child
child_SOURCE_DIR        = /somewhere/src/child
Grandchild:
PROJECT_SOURCE_DIR  = /somewhere/src/child
child_SOURCE_DIR    = /somewhere/src/child
topLevel_SOURCE_DIR = /somewhere/src
```

The above example shows the versatility of the project-related variables. They can be used to robustly refer to the directory of any other project defined in the current scope or any parent scope. For the scenario discussed at the start of this section, using `${PROJECT_SOURCE_DIR}/someFile` or perhaps `${projectName_SOURCE_DIR}/someFile` instead of `${CMAKE_SOURCE_DIR}/someFile` would ensure that the path to `someFile` would be correct, regardless of whether the project is being built stand-alone or being incorporated into a larger project hierarchy.

Some hierarchical build arrangements allow a project to be built either stand-alone or as part of a larger parent project (see [Chapter 39, *FetchContent*](#)). Some parts of the project might only make sense if it is the top of the build, such as setting up packaging support. A project can detect whether it is the top level by comparing the value of `CMAKE_SOURCE_DIR` with `CMAKE_CURRENT_SOURCE_DIR`. If they are the same, then the current directory scope must be the top level of the source tree.

```
if(CMAKE_CURRENT_SOURCE_DIR STREQUAL CMAKE_SOURCE_DIR)
    add_subdirectory(packaging)
endif()
```

The above technique is supported by all versions of CMake and is a very common pattern. With CMake 3.21 or later, a dedicated `PROJECT_IS_TOP_LEVEL` variable is provided which can achieve the same result, but is clearer in its intent:

```
# Requires CMake 3.21 or later
if(PROJECT_IS_TOP_LEVEL)
    add_subdirectory(packaging)
endif()
```

The value of `PROJECT_IS_TOP_LEVEL` will be true if the most recent call to `project()` in the current directory scope or above was in the top level `CMakeLists.txt` file. A similar variable, `< projectName >_IS_TOP_LEVEL`, is also defined by CMake 3.21 or later for every call to `project()`. `< projectName >` corresponds to the name given to the `project()` command of interest. This

alternative variable is useful when there may be intervening calls to `project()` between the current scope and the scope of the project of interest.

8.4. Ending Processing Early

There can be occasions where a project may want to stop processing the remainder of the current file and return control back to the caller. The `return()` command can be used for this purpose. If not called from inside a function, `return()` ends processing of the current file regardless of whether it was brought in via `include()` or `add_subdirectory()`. The effect of calling `return()` inside a function is covered in [Section 9.4, “Returning Values”](#), including special attention for a common mistake that can result in returning from the current file unintentionally.

With CMake 3.24 and earlier, the `return()` command cannot return any values to the caller. Starting with CMake 3.25, `return()` accepts a `PROPAGATE` keyword which has similarities to the same keyword of the `block()` command. Variables listed after the `PROPAGATE` keyword will be updated in the scope that control returns to. Historically, the `return()` command used to ignore all arguments given to it. Therefore, if using the `PROPAGATE` keyword, the `CMP0140` policy must be set to `NEW` to indicate that the old behavior is not applicable ([Chapter 13, Policies](#) discusses policies in depth).

CMakeLists.txt

```
set(x 1)
set(y 2)
add_subdirectory(subdir)
# Here, x will have the value 3 and y will be unset
```

subdir/CMakeLists.txt

```
# This ensures we have a version of CMake that supports
# PROPAGATE and that the CMP0140 policy is set to NEW.
cmake_minimum_required(VERSION 3.25)
```

```
set(x 3)
unset(y)
return(PROPAGATE x y)
```

Two cases involving variable propagation and interaction with the `block()` command are worth highlighting. Both are consequences of the fact that the `return()` command updates variables *in the scope it returns to*. For the first of the two cases, if that returned-to scope is within a block, then that block's scope is the one that gets updated. The top level `CMakeLists.txt` of the previous example can be modified as follows to demonstrate this behavior:

CMakeLists.txt

```
set(x 1)
set(y 2)

block()
  add_subdirectory(subdir)
  # Here, x will have the value 3 and y will be unset
endblock()
# Here, x is 1 and y is 2
```

The other case to highlight is more interesting. If the `return()` statement is itself inside a block, that block doesn't affect the propagation of variables to the returned-to scope.

CMakeLists.txt

```
set(x 1)
set(y 2)
add_subdirectory(subdir)
# Here, x will have the value 3 and y will be unset
```

subdir/CMakeLists.txt

```
cmake_minimum_required(VERSION 3.25)

# The block() here does not change the propagation of the
# variables specified by return(). The propagation is to
# the scope that return() gives control back to, which is
# the parent CMakeLists.txt file's scope.
block()
  set(x 3)
  unset(y)
  return(PROPAGATE x y)
endblock()
```

A word of caution is in order regarding the use of `return(PROPAGATE)` with directory scopes. While it may seem like an attractive way to pass information back to a parent scope, such usage is not consistent with the more target-centered approach of CMake best practice. Propagating variables to parent scopes drives the project structure to be more like the old-style variable-based methods. Those are known to be fragile, and they lack the power and expressiveness of target-centered methods. Variable propagation with `return()` is

potentially appropriate when returning from functions though, as discussed in [Section 9.4, “Returning Values”](#).

The `return()` command isn’t the only way to end processing of a file early. As noted in the previous section, different parts of a project may include the same file from multiple places. It can sometimes be desirable to check for this and only include the file once, returning early for subsequent inclusions to prevent reprocessing the file multiple times. This is very similar to the situation for C and C++ headers. It is therefore common to see a similar form of include guard used:

```
if(DEFINED cool_stuff_include_guard)
    return()
endif()

set(cool_stuff_include_guard 1)
# ...
```

With CMake 3.10 or later, this can be expressed more succinctly and robustly with a dedicated command whose behavior is analogous to the `#pragma once` of C and C++:

```
include_guard()
```

Compared to manually writing out the `if-endif` code, this is more robust because it handles the name of the guard variable internally. The command also accepts an optional keyword argument `DIRECTORY` or `GLOBAL` to specify a different scope within which to check for the file having been processed previously.

These keywords are unlikely to be needed in most situations though. With neither argument specified, variable scope is assumed and the effect is exactly equivalent to the `if-endif` code above. `GLOBAL` ensures the command ends processing of the file if it has been processed before anywhere else in the project (i.e. variable scope is ignored). `DIRECTORY` checks for previous processing only within the current directory scope and below.

8.5. Recommended Practices

The best choice between using `add_subdirectory()` or `include()` to bring another directory into the build is not always obvious. On the one hand, `add_subdirectory()` is simpler and does a better job of keeping directories relatively self-contained because it creates its own scope. On the other, some CMake commands have restrictions which only allow them to operate on things defined within the current file scope, so `include()` works better for those cases. [Section 16.2.6, “Source Files”](#) and [Section 43.5.1, “Building Up A Target Across Directories”](#) discuss aspects of this topic.

As a general guide, most simple projects are probably better off preferring to use `add_subdirectory()` over `include()`. It promotes cleaner definition of the project and allows the `CMakeLists.txt` for a given directory to focus more on just what that directory needs to define. Following this strategy will promote better locality of information throughout the project and will also tend

to introduce complexity only where it is needed and where it brings useful benefits. It's not that `include()` itself is any more complicated than `add_subdirectory()`, but the use of `include()` tends to result in paths to files needing to be more explicitly spelled out, since what CMake considers the current source directory is not that of the included file. Many of the restrictions associated with calling certain commands from different directories have been removed in more recent CMake versions too, which further strengthens the argument to prefer `add_subdirectory()`.

Irrespective of whether using `add_subdirectory()`, `include()`, or a combination of both, the `CMAKE_CURRENT_LIST_DIR` variable is generally going to be a better choice than `CMAKE_CURRENT_SOURCE_DIR`. By establishing the habit of using `CMAKE_CURRENT_LIST_DIR` early, it is much easier to switch between `add_subdirectory()` and `include()` as a project grows in complexity and to move entire directories to restructure a project.

Where possible, avoid using the `CMAKE_SOURCE_DIR` and `CMAKE_BINARY_DIR` variables, as these typically break the ability of the project to be incorporated into a larger project hierarchy. In the vast majority of cases, `PROJECT_SOURCE_DIR` and `PROJECT_BINARY_DIR`, or their project-specific equivalents `projectName_SOURCE_DIR` and `projectName_BINARY_DIR` are more appropriate variables to use.

Avoid using the `PROPAGATE` keyword with `return()` statements that end processing of the current file. Propagating variables to the parent file violates the best practice of preferring to attach information to targets rather than passing details around in variables. [Chapter 16, *Compiler And Linker Essentials*](#) covers a lot of relevant material related to preferring target-centered practices.

If the project requires CMake 3.10 or later, prefer to use the `include_guard()` command without arguments instead of an explicit `if-endif` block in cases where multiple inclusion of a file must be prevented.

Avoid the practice of arbitrarily calling `project()` in the `CMakeLists.txt` of every subdirectory. Only consider putting a `project()` command in a subdirectory's `CMakeLists.txt` file if that subdirectory can be treated as a more or less standalone project. Unless the whole build has a very high number of targets, there is little need to call `project()` anywhere other than in the top level `CMakeLists.txt` file.

9. FUNCTIONS AND MACROS

Looking back on the material covered in this book so far, CMake's syntax is already starting to look a lot like a programming language in its own right. It supports variables, if-then-else logic, looping, and inclusion of other files to be processed. It should be no surprise to learn that CMake also supports the common programming concepts of functions and macros too. Much like their role in other programming languages, functions and macros are the primary mechanism for projects and developers to extend CMake's functionality and to encapsulate repetitive tasks in a natural way. They allow the developer to define reusable blocks of CMake code which can be called just like regular built-in CMake commands. They are also a cornerstone of CMake's own module system (covered separately in [Chapter 12, *Modules*](#)).

9.1. The Basics

Functions and macros in CMake have very similar characteristics to their same-named counterparts in C/C++. Functions introduce a new scope, and the function arguments become variables accessible inside the function body. Macros,

on the other hand, effectively paste their body into the point of the call, and the macro arguments are substituted as simple string replacements. These behaviors mirror the way functions and `#define` macros work in C/C++. A CMake function or macro is defined as follows:

```
function(name [arg1 [arg2 [...]]])
    # Function body (i.e. commands) ...
endfunction()

macro(name [arg1 [arg2 [...]]])
    # Macro body (i.e. commands) ...
endmacro()
```

Once defined, the function or macro is called in exactly the same way as any other CMake command. The function or macro's body is then executed at the point of the call. For example:

```
function(print_me)
    message("Hello from inside a function")
    message("All done")
endfunction()

# Called like so:
print_me()
```

As shown above, the `name` argument defines the name used to call the function or macro. The name should only contain letters, numbers and underscores, and it will be treated case-insensitively. Upper/lowercase conventions are more a matter of style, but as a guideline, the CMake documentation follows

the convention that command names are all lowercase with words separated by underscores. Very early versions of CMake required the name to be repeated as an argument to `endfunction()` or `endmacro()`, but new projects should avoid this. Repeating the name adds unnecessary clutter and is now discouraged.

9.2. Argument Handling Essentials

The argument handling of functions and macros is the same except for one very important difference. For functions, each argument is a CMake variable and has all the usual behaviors of a CMake variable. For example, they can be tested in `if()` statements as variables. In comparison, macro arguments are string replacements, so whatever was used as the argument to the macro call is essentially pasted into wherever that argument appears in the macro body. If a macro argument is used in an `if()` statement, it would be treated as a string rather than a variable. The following example and its output demonstrate the difference:

```
function(func arg)
    if(DEFINED arg)
        message("Function arg is a defined variable")
    else()
        message("Function arg is NOT a defined variable")
    endif()
endfunction()

macro(macr arg)
    if(DEFINED arg)
```

```

    message("Macro arg is a defined variable")
else()
    message("Macro arg is NOT a defined variable")
endif()
endmacro()

func(foobar)
macr(foobar)

```

Function arg is a defined variable
 Macro arg is NOT a defined variable

Aside from that difference, functions and macros both support the same features when it comes to argument processing. Each argument in the function definition serves as a case-sensitive label for the argument it represents. For functions, that label acts like a variable, whereas for macros it acts like a string substitution. The value of that argument can be accessed in the function or macro body using the usual variable notation, even though macro arguments are not technically variables.

```

function(func myArg)
    message("myArg = ${myArg}")
endfunction()

macro(macr myArg)
    message("myArg = ${myArg}")
endmacro()

func(foobar)
macr(foobar)

```

Both the call to `func()` and the call to `macr()` print the same thing:

```
myArg = foobar
```

In addition to the named arguments, functions and macros come with a set of automatically defined variables (or variable-like names in the case of macros) which allow processing of arguments in addition to or instead of the named ones:

ARGC

This will be set to the total number of arguments passed to the function. It counts the named arguments plus any additional unnamed arguments that were given.

ARGV

This is a list containing each of the arguments passed to the function, including both the named arguments and any additional unnamed arguments that were given.

ARGN

Like ARGV, except this only contains arguments beyond the named ones (i.e. the optional, unnamed arguments).

In addition to the above, each argument can be referenced with a name of the form ARGVx, where x is the number of the argument (e.g. ARGV0, ARGV1, etc.). This includes the named arguments, so the first named argument could also be referenced via ARGV0, and so on. Note that it should be considered undefined behavior to use ARGVx with $x \geq \text{ARGC}$.

Typical situations where the ARG... names are used include supporting optional arguments, and implementing a command which can take an arbitrary number of items to be processed. Consider a function that defines an executable target, links that target to some library, and defines a test case for it. Such a function is frequently encountered when writing test cases (a topic covered in [Chapter 27, Testing Fundamentals](#)). Rather than repeating the steps for every test case, the function allows the steps to be defined once, and then each test case becomes a simple one-line definition.

```
# Use a named argument for the target and treat all other
# (unnamed) arguments as the source files for the test case
function(add_mytest targetName)
    add_executable(${targetName} ${ARGN})

    target_link_libraries(${targetName} PRIVATE foobar)

    add_test(NAME    ${targetName}
            COMMAND ${targetName})
endfunction()

# Define some test cases using the above function
add_mytest(smallTest small.cpp)
add_mytest(bigTest   big.cpp algo.cpp net.cpp)
```

The above example shows the usefulness of ARGN in particular. It allows a function or macro to take a varying number of arguments, yet still specify a set of named arguments which must be provided. There is, however, a specific case to be aware of which can result in unexpected behavior. Because macros treat their arguments as string substitutions rather than as

variables, if they use ARGN in a place where a variable name is expected, the variable it will refer to will be in the scope from which the macro is called, not the ARGN from the macro's own arguments. The following example highlights the situation:

```
# WARNING: This macro is misleading
macro(dangerous)
    # Which ARGN?
    foreach(arg IN LISTS ARGN)
        message("Argument: ${arg}")
    endforeach()
endmacro()

function(func)
    dangerous(1 2)
endfunction()

func(3)
```

The output from the above would be:

```
Argument: 3
```

When using the LISTS keyword with `foreach()`, a variable name has to be given, but the ARGN provided for a macro is not a variable name. When the macro is called from inside another function, the macro ends up using the ARGN *variable* from that enclosing function, not the ARGN from the macro itself. The situation becomes clear when pasting the contents of the macro body directly into the function where it is called (which is effectively what CMake will do with it):

```
function(func)
  # Now it is clear, ARGN here will use the arguments
  # from func
  foreach(arg IN LISTS ARGN)
    message("Argument: ${arg}")
  endforeach()
endfunction()
```

In such cases, consider making the macro a function instead, or if it must remain a macro, then avoid treating arguments as variables. For the above example, the implementation of dangerous() could be changed to use foreach(arg IN ITEMS \${ARGN}) instead, but see [Section 9.8, “Problems With Argument Handling”](#) for some potential caveats.

9.3. Keyword Arguments

The previous section illustrated how the ARG... variables can be used to handle a varying set of arguments. That functionality is good enough for simple cases where only one set of varying or optional arguments is needed, but if multiple optional or variable sets of arguments must be supported, the processing becomes quite tedious. Furthermore, the basic argument handling described above is quite rigid compared to many of CMake’s own built-in commands which support keyword-based arguments and flexible argument ordering.

Consider the target_link_libraries() command:

```
target_link_libraries(targetName
  <PRIVATE|PUBLIC|INTERFACE> item1 [item2 ...]
```

```
[<PRIVATE|PUBLIC|INTERFACE> item3 [item4 ...]]  
...  
)
```

The `targetName` is required as the first argument, but after that, callers can provide any number of PRIVATE, PUBLIC, or INTERFACE sections in any order. Each section is permitted to contain any number of items. User-defined functions and macros can support a similar level of flexibility by using the `cmake_parse_arguments()` command, of which there are two forms. The first form is supported by all CMake versions and works for both functions and macros:

```
# Needed only for CMake 3.4 and earlier  
include(CMakeParseArguments)  
  
cmake_parse_arguments(  
    prefix  
    valuelessKeywords singleValueKeywords multiValueKeywords  
    argsToParse...  
)
```

The `cmake_parse_arguments()` command used to be provided by the `CMakeParseArguments` module, but it became a built-in command in CMake 3.5. The `include(CMakeParseArguments)` line will do nothing in CMake 3.5 and later, while for earlier versions of CMake it will define the `cmake_parse_arguments()` command (see [Chapter 12, *Modules*](#) for more on this sort of usage of `include()`).

The second form was introduced in CMake 3.7 and can only be used in functions, not macros:

```
# Available with CMake 3.7 or later, do not use in macros
cmake_parse_arguments(
    PARSE_ARGV startIndex
    prefix
    valuelessKeywords singleValueKeywords multiValueKeywords
)
```

Both forms of the command are similar, differing only in the way they take in the set of arguments to parse. With the first form, `argsToParse` will typically be given as `ARGVN` without quotes. This provides all arguments given to the enclosing function or macro beyond the named arguments, except for a few specific corner cases that don't apply in most situations (see [Section 9.8, “Problems With Argument Handling”](#)).

In the second form, the `PARSE_ARGV` option tells `cmake_parse_arguments()` to read the arguments directly from the set of `ARGVx` variables, with `x` ranging from `startIndex` to `(ARGC - 1)`. Because it reads variables directly, it does not support being used inside macros. As already explained in [Section 9.2, “Argument Handling Essentials”](#), macros use string replacement rather than variables for its arguments. The main advantage of the second form is that for functions, it robustly handles the corner cases that the first form does not. If there are no named arguments for the enclosing function, then passing `ARGV` or `ARGVN` to the first form is equivalent to

giving PARSE_ARGUMENTS 0 to the second form when none of the corner cases apply.

The rest of the behavior for the two forms of the command is the same. Each of the ...Keywords is a list of keyword names to search for during parsing. Because they are a list, they need to be surrounded by quotes to ensure they are handled correctly. The valuelessKeywords define standalone keyword arguments which act like boolean switches. The keyword being present means one thing, its absence another. The singleValueKeywords each require exactly one additional argument after the keyword when they are used, whereas multiValueKeywords require zero or more additional arguments after the keyword. While not required, the prevailing convention is for keywords to be all uppercase, with words separated by underscores if required. Keywords should not be too long, otherwise they can be cumbersome to use.

When `cmake_parse_arguments()` returns, variables may be defined whose names consist of the specified prefix, an underscore, and the name of the keyword they are associated with. For example, with a prefix of `arg`, the variable corresponding to a keyword named `FOO` would be `arg_FOO`. For each of the valuelessKeywords, the corresponding variable will be defined with the value `TRUE` if the keyword is present, or `FALSE` if it is not. For each of the singleValueKeywords and multiValueKeywords, the corresponding variable will only be

defined if that keyword is present and a value is provided after the keyword.

The following example illustrates how the three different keyword types are defined and handled:

```
function(func)
    # Define the supported set of keywords
    set(noValues      ENABLE_NET COOL_STUFF)
    set(singleValues  TARGET)
    set(multiValues   SOURCES IMAGES)

    # Process the arguments passed in
    include(CMakeParseArguments)
    cmake_parse_arguments(
        arg
        "${noValues}" "${singleValues}" "${multiValues}"
        ${ARGN}
    )

    # Log details for each supported keyword
    message("Option summary:")

    foreach(opt IN LISTS noValues)
        if(arg_${opt})
            message("  ${opt} enabled")
        else()
            message("  ${opt} disabled")
        endif()
    endforeach()

    foreach(opt IN LISTS singleValues multiValues)
        # Single argument values will print as a string
        # Multiple argument values will print as a list
        message("  ${opt} = ${arg_${opt}}")
    endforeach()
endfunction()
```

```
# Examples of calling with different combinations
# of keyword arguments

func(SOURCES foo.cpp bar.cpp
      TARGET MyApp
      ENABLE_NET
)
func(COOL_STUFF
      TARGET dummy
      IMAGES here.png there.png gone.png
)
```

The corresponding output would look like this:

```
Option summary:
ENABLE_NET enabled
COOL_STUFF disabled
TARGET = MyApp
SOURCES = foo.cpp;bar.cpp
IMAGES =
Option summary:
ENABLE_NET disabled
COOL_STUFF enabled
TARGET = dummy
SOURCES =
IMAGES = here.png;there.png;gone.png
```

The call to `cmake_parse_arguments()` in the above example could also have been written using the second form like so:

```
cmake_parse_arguments(
  PARSE_ARGV 0
  arg
  "${noValues}" "${singleValues}" "${multiValues}"
)
```

Arguments can be given to a command such that there are leftover arguments not associated with any keyword. The `cmake_parse_arguments()` command provides all leftover arguments as a list in the variable `<prefix>_UNPARSED_ARGUMENTS`. An advantage of the `PARSE_ARGV` form is that if any unparsed arguments are themselves a list, their embedded semicolons will be escaped. This preserves the original structure of the arguments, unlike the other form of the command which doesn't. The following reduced example demonstrates this more clearly:

```
function(demoArgs)
    set(noValues      "")
    set(singleValues SPECIAL)
    set(multiValues  EXTRAS)
    cmake_parse_arguments(
        PARSE_ARGV 0
        arg
        "${noValues}" "${singleValues}" "${multiValues}"
    )

    message("Left-over args: ${arg_UNPARSED_ARGUMENTS}")
    foreach(opt IN LISTS arg_UNPARSED_ARGUMENTS)
        message("${opt}")
    endforeach()
endfunction()

demoArgs(burger fries "cheese;tomato" SPECIAL secretSauce)
```

```
Left-over args: burger;fries;cheese\;tomato
burger
fries
cheese;tomato
```

Inside the `demoArgs()` function, the call to `cmake_parse_arguments()` will define the variable `arg_SPECIAL` with the value `secretSauce`. The `burger`, `fries` and `cheese;tomato` arguments do not correspond to any recognized keywords, so they are treated as leftover arguments. As the above output shows, the original `cheese;tomato` list is preserved because the `PARSE_ARGV` form was used. This important point is revisited in [Section 9.8.2, “Forwarding Command Arguments”](#).

In the above example, the `SPECIAL` keyword expects a single argument to follow it. If the call had omitted the value, `cmake_parse_arguments()` would not raise an error. With CMake 3.14 or earlier, the project would not be able to detect this situation, but with later versions, it can. With CMake 3.15 or later, the `<prefix>_KEYWORDS_MISSING_VALUES` variable will be populated with a list containing all single- or multi-value keywords that were present, but which did not have any value following them. This can be demonstrated by modifying the previous example:

```
function(demoArgs)
    set(noValues "")
    set(singleValues SPECIAL)
    set(multiValues ORDINARY EXTRAS)
    cmake_parse_arguments(
        PARSE_ARGV 0
        arg
        "${noValues}" "${singleValues}" "${multiValues}"
    )
    message("Keywords missing values: "
        "${arg_KEYWORDS_MISSING_VALUES}")
```

```
)  
endfunction()  
  
demoArgs(burger fries SPECIAL ORDINARY EXTRAS high low)
```

In the above, SPECIAL and ORDINARY are each immediately followed by another keyword, so they have no values associated with them. Both can or should have values, so they will both be present in the `arg_KEYWORDS_MISSING_VALUES` variable populated by `cmake_parse_arguments()`. In the case of SPECIAL, it is probably an error, but for ORDINARY, it may still be valid since multi-value keywords can legitimately have no values. Projects should therefore be careful how they make use of `<prefix>_KEYWORDS_MISSING_VALUES`.

The `cmake_parse_arguments()` command provides considerable flexibility. While the first form of the command usually takes `ARGVN` as the set of arguments to parse, other arguments can be given. One can take advantage of this to do things like multi-level argument parsing:

```
function(libWithTest)  
    # First level of arguments  
    set(groups LIB TEST)  
    cmake_parse_arguments(group  
        "" "" "${groups}"  
        ${ARGVN}  
    )  
  
    # Second level of arguments  
    set(args SOURCES PRIVATE_LIBS PUBLIC_LIBS)  
    cmake_parse_arguments(lib  
        "" "TARGET" "${args}")
```

```

    ${group_LIB}
)
cmake_parse_arguments(test
  "" "TARGET" "${args}"
  ${group_TEST}
)

add_library(${lib_TARGET} ${lib_SOURCES})
target_link_libraries(${lib_TARGET}
  PUBLIC ${lib_PUBLIC_LIBS}
  PRIVATE ${lib_PRIVATE_LIBS}
)

add_executable(${test_TARGET} ${test_SOURCES})
target_link_libraries(${test_TARGET}
  PUBLIC ${test_PUBLIC_LIBS}
  PRIVATE ${test_PRIVATE_LIBS} ${lib_TARGET}
)
endfunction()

libWithTest(
  LIB
    TARGET Algo
    SOURCES algo.cpp algo.h
    PUBLIC_LIBS SomeMathHelpers
  TEST
    TARGET AlgoTest
    SOURCES algoTest.cpp
    PRIVATE_LIBS gtest_main
)

```

In the above example, the first level of arguments parsed by `cmake_parse_arguments()` is the usual `ARGV`. The only keywords at this first level are the two multi-value keywords `LIB` and `TEST`. These define which target the sub-options following it should be applied to. The second level of parsing is fed either `group_LIB` or `group_TEST` as the set of arguments to parse rather than

`ARGVN`. There is no conflict as a result of sub-options appearing more than once in the original set of ARGN arguments, since each target's sub-options are parsed separately.

Compared to basic argument handling using named arguments or using the `arg...` variables, the advantages of `cmake_parse_arguments()` are numerous:

- Being keyword-based, the calling site has improved readability, since the arguments essentially become self-documenting. Other developers reading the call site usually won't need to look at the function implementation or its documentation to understand what each of the arguments means.
- The caller gets to choose the order in which the arguments are given.
- The caller can omit those arguments which don't need to be provided.
- Since each of the supported keywords has to be passed to `cmake_parse_arguments()` and it is typically called near the top of the function, it is generally very clear what arguments the function supports.
- Since parsing the keyword-based arguments is handled by the `cmake_parse_arguments()` command rather than from an ad hoc, manually coded parser, argument parsing bugs are virtually eliminated.

While these capabilities are quite powerful, the command still has some limitations. Built-in commands are able to support keywords being repeated. For example, commands like `target_link_libraries()` allow the PRIVATE, PUBLIC, and INTERFACE keywords to be used more than once in the same command. The `cmake_parse_arguments()` command does not support this to the same extent. It will only return the values associated with the last occurrence of a keyword and discard the earlier ones. A keyword can only be repeated if using a multi-level set of keywords, and the keyword can only appear once in any given set of arguments being processed.

9.4. Returning Values

A fundamental difference between functions and macros is that functions introduce a new variable scope, whereas macros do not. Functions receive a *copy* of all variables from the calling scope. Variables defined or modified inside a function have no effect on variables of the same name outside the function (unless explicitly propagated, as discussed below). As far as variables are concerned, the function is essentially its own self-contained sandbox, much like a scope created by the `block()` command (see [Section 6.4, “Scope Blocks”](#)). Macros, on the other hand, share the same variable scope as their caller and can therefore modify the caller’s variables directly. Note that functions do not introduce a new *policy* scope (see [Section 13.7, “Recommended Practices”](#) for further discussion of this).

9.4.1. Returning Values From Functions

With CMake 3.25 or later, a function can effectively return values by specifying variables to propagate to the caller. This is achieved using the `PROPAGATE` keyword with the `return()` command, similar to the behavior described previously in [Section 8.4, “Ending Processing Early”](#). For each variable name listed after `PROPAGATE`, that variable will be updated in the calling scope to have the same value as in the function at the point of the `return()` call. If a propagated variable is unset in the function scope, it will also be unset in the calling scope. The `CMP0140` policy must be set to `NEW` when the function is defined if the `PROPAGATE` keyword is used ([Chapter 13, Policies](#) discusses policies in depth).

```
# This ensures we have a version of CMake that supports
# PROPAGATE and that the CMP0140 policy is set to NEW
cmake_minimum_required(VERSION 3.25)

function(doSomething outVar)
    set(${outVar} 42)
    return(PROPAGATE ${outVar})
endfunction()

doSomething(result)
# Here, a variable named result now holds the value 42
```

A function should not normally dictate the name of variables to be set in the calling scope. Instead, function arguments should be used to tell the function the names of variables to be set in the calling scope. This ensures the caller is in full control of

what the function does and that the function won't overwrite variables the caller does not expect. CMake's own built-in commands generally follow this pattern. The above example follows this recommendation by allowing the caller to specify the name of the result variable as the first argument to the function.

The `return()` statement propagates variables to the *calling* scope. This means any `block()` statements within the function do not prevent propagation to the function's caller, but they will affect the value of the variable(s) being propagated. The previous example can be modified slightly to demonstrate this:

```
cmake_minimum_required(VERSION 3.25)

function(doSomething outVar)
    set(${outVar} 42)
    block()
        set(${outVar} 27)
        return(PROPAGATE ${outVar})
    endblock()
endfunction()

doSomething(result)
# Here, a variable named result now holds the value 27
```

With CMake 3.24 and earlier, functions do not support returning a value directly. Since functions introduce their own variable scope, it may seem that there is no easy way to pass information back to the caller, but this is not the case. As discussed previously in [Section 6.4, “Scope Blocks”](#) and [Section](#)

[8.1.2, “Scope”](#), the `set()` and `unset()` commands support a `PARENT_SCOPE` keyword, which can be used to modify a variable in the caller’s scope rather than a local variable within the function. While this isn’t the same as returning values from the function, it does allow values to be passed back to the calling scope to achieve a similar effect.

```
function(func resultVar1 resultVar2)
    set(${resultVar1} "First result" PARENT_SCOPE)
    set(${resultVar2} "Second result" PARENT_SCOPE)
endfunction()

func(myVar otherVar)

message("myVar: ${myVar}")
message("otherVar: ${otherVar}")
```

```
myVar: First result
otherVar: Second result
```

9.4.2. Returning Values From Macros

Macros can “return” specific variables in the same way as functions, specifying the names of variables to be set by passing them in as arguments. The only difference is that the `PARENT_SCOPE` keyword should not be used within the macro when calling `set()` because the macro already modifies the variables in the caller’s scope. In fact, about the only reason one would use a macro instead of a function is if variables need to be set in the calling scope. A macro will affect the calling scope with every `set()` or `unset()` call, whereas a function only affects

the calling scope when PARENT_SCOPE is explicitly given to set() or unset().

The last example of the previous section could be implemented equivalently as a macro like so:

```
macro(func resultVar1 resultVar2)
    set(${resultVar1} "First result")
    set(${resultVar2} "Second result")
endmacro()
```

The behavior of return() within a macro is very different to a function. Because a macro does not introduce a new scope, the behavior of the return() statement is dependent on where the macro is called. Recall that a macro effectively pastes its commands at the call site. That being the case, any return() statement from a macro will actually be returning from the scope of whatever called the macro, not from the macro itself. Consider the following example:

```
macro(inner)
    message("From inner")
    return() # Usually dangerous within a macro
    message("Never printed")
endmacro()

function(outer)
    message("From outer before calling inner")
    inner()
    message("Also never printed")
endfunction()

outer()
```

The output from the above would be:

```
From outer before calling inner  
From inner
```

To highlight why the second message in the function body is never printed, paste the contents of the macro body into where it is called:

```
function(outer)  
  message("From outer before calling inner")  
  
  # === Pasted macro body ===  
  message("From inner")  
  return()  
  message("Never printed")  
  # === End of macro body ===  
  
  message("Also never printed")  
endfunction()  
  
outer()
```

It is now much clearer why the `return()` statement causes processing to leave the function, even though it was originally called from inside the macro. This highlights the danger of using `return()` within macros. Because macros do not create their own scope, the result of a `return()` statement is often not what was expected.

9.5. Overriding Commands

When `function()` or `macro()` is called to define a new command, if a command already exists with that name, the undocumented CMake behavior is to make the old command available using the same name except with an underscore prepended. This applies whether the old name is for a built-in command or a custom function or macro. Developers who are aware of this behavior are sometimes tempted to exploit it to try to create a wrapper around an existing command like so:

```
function(someFunc)
    # Do something...
endfunction()

# Later in the project...
function(someFunc)
    if(...)
        # Override the behavior with something else...
    else()
        # WARNING: Intended to call the original command,
        #           but it is not safe
        _someFunc()
    endif()
endfunction()
```

If the command is only ever overridden like this once, it appears to work. But if it is overridden again, then the original command is no longer accessible. The prepending of one underscore to "save" the previous command only applies to the current name, it is not applied recursively to all previous overrides. This has the potential to lead to infinite recursion, as the following contrived example demonstrates:

```
function(printme)
    message("Hello from first")
endfunction()

function(printme)
    message("Hello from second")
    _printme()
endfunction()

function(printme)
    message("Hello from third")
    _printme()
endfunction()

printme()
```

One would naively expect the output to be as follows:

```
Hello from third
Hello from second
Hello from first
```

But instead, the first implementation is never called because the second one ends up calling itself in an infinite loop. When CMake processes the above, here's what occurs:

1. The first implementation of `printme` is created and made available as a command of that name. No command by that name previously existed, so no further action is required.
2. The second implementation of `printme` is encountered. CMake finds an existing command by that name, so it defines the name `_printme` to point to the old command and sets `printme` to point to the new definition.

3. The third implementation of `printme` is encountered. Again, CMake finds an existing command by that name, so it *redefines* the name `_printme` to point to the old command (which is the second implementation) and sets `printme` to point to the new definition.

When `printme()` is called, execution enters the third implementation, which calls `_printme()`. This enters the second implementation which also calls `_printme()`, but `_printme()` points back at the second implementation again and infinite recursion results. Execution never reaches the first implementation.

In general, it is fine to override a function or macro as long as it does not try to call the previous implementation like in the above discussion. Projects should assume that the new implementation replaces the old one, with the old one considered to be no longer available.

9.6. Special Variables For Functions

CMake 3.17 added support for a number of variables to help with debugging and implementing functions. The following variables will be available during execution of a function:

`CMAKE_CURRENT_FUNCTION`

Holds the name of the function currently being executed.

CMAKE_CURRENT_FUNCTION_LIST_FILE

Contains the full path to the file that defined the function currently being executed.

CMAKE_CURRENT_FUNCTION_LIST_DIR

Holds the absolute directory containing the file that defined the function currently being executed.

CMAKE_CURRENT_FUNCTION_LIST_LINE

Holds the line number at which the currently executing function was defined within the file that defined it.

The CMAKE_CURRENT_FUNCTION_LIST_DIR variable is particularly useful when a function needs to refer to a file that is an internal implementation detail of the function. The value of CMAKE_CURRENT_LIST_DIR would contain the directory of the file where the function is *called*, whereas CMAKE_CURRENT_FUNCTION_LIST_DIR holds the directory where the function is *defined*. To see how this can be used, consider the following example. It demonstrates a common pattern where a function uses the `configure_file()` command to copy a file from the same directory as the file defining the function (see [Section 21.2, “Copying Files”](#) for further discussion):

```
function(writeSomeFile toWhere)
    configure_file(
        ${CMAKE_CURRENT_FUNCTION_LIST_DIR}/template.cpp.in
        ${toWhere}
        @ONLY
```

```
)  
endfunction()
```

Before CMake 3.17, the above would instead typically be implemented like the following (CMake's own modules used this technique prior to CMake 3.17):

```
set(__writeSomeFile_DIR ${CMAKE_CURRENT_LIST_DIR})  
  
function(writeSomeFile toWhere)  
    configure_file(  
        ${__writeSomeFile_DIR}/template.cpp.in  
        ${toWhere}  
        @ONLY  
    )  
endfunction()
```

This second example relies on the `__writeSomeFile_DIR` variable remaining visible at the point of the call to the function. Normally, that should be a reasonable assumption, but because functions have global scope visibility, projects can technically define a function in one place and call it in an unrelated variable scope. While that is technically legal, it is not a recommended practice. Extra care must also be taken with this technique when include guards are used in files that define functions (see [Section 8.4, “Ending Processing Early”](#)).

The `CMAKE_CURRENT_FUNCTION...` variables are only updated for functions, they are not modified inside macros. When executing code for a macro, these variables will hold whatever values they had when the macro was called.

9.7. Other Ways Of Invoking CMake Code

Functions and macros provide powerful ways of defining code to be executed at some later time. They are an essential part of re-using common logic for similar or repetitive tasks. Nevertheless, there are situations where projects may want to define CMake code to be executed in a way that functions and macros alone cannot capture.

CMake 3.18 added the `cmake_language()` command which can be used to invoke arbitrary CMake code directly without having to define a function or macro. This functionality isn't designed to replace functions or macros, but rather to complement them by enabling more concise code and the ability to express logic in ways that were not previously possible. The two sub-commands provided by CMake 3.18 are `CALL` and `EVAL CODE`:

```
cmake_language(CALL command [args...])
cmake_language(EVAL CODE code...)
```

The `CALL` sub-command invokes a single CMake command, with arguments if required. It provides the ability to parameterize the command to be invoked without having to hard-code all available choices. Certain built-in commands cannot be invoked this way, specifically those commands that start or end a block like `if()`, `endif()`, `foreach()`, `endforeach()`, and so on.

The following example demonstrates how a generic wrapper can be defined around a set of functions that include a version

number in their name:

```
function(qt_generate_moc)
    set(cmd qt${QT_DEFAULT_MAJOR_VERSION}_generate_moc)

    cmake_language(CALL ${cmd} ${ARGV})
endfunction()
```

The above example assumes the QT_DEFAULT_MAJOR_VERSION variable has been set previously. As future Qt major versions are released, the above would continue to work as long as the appropriate versioned command was still provided. The alternative would be to implement an ever-expanding set of if() tests for each version individually.

The CALL sub-command is fairly limited in its usefulness. The EVAL CODE sub-command is much more powerful, as it supports executing any valid CMake script. One advantage of this is that it does not interfere with variables that get updated inside a function invocation, such as ARGV, CMAKE_CURRENT_FUNCTION, and so on. The following example takes advantage of this behavior to implement a form of call tracing for functions:

```
set(myProjTraceCall [=
    message("Called ${CMAKE_CURRENT_FUNCTION}")
    set(_x 0)
    while(_x LESS ${ARGC})
        message("  ARGV${_x} = ${ARGV${_x}}")
        math(EXPR _x "${_x} + 1")
    endwhile()
    unset(_x)
]=)
```

```
function(func)
    cmake_language(EVAL CODE "${myProjTraceCall}")
    #
endfunction()

func(one two three)
```

```
Called func
ARGV0 = one
ARGV1 = two
ARGV2 = three
```

Note how the code stored in `myProjTraceCall` makes use of the various `ARG*` variables and also the `CMAKE_CURRENT_FUNCTION` variable. Bracket syntax `[=[` and `]=]` is used to prevent the evaluation of these variables when `myProjTraceCall` is set. The variables will be evaluated only when `cmake_language()` is called, so they will reflect the details of the enclosing function. Because of this delayed evaluation, the tracing code won't work as expected inside a macro, so only use it from inside a function.

See [Section 9.8.2, “Forwarding Command Arguments”](#) for another particularly interesting example of the `EVAL CODE` sub-command.

CMake 3.19 added the `DEFER` set of sub-commands. These allow a command to be queued for execution at a later time:

```
cmake_language(DEFER
    [DIRECTORY dir]
    [...other options for ID management...]
```

```
    CALL command [args...]
)
```

Evaluation of variables within `command` and `args` doesn't follow the usual behavior of most other CMake commands. See [Section 9.8.3, “Special Cases For Argument Expansion”](#) for a discussion of the important differences.

The command and its arguments will be queued for execution at the end of the current directory scope. The `DIRECTORY` option can be given to specify a different directory scope instead. In that case, the `dir` directory must already be known to CMake, and it must be either the current or one of the parent directory scopes.

```
cmake_language(DEFER
    CALL message "End of current scope processing"
)
cmake_language(DEFER
    DIRECTORY ${CMAKE_SOURCE_DIR}
    CALL message "End of top level processing"
)
```

Each queued command has an identifier associated with it. For most projects, that identifier isn't important and can be ignored. The `cmake_language(DEFER)` command does support a number of other keywords that can be used to record, manage and cancel deferred commands using these identifiers, if needed. Such logic can be a sign the project may be trying to do too much with deferred commands, and the complexity may be

questionable. The reader should consult the `cmake_language(DEFER)` documentation for details if such logic needs to be used.

At this point, it would be natural to start thinking of different ways one might put the DEFER functionality to use. Before doing so, consider the following observations:

- Special rules apply to variable expansion within deferred commands and their arguments (see [Section 9.8.3, “Special Cases For Argument Expansion”](#)). These can lead to subtle problems that can be difficult to trace.
- Deferred commands make it harder for developers to follow the flow of execution. This is especially true when deferred commands are created inside functions or macros and their creation isn't made obvious.
- In deferring commands, the project may be making assumptions about what can happen between the deferral and the execution of the commands. It may be quite difficult to guarantee that these assumptions remain valid, especially for commands deferred to parent scopes or where deferred commands are created inside a function or macro that could be called from anywhere.
- Deferred commands can be a sign of a project's CMake API trying to do too much in one function or macro.

Given the above, where there is a choice, prefer other techniques or refactoring over deferring commands. As an example, a function might wrap a command that creates a target, then call other commands that use properties of that target before returning (properties are covered in the next chapter). By encapsulating all of this in a single function, the caller has no opportunity to modify target properties before they are used. Rather than deferring the commands that use the target so that the caller can modify the target properties, consider breaking up the function so that it doesn't have so many responsibilities. Requiring the target to be passed in instead of creating it would be one alternative solution for this particular example.

9.8. Problems With Argument Handling

CMake's implementation of command arguments contains a few subtle behaviors. For the most part, these behaviors don't lead to problems, but occasionally they can cause confusion or give rise to unexpected results. To appreciate why these behaviors exist and how to handle them safely, it helps to understand the way in which CMake constructs and passes arguments to commands.

Consider the following equivalent calls where `someCommand` could be any valid command:

```
someCommand(a b c)
someCommand(a     b     c)
```

Arguments are separated by spaces, and consecutive spaces are treated as a single separator. Semicolons act as argument separators too, so the following are also equivalent to the above:

```
someCommand(a b;c)
someCommand(a;;;;b;c)
```

Where an argument needs to contain embedded spaces or semicolons, quoting must be used:

```
someCommand(a "b b" c)
someCommand(a "b;b" c)
```

Both of the above calls result in three arguments being passed to the command. The first call passes b b for the second argument, the second call passes b;b for the second argument.

Where spaces and semicolons differ is how they are handled when variable evaluation is involved and arguments are not quoted:

```
set(containsSpace      "b b")
set(containsSemiColon "b;b")

someCommand(a ${containsSpace} c)
someCommand(a ${containsSemiColon} c)
```

The first call to `someCommand()` results in *three* arguments being passed, whereas the second call results in *four* arguments. The embedded space in `containsSpace` does not act as an argument separator, but the embedded semicolon in `containsSemiColon` does. Spaces only act as argument separators before any variable evaluation is performed. The interaction between these two different behaviors can lead to some surprising results:

```
set(empty          "")  
set(space          " ")  
setsemicolon      ";"")  
set(semiSpace     ";" ")  
set(spaceSemi     " ;")  
set(spaceSemiSpace " ; ")  
set(spaceSemiSemi  ";;")  
set(semiSemiSpace ";; ")  
set(spaceSemiSemiSpace ";; ")  
  
someCommand(${empty})           # 0 args  
someCommand(${space})          # 1 arg  
someCommand(${semicolon})       # 0 args  
someCommand(${semiSpace})       # 1 arg  
someCommand(${spaceSemi})       # 1 arg  
someCommand(${spaceSemiSpace})   # 2 args  
someCommand(${spaceSemiSemi})   # 1 arg  
someCommand(${semiSemiSpace})   # 1 arg  
someCommand(${spaceSemiSemiSpace}) # 2 args
```

Some important observations should be noted from the above:

OBSERVATION 1

When they are the result of variable evaluations, spaces are never discarded and never act as argument separators.

OBSERVATION 2

One or more semicolons at the start or the end of an unquoted argument are discarded.

OBSERVATION 3

Consecutive semicolons not at the start or end of an unquoted argument are merged and act as a single argument separator.

Much of the confusion can be avoided by quoting arguments if they contain any variable evaluations. This eliminates any special interpretation of embedded spaces or semicolons. While not generally harmful, this isn't always desirable. As the next subsection will highlight, there are some situations which *require* arguments to be unquoted precisely because they rely on the above behavior.

9.8.1. Parsing Arguments Robustly

Consider the `cmake_parse_arguments()` command discussed earlier in [Section 9.3, “Keyword Arguments”](#). The original form of this command is typically used like so:

```
function(func)
    set(noValues    ENABLE_A ENABLE_B)
    set(singleValues FORMAT ARCH)
    set(multiValues SOURCES IMAGES)

    cmake_parse_arguments(
        arg
        "${noValues}" "${singleValues}" "${multiValues}"
```

```
    ${ARGV}  
)  
endfunction()
```

Note the quoting around the evaluation of `noValues`, `singleValues`, and `multiValues`. When evaluated, each of these variables yields a string that contains a semicolon. For example, `${singleValues}` will evaluate to `FORMAT;ARCH`. The quotes are necessary to prevent those semicolons from acting as argument separators. The result is that `cmake_parse_arguments()` will see `arg` for its first argument, `ENABLE_A;ENABLE_B` as the second, `FORMAT;ARCH` as the third, and `SOURCES;IMAGES` as the fourth.

The `${ARGV}` provided at the end of the call does not have quotes. This is specifically to take advantage of the fact that embedded semicolons will act as argument separators. The `cmake_parse_arguments()` command interprets the fifth and subsequent arguments it receives as the arguments to parse. By using an unquoted `${ARGV}`, `cmake_parse_arguments()` sees the same set of arguments as was passed in to `func()`.

The problem with the above is that using `${ARGV}` fails to preserve the original arguments in two specific cases. Consider the following calls:

```
func(a "" c)  
func("a;b;c" "1;2;3")
```

For the first call, inside `func()` the evaluation of `ARGV` will be `a;;c`. As noted in **OBSERVATION 3**, the two semicolons will be merged and `cmake_parse_arguments()` will see only `a` and `c` as the arguments to be parsed. Empty arguments are silently dropped.

For the second call, the evaluation of `ARGV` will be `a;b;c;1;2;3`. The original call to `func()` had `a;b;c` as the first argument and `1;2;3` as the second, but this gets flattened by the `ARGV` evaluation. The `cmake_parse_arguments()` command instead sees six individual arguments rather than two lists.

Both of the above problems can be solved by using the other form of the `cmake_parse_arguments()` command to avoid evaluating `ARGV` directly:

```
cmake_parse_arguments(  
    PARSE_ARGV 0 arg  
    "${noValues}" "${singleValues}" "${multiValues}"  
)
```

In practice, the `cmake_parse_arguments()` command is often used in situations where dropping empty arguments or flattening lists has no real impact. In these cases, either form of the `cmake_parse_arguments()` command can safely be called. Where the arguments need to be preserved exactly as passed in though, the `PARSE_ARGV` form should always be used.

9.8.2. Forwarding Command Arguments

A relatively common need is to create some sort of wrapper around an existing command. The project may wish to support some extra options or remove existing ones, or it may want to perform certain processing before or after the call. Preserving arguments and forwarding them on without changing their structure or losing information can be surprisingly difficult.

Consider the following example and its output, which picks up on one of the points in the previous subsection:

```
function(printArgs)
    message("ARGC = ${ARGC}\n"
           "ARGN = ${ARGN}"
    )
endfunction()

printArgs("a;b;c" "d;e;f")
```

```
ARGC = 2
ARGN = a;b;c;d;e;f
```

The arguments to `printArgs()` are quoted, so the function does see only two arguments. In forming the value for `${ARGN}` though, these two lists are joined with a semicolon and the result is a single list of six items. The original form of the arguments is lost as a result of this list flattening. Consider the consequences of this for a wrapper command when it attempts to forward arguments to the command being wrapped:

```
function(inner)
    message("inner:\n"
```

```

"ARGC = ${ARGC}\n"
"ARGN = ${ARGN}"
)
endfunction()

function(outer)
message("outer:\n"
    "ARGC = ${ARGC}\n"
    "ARGN = ${ARGN}"
)
inner(${ARGN}) # Naive forwarding, not robust
endfunction()

outer("a;b;c" "d;e;f")

```

```

outer:
ARGC = 2
ARGN = a;b;c;d;e;f
inner:
ARGC = 6
ARGN = a;b;c;d;e;f

```

The `outer()` function wants to wrap the `inner()` function and forward its arguments exactly, but as the above output shows, the number of arguments seen by `inner()` is different. The evaluation of `${ARGN}` as a way to pass arguments through to `inner()` triggers the list flattening behavior described previously. The original structure of the arguments is lost.

The `PARSE_ARGV` form of the `cmake_parse_arguments()` command can be used to avoid the list flattening problem:

```

function(outer)
cmake_parse_arguments(PARSE_ARGV 0 fwd "" "" "")

```

```
inner(${fwd_UNPARSED_ARGUMENTS})
endfunction()
```

With no keywords to parse, all arguments given to `outer()` will be placed in `fwd_UNPARSED_ARGUMENTS`. As noted back in [Section 9.3, “Keyword Arguments”](#), when the `PARSE_ARGV` form of `cmake_parse_arguments()` populates `fwd_UNPARSED_ARGUMENTS`, it escapes any embedded semicolons from the original arguments. Therefore, when that variable is passed to `inner()`, the escaping preserves the structure of the original arguments and `inner()` will see the same arguments as `outer()`.

Unfortunately, the above technique still has a weakness. As a consequence of **OBSERVATIONS 2** and **3**, it does not preserve any empty arguments. To avoid dropping empty arguments, each argument needs to be listed individually and be quoted. The `cmake_language(EVAL CODE)` command available with CMake 3.18 or later provides the functionality needed:

```
function(outer)
    cmake_parse_arguments(PARSE_ARGV 0 fwd "" "")
    set(quotedArgs "")
    foreach(arg IN LISTS fwd_UNPARSED_ARGUMENTS)
        string(APPEND quotedArgs " [===[${arg}]]==]")
    endforeach()
    cmake_language(EVAL CODE "inner(${quotedArgs})")
endfunction()
```

Note the use of the bracket form for quoting. This ensures that any arguments with embedded quotes will be handled robustly too.

The above implementation provides robust argument forwarding, but it requires a minimum CMake version of 3.18 or higher. For earlier versions, the `cmake_language()` command is not available. An equivalent capability can be implemented by writing out the command to be executed to a file and asking CMake to process that file via a call to `include()`, but this is very inefficient and not recommended as a general solution.

The above technique works only for functions. The `PARSE_ARGV` form of `cmake_parse_arguments()` can't be used with macros, which means list flattening cannot be avoided. However, if list flattening is not a concern, one can at least preserve empty strings. The following implementation demonstrates one way to achieve that, under the assumption that no value will ever need to contain a semicolon:

```
# WARNING: This example does not preserve list structure.  
#           It does preserve empty string arguments.  
macro(outer)  
    string(REPLACE  
        ";" "]==]" [==[" args "[==[$ARGV]==]"  
    )  
    cmake_language(EVAL CODE "inner(${args})")  
endmacro()
```

See [Section 41.2.6, “Delegating Providers”](#) for an example of a scenario where the above technique may be needed.

9.8.3. Special Cases For Argument Expansion

While the above techniques work well in general, some built-in commands handle their arguments in special ways, causing them to diverge from the expected behavior. These exceptions fall into two main categories: `cmake_language()` and evaluating boolean expressions.

Variable Evaluation For `cmake_language()`

`cmake_language(CALL)` provides an alternative way of executing a command. The command to call can be provided by a variable instead of having to be hard-coded. To faithfully reproduce the normal argument expansion and quote handling behavior for the arguments given to the forwarded-to command, those arguments are required to be separated from the command itself in the call to `cmake_language(CALL)`. The following example demonstrates the limitation:

```
# ERROR: command must be its own argument
set(cmdWithArgs message STATUS "Hello world")
cmake_language(CALL ${cmdWithArgs})

# OK: Command can be a variable expansion, but it must
# evaluate to a single value. Arguments can also be a
# variable expansion and they can evaluate to a list.
set(cmd message)
set(args STATUS "Hello world")
cmake_language(CALL ${cmd} ${args})
```

The `cmake_language(DEFER CALL)` command has similar restrictions, but it has further differences. Variable evaluations are performed immediately for the command to be executed, but evaluations are deferred for the command arguments. The following example highlights this behavior:

```
set(cmd message)
set(args "before deferral")
cmake_language(DEFER CALL ${cmd} ${args})

set(cmd somethingElse)      # Doesn't affect the command
set(args "after deferral")  # But this does!
```

after deferral

The evaluation of `${cmd}` happens immediately, but `${args}` is not evaluated until the deferred command is called. At the end of the directory scope, `args` will have the value `after deferral`.

If evaluation of variables in command arguments needs to be performed immediately, one has to wrap the deferral within a call to `cmake_language(EVAL CODE)`. An example of this scenario is where the deferral is created inside a function or macro, and the deferred command arguments need to incorporate information passed as arguments to the deferring function or macro:

```
function(endOfScopeMessage msg)
    cmake_language(EVAL CODE "
        cmake_language(DEFER CALL message [[${msg}]])
```

```
    ")
endfunction()
```

Note how quoting with bracket syntax is used around the \${msg} evaluation to ensure spaces in the evaluated variable are handled correctly.

Boolean Expressions

Commands that treat their arguments as a boolean expression also have some special rules associated with quoting and argument expansion. The if() command best demonstrates this, but the rules also apply to while(). Consider the following example, which shows the subtle behavior of how unquoted arguments can be treated as either variable names or string values (see [Section 7.1.1, “Basic Expressions”](#) for a deeper discussion of this behavior):

```
cmake_minimum_required(VERSION 3.1)

set(someVar xxxx)
set(xxxx "some other value")

# Here, xxxx is unquoted, so it is treated as the name of
# a variable and its value is used. Result: prints NO
if(someVar STREQUAL xxxx)
    message(YES)
else()
    message(NO)
endif()

# Now use xxxx in quotes. This prevents it from being
# treated as a variable name and the value is used
# directly. Result: prints YES
if(someVar STREQUAL "xxxx")
```

```
    message(YES)
else()
    message(NO)
endif()
```

Attempting to reproduce the above using variables to provide arguments to the if() commands, one might try something like the following:

```
set(noQuotes    someVar STREQUAL xxxx)
set(withQuotes  someVar STREQUAL [{"xxxx"]})

if(${noQuotes})
    message(YES)
else()
    message(NO)
endif()

if(${withQuotes}) # Doesn't work as expected
    message(YES)
else()
    message(NO)
endif()
```

The value of withQuotes uses bracket syntax to make the quotes part of the value stored. The idea is to try to get the if() command to treat xxxx as a quoted argument, but it does not have the desired effect. The if() command checks for quotes *before* expansion, so in this case, the quotes get treated as part of the argument value. There is no way to get an argument to be treated as quoted when providing the arguments to if() through an expanded variable evaluation like in the above.

One other special case to be aware of is the way square brackets affect how semicolons are interpreted for lists, as discussed previously in [Section 6.7.1, “Problems With Unbalanced Square Brackets”](#). Semicolons between unbalanced square brackets are not interpreted as list separators when evaluating a variable. This does not extend to the way CMake assembles command arguments though, as demonstrated by the following example and its output:

```
function(func)
    message("Number of arguments: ${ARGC}")

    math(EXPR lastIndex "${ARGC} - 1")
    foreach(n RANGE 0 ${lastIndex})
        message("ARGV${n} = ${ARGV${n}}")
    endforeach()

    foreach(arg IN LISTS ARGV)
        message("${arg}")
    endforeach()
endfunction()

func("a[a" "b]b" "c[c]c" "d[d" "eee")
```

```
Number of arguments: 5
ARGV0 = a[a
ARGV1 = b]b
ARGV2 = c[c]c
ARGV3 = d[d
ARGV4 = eee
a[a;b]b
c[c]c
d[d;eee]
```

The `func()` command *does* see the five original arguments, as demonstrated by the first `foreach()` loop. The evaluation of the `ARGV` variable by the second `foreach()` command is where the embedded unbalanced square brackets interfere with how the variable is interpreted as a list.

In practice, it is relatively uncommon to find situations where unbalanced square brackets may reasonably be present. Occasionally, balanced square brackets may be encountered, but as the `c[c]c` argument in the above example shows, they do not interfere with list interpretation.

9.9. Recommended Practices

Functions and macros are a great way to re-use the same piece of CMake code throughout a project. In general, prefer to use functions rather than macros, since the use of a new variable scope within the function better isolates that function's effects on the calling scope. Macros should generally only be used where the contents of the macro body really do need to be executed within the scope of the caller. These situations should generally be relatively rare. To avoid unexpected behavior, also avoid calling `return()` from inside a macro.

Prefer to pass all values a function or macro needs as command arguments rather than relying on variables being set in the calling scope. This tends to make the implementation more

robust to future changes, and it is much clearer and easier to maintain.

For all but very trivial functions or macros, it is highly recommended to use the keyword-based argument handling provided by `cmake_parse_arguments()`. This leads to better usability and improved robustness of calling code, since there is little chance of getting arguments mixed up. It also allows the function to be more easily extended in the future because there is no reliance on argument ordering, or for all arguments to always be provided, even if not relevant.

Beware of dropping empty arguments and list flattening when parsing or forwarding command arguments. Where the project's minimum CMake version allows, prefer to use the `PARSE_ARGV` form of `cmake_parse_arguments()` inside functions. When forwarding arguments, use `cmake_language(EVAL CODE)` to quote each argument individually if preserving empty arguments and lists is required.

While `cmake_parse_arguments()` can be used to implement quite complex keyword and argument parsing, projects should avoid combining too many things in the one command. Commands that have a large number of options and that perform a number of tasks internally are often poorly understood by developers working on the project. Such commands also tend to grow in complexity over time, and they frequently become hard to follow and maintain. Prefer to give functions a narrow set of

responsibilities, often just one. Avoid wrapping built-in CMake functions that could just as easily be called directly by the project, except for very specific cases that have no prospect of needing additional flexibility in the future.

Prefer to avoid deferring commands via `cmake_language(DEFER)` if there are other alternatives. Deferred commands introduce fragility, hinders the ability to debug a project, and can be a sign that CMake functions and macros should be refactored.

Rather than distributing functions and macros throughout the source tree, a common practice is to nominate a particular directory (usually just below the top level of the project) where various `XXX.cmake` files can be collected. That directory acts like a catalog of ready-to-use functionality, able to be conveniently accessed from anywhere in the project. Each of the files can provide functions, macros, variables, and other features as appropriate. Using a `.cmake` file name suffix allows the `include()` command to find the files as modules, a topic covered in detail in [Chapter 12, *Modules*](#). It also tends to allow IDE tools to recognize the file type and apply CMake syntax highlighting.

Do not define or call a function or macro with a name that starts with a single underscore. In particular, do not rely on the undocumented behavior whereby the old implementation of a command is made available by such a name when a function or macro redefines an existing command. Once a command has been overridden more than once, its original implementation is

no longer accessible. This undocumented behavior may even be removed in a future version of CMake, so it should not be used. Along similar lines, do not override any builtin CMake command. Consider those to be off-limits so that projects will always be able to assume the builtin commands behave as per the official documentation, and there will be no opportunity for the original command to become inaccessible.

Where the project's minimum CMake version is set to 3.17 or later, prefer to use `CMAKE_CURRENT_FUNCTION_LIST_DIR` to refer to any file or directory expected to exist at a location relative to the file in which a function is defined.

10. PROPERTIES

Properties affect just about all aspects of the build process, from how a source file is compiled into an object file, right through to the install location of built binaries in a packaged installer. They are always attached to a specific entity, whether that be a directory, target, source file, test case, cache variable, or even the overall build process itself. Rather than holding a standalone value like a variable does, a property provides information specific to the entity it is attached to.

For those new to CMake, properties are sometimes confused with variables. Though both may initially seem similar in terms of function and features, properties serve a very different purpose. A variable is not attached to any particular entity, and it is very common for projects to define and use their own variables. Compare this with properties which are typically well-defined and documented by CMake, and they always apply to a specific entity. A likely contributor to the confusion between the two is that a property's default value is sometimes provided by a variable. The names CMake uses for related properties and variables usually follow the same pattern, with

the variable name being the property name with `CMAKE_` prepended.

10.1. General Property Commands

CMake provides a number of commands for manipulating properties. The most generic of these, `set_property()` and `get_property()`, allow setting and getting any property on any type of entity.

```
set_property(entitySpecific  
    [APPEND | APPEND_STRING]  
    PROPERTY propertyName values...  
)
```

`entitySpecific` defines the entity whose property is being set. It must be *one* of the following:

```
GLOBAL  
DIRECTORY [dir]  
TARGET targets...  
SOURCE sources... # Additional options with CMake 3.18  
INSTALL files...  
TEST tests... # Additional options with CMake 3.28  
CACHE vars...
```

The first word of each of the above defines the type of entity whose property is being set. `GLOBAL` means the build itself, so there is no specific entity name required. For `DIRECTORY`, if no `dir` is named, the current source directory is used. For all the other types of entities, any number of items of that type can be

listed. The SOURCE entity type supports some additional options when using CMake 3.18 or later, as does the TEST entity type with CMake 3.28 or later. See [Section 10.5, “Source Properties”](#) and [Section 10.7, “Test Properties”](#) respectively.

The property name and value(s) follow the mandatory PROPERTY keyword. The propertyName would normally match one of the properties defined in the CMake documentation, a number of which are discussed in later chapters. The meaning of the value(s) is property-specific.

```
# Global property applies to the whole project
set_property(GLOBAL PROPERTY USE_FOLDERS YES)

# Applies to the current directory, multiple labels set
set_property(DIRECTORY PROPERTY LABELS specialItem local)

# Groups multiple targets under an Apps folder in IDEs
set_property(TARGET MainApp Tester PROPERTY FOLDER Apps)

# Disable linting of one specific source file
set_property(SOURCE gen_src.c PROPERTY SKIP_LINTING YES)

# Preserve one file when reinstalling a WIX package
set_property(INSTALL config.ini PROPERTY CPACK_NEVER_OVERWRITE YES)

# Tell test scheduler these tests are more expensive
set_property(TEST testThreads testProcs PROPERTY COST 2)

# Tell IDEs valid values for the "status" cache variable
set_property(CACHE status PROPERTY STRINGS red orange green)
```

A project may also set its own custom properties, and it is up to the project what those properties mean and how they affect the

build. A project-specific prefix should be used on custom property names to avoid potential name clashes with properties defined by CMake or other third party packages.

```
set_property(TARGET MyApp1 MyApp2  
    PROPERTY MYPROJ_CUSTOM_PROP  
    val1 val2 val3  
)
```

The above example defines a custom `MYPROJ_CUSTOM_PROP` property which will have the list `val1;val2;val3` as its value. Property names should generally follow the same convention CMake uses by using all uppercase names, with words separated by underscores.

The `APPEND` and `APPEND_STRING` keywords can be used to control how the named property is updated if it already has a value. With neither keyword specified, the value(s) given replace any previous value. The `APPEND` keyword changes the behavior to append the value(s) to the existing one, forming a list. The `APPEND_STRING` keyword takes the existing value and appends the new value(s) by concatenating the two as strings rather than as a list (see also the special note for inherited properties further below). `APPEND` is usually the more appropriate of the two in most cases. The following table demonstrates the differences.

Previous Value(s)	New Value(s)	No Keyword	APPEND	APPEND_STRING
-------------------	--------------	------------	--------	---------------

Previous Value(s)	New Value(s)	No Keyword	APPEND	APPEND_STRING
foo	bar	bar	foo;bar	foobar
a;b	c;d	c;d	a;b;c;d	a;bc;d

The `get_property()` command follows a similar form:

```
get_property(resultVar entitySpecific
    PROPERTY propertyName
    [...other keywords...]
)
```

The `PROPERTY` keyword and `propertyName` are always required. The `entitySpecific` part is similar to that for `set_property()` and must be *one* of the following:

```
GLOBAL
DIRECTORY [dir]
TARGET target
SOURCE source # Additional options with CMake 3.18
INSTALL file
TEST test # Additional options with CMake 3.28
CACHE var
VARIABLE
```

As before, `GLOBAL` refers to the build as a whole and therefore requires no specific entity to be named. `DIRECTORY` can be used with or without specifying a particular directory, with the current source directory being assumed if no directory is provided. For most of the other scopes, the particular entity within that scope must be named. Again, the `SOURCE` entity type

supports additional options when using CMake 3.18 or later, as does the TEST entity type with CMake 3.28 or later. See [Section 10.5, “Source Properties”](#) and [Section 10.7, “Test Properties”](#) respectively.

```
get_property(role GLOBAL PROPERTY CMAKE_ROLE)
if(NOT role STREQUAL "PROJECT")
    message(FATAL_ERROR "Can only use in project mode")
endif()
```

```
add_subdirectory(unit_tests)
add_subdirectory(integ_tests)

get_property(unit DIRECTORY unit_tests PROPERTY TESTS)
get_property(integ DIRECTORY integ_tests PROPERTY TESTS)

# Make unit tests run before integration tests
set_property(TEST ${integ} PROPERTY DEPENDS ${unit})
```

```
function(test_with_harness target)
    # Verify the target is of the expected type
    get_property(type TARGET target PROPERTY TYPE)
    if(NOT type STREQUAL "EXECUTABLE")
        message(FATAL_ERROR "target must be an executable")
    endif()
    # ... other logic
endfunction()
```

The VARIABLE type is a bit different. For that, the variable name is specified as the propertyName rather than being attached to the VARIABLE keyword. This can seem somewhat unintuitive, but consider the situation if the variable was named as the entity along with the VARIABLE keyword, just like for the other entity

type keywords. In that situation, there would be nothing to specify for the property name. It may help to think of VARIABLE as specifying the current *scope*, then the property of interest is the variable named by `propertyName`. When understood this way, VARIABLE is consistent with how the other entity types are handled. VARIABLE is rarely used, and even then, should only be used when accompanied by one of the optional keywords discussed next.

If none of the optional keywords are given, the value of the property is stored in the variable named by `resultVar`. This is the typical usage of the `get_property()` command. For the VARIABLE scope, variable values can and should be obtained more directly with the `${}` syntax instead. The optional keywords can be used to retrieve other details about a property:

DEFINED

The result of the retrieval will be a boolean value indicating whether the named property has been defined. In the case of VARIABLE scope queries, the result will only be true if the named variable has been explicitly defined with the `define_property()` command (see below).

SET

The result of the retrieval will be a boolean value indicating whether the named property has been set. It differs from

DEFINED in that it queries whether the named property has actually been set to some value (the value itself is irrelevant), whereas DEFINED is more about describing what the property means. SET is usually what projects need rather than DEFINED in most scenarios. Note also that a property can return true for DEFINED and false for SET, or vice versa.

BRIEF_DOCS

Retrieves the brief documentation string for the named property. If no brief documentation has been defined for the property, the result will be the string NOTFOUND.

FULL_DOCS

Retrieves the full documentation for the named property. If no full documentation has been defined for the property, the result will be the string NOTFOUND.

Of the optional keywords, all but SET have little value unless the project has explicitly called `define_property()` to populate the requested information for the entity:

```
define_property(entityType
    PROPERTY propertyName
    [INHERITED]

    # Mandatory for CMake 3.22 and earlier
    [BRIEF_DOCS briefDoc [moreBriefDocs...]]
    [FULL_DOCS fullDoc [moreFullDocs...]]

    # Requires CMake 3.23 or later
```

```
[INITIALIZE_FROM_VARIABLE variableName]  
)
```

The `define_property()` command does not set the property's value. Rather, it controls how that property is initialized or inherited, and potentially provides documentation. CMake 3.22 and earlier require `BRIEF_DOCS` and `FULL_DOCS` to be present, but they are unused by CMake other than providing them back to the project via `get_property()`. It is likely these documentation options will be deprecated in a future version of CMake due to their lack of usefulness.

The `entityType` must be one of `GLOBAL`, `DIRECTORY`, `TARGET`, `SOURCE`, `TEST`, `VARIABLE`, or `CACHED_VARIABLE`. The `propertyName` specifies the property being defined. No entity is specified, although like for the `get_property()` command, in the case of `VARIABLE`, the variable name is specified as `propertyName`.

If the `INHERITED` option is given, the `get_property()` command will chain up to the parent scope if that property is not set in the named scope. For example, if a `DIRECTORY` property is requested, but is not set for the directory specified, the parent directory scope is queried recursively up the directory scope hierarchy until the property is found, or the top level of the source tree is reached. If still not found at the top level directory, then the `GLOBAL` scope will be searched. Similarly, if a `TARGET`, `SOURCE`, or `TEST` property is requested, but is not set for the specified entity, the `DIRECTORY` scope will be searched

(including recursively up the directory hierarchy and ultimately to the GLOBAL scope if necessary). No such chaining functionality is provided for VARIABLE or CACHE, since these already chain to the parent variable scope by design.

```
set_property(DIRECTORY PROPERTY MY_THING HiThere)
add_executable(MyApp ...)

define_property(TARGET PROPERTY MY_THING INHERITED)

get_property(result TARGET MyApp PROPERTY MY_THING)
message("result = ${result}")
```

In the above example, there is no MY_THING property set on target MyApp. But the define_property() command specifies an inheriting relationship for that target property, so the call to get_property() then looks for a MY_THING directory property, which is set. Therefore, the output is result = HiThere.

The inheriting behavior of INHERITED properties only applies to the get_property() command and its analogous get_... functions for specific property types (covered in the sections below). When calling set_property() with APPEND or APPEND_STRING options, only the immediate value of the property is considered. No inheriting occurs when working out the value to append to.

```
set_property(DIRECTORY PROPERTY MY_THING HiThere)
add_executable(MyApp ...)

define_property(TARGET PROPERTY MY_THING INHERITED)

# Appends to the current value of the target property,
```

```
# no inheriting occurs for this
set_property(TARGET MyApp APPEND PROPERTY MY_THING Buddy)

# Now the target property will be defined, so this will
# just return the value held in that property
get_property(result TARGET MyApp PROPERTY MY_THING)
message("result = ${result}") # Prints "result = Buddy"
```

CMake 3.23 added support for the `INITIALIZE_FROM_VARIABLE` keyword with `define_property()`. This specifies a variable to be used to initialize the named property. It can only be used with target properties, and it only affects targets created after the call to `define_property()`. The variable name must end with the name of the property and cannot begin with `CMAKE_` or `_CMAKE_`. This feature is a particularly useful way of providing a default value for a custom property defined by the project, and it is usually clearer than using `INHERITED` to achieve a similar result. With that in mind, the property name must also contain at least one underscore. This constraint exists to encourage projects to name their custom properties with a project-specific prefix.

```
# Example of setting the variable, but it could instead be
# set by the user, or even left unset to initialize the
# property with an empty value
set(MYPROJ_SOMETOOL_OPTIONS --verbose)

define_property(TARGET PROPERTY MYPROJ_SOMETOOL_OPTIONS
    INITIALIZE_FROM_VARIABLE MYPROJ_SOMETOOL_OPTIONS
)
```

CMake has a large number of pre-defined properties of each type. Developers should consult the CMake reference

documentation for the available properties and their intended purpose. In later chapters, many of these properties are discussed and their relationship to other CMake commands, variables, and features are explored.

10.2. Global Properties

Global properties relate to the overall build as a whole. They are typically used for things like modifying how build tools are launched or other aspects of tool behavior, for defining aspects of how project files are structured, and for providing some degree of build-level information.

In addition to the generic `set_property()` and `get_property()` commands, CMake also provides `get_cmake_property()` for querying global entities. It is more than just shorthand for `get_property()`, although it can be used simply to retrieve the value of any global property.

```
get_cmake_property(resultVar property)
```

Just like for `get_property()`, `resultVar` is the name of a variable in which the value of the requested property will be stored when the command returns. The `property` argument can be the name of any global property, or one of the following pseudo properties:

VARIABLES

Return a list of all regular (i.e. non-cache) variables.

CACHE_VARIABLES

Return a list of all cache variables.

COMMANDS

Return a list of all defined commands, functions, and macros. Commands are pre-defined by CMake, whereas functions and macros can be defined either by CMake (typically through modules) or by projects themselves. Some of the returned names may correspond to undocumented or internal entities not intended for projects to use directly. The names may be returned with different upper/lowercase than the way they were originally defined.

MACROS

Return a list of just the defined macros. This will be a subset of what the COMMANDS pseudo property would return, but note that the upper/lowercase of the names can be different to what the COMMANDS pseudo property reports.

COMPONENTS

Return a list of all components defined by `install()` commands, which is covered in [Chapter 35, *Installing*](#).

These read-only pseudo properties are technically not global properties (they cannot be retrieved using `get_property()`, for example), but they are notionally very similar. They can only be

retrieved via `get_cmake_property()`. The following example is a reduced version of one taken from [Section 36.2.5, “Component And Group Selection”](#):

```
# Filter out some unwanted install components for packaging
get_cmake_property(CPACK_COMPONENTS_ALL COMPONENTS)
list(REMOVE_ITEM CPACK_COMPONENTS_ALL
    MyProj_Samples
    MyProj_ApiDocs
)
include(CPack)
```

10.3. Directory Properties

Directories also support their own set of properties. Logically, directory properties sit somewhere between global properties which apply everywhere and target properties which only affect individual targets. As such, directory properties mostly focus on setting defaults for target properties and overriding global properties or defaults for the current directory. A few read-only directory properties also provide a degree of introspection, holding information about how the build reached the directory, what things have been defined at that point, etc.

For convenience, CMake provides dedicated commands for setting and getting directory properties which are a little more concise than their generic counterparts.

```
set_directory_properties(PROPERTIES
    prop1 val1
```

```
[prop2 val2] ...  
)
```

While being a little more concise, the directory-specific setter command lacks any APPEND or APPEND_STRING option. This means it can only be used to set or replace a property, it cannot be used to add to an existing property directly. A further restriction of this command compared to the more generic set_property() is that it always applies to the current directory. Projects may choose to use this more specific form where it is convenient and use the generic form elsewhere, or for consistency the more generic form may be used everywhere. Neither approach is more correct, it's more a matter of preference. The main reason to use set_directory_properties() rather than set_property() is when multiple properties need to be set. On the other hand, set_property() is more convenient when assigning multiple values as a list to one property.

```
# Note the quoting needed to pass a list to LABELS  
set_directory_properties(PROPERTIES  
    LABELS "someThings;local"  
    ADDITIONAL_CLEAN_FILES some_tmp_file.txt  
)  
  
# No quoting needed, but can only set one property at a time  
set_property(DIRECTORY PROPERTY  
    LABELS someThings local  
)  
set_property(DIRECTORY PROPERTY  
    ADDITIONAL_CLEAN_FILES some_tmp_file.txt  
)
```

The directory-specific getter command has two forms:

```
get_directory_property(resultVar
    [DIRECTORY dir] property
)
get_directory_property(resultVar
    [DIRECTORY dir] DEFINITION varName
)
```

The first form is used to get the value of a property from a particular directory, or from the current directory if the DIRECTORY argument is not used. The second form retrieves the value of a *variable*. This may not seem all that useful, but it provides a way to retrieve the value of a variable from a different directory scope other than the current one (when the DIRECTORY argument is used). In practice, this second form should rarely be needed, and its use should be avoided for scenarios other than debugging the build or similar temporary tasks.

For either form of the `get_directory_property()` command, if the DIRECTORY argument is used, CMake must have already processed the named directory. It is not possible for CMake to know the properties of a directory scope it has not yet encountered.

If the requested property is not set, the result stored in the variable will be an empty string, which is the same behavior as `get_property()`.

```
add_subdirectory(unit_tests)
get_directory_property(unit DIRECTORY unit_tests TESTS)

get_directory_property(myThing MY_THING)
if(myThing STREQUAL "")
    message(WARNING
        "myThing directory property is empty or not set"
    )
endif()
```

10.4. Target Properties

Few things in CMake have such a strong and direct influence on how targets are built as target properties. They control and provide information about everything from the flags used to compile source files through to the type and location of the built binaries and intermediate files. Some target properties affect how targets are presented in the developer's IDE, while others affect the tools used when compiling or linking. In short, target properties are where most of the details about how to actually turn source files into binaries are collected and applied.

A number of methods have evolved in CMake for manipulating target properties. In addition to the generic `set_property()` and `get_property()` commands, CMake also provides some target-specific equivalents for convenience:

```
set_target_properties(target1 [target2...]
PROPERTIES
    propertyName1 value1
    [propertyName2 value2] ...
```

```
)  
get_target_property(resultVar target propertyName)
```

As for the `set_directory_properties()` command, `set_target_properties()` lacks the full flexibility of `set_property()`, but it provides a simpler syntax for common cases. The `set_target_properties()` command does not support appending to existing property values, and if a list value needs to be provided for a given property, the `set_target_properties()` command requires that value to be specified in string form, e.g. `"this;is;a;list"`.

```
# Generated sources are too big for unity builds, and we  
# don't want verification checks for generated headers  
set_target_properties(GenSources PROPERTIES  
    UNITY_BUILD NO  
    VERIFY_INTERFACE_HEADER_SETS NO  
)
```

The `get_target_property()` command is the simplified version of `get_property()`. It focuses purely on providing a simple way to obtain the value of a target property and is basically just a shorthand version of the generic command. One important difference between the two is that `get_property()` returns an empty string if the requested property is not set, whereas `get_target_property()` returns `variableName-NOTFOUND` (note the inconsistency compared to `get_directory_property()` and `get_property()`). The more specific `get_target_property()`

command allows the project to differentiate between a property being unset and it being set to an empty string.

```
# Check to ensure version details are set for a library.  
# Explicitly setting it to an empty string is allowed.  
get_target_property(version SomeLib VERSION)  
if(version STREQUAL "version-NOTFOUND")  
    message(FATAL_ERROR "Version not set for SomeLib")  
endif()
```

In addition to the generic and target-specific property getters and setters, CMake also has a number of other commands which modify target properties. In particular, the family of target_...() commands are a critical part of CMake, and all but the most trivial of projects would typically use them. Those commands define not only properties for a particular target, they also define how that information might be propagated to other targets that link to it. [Chapter 16, *Compiler And Linker Essentials*](#) covers those commands and how they relate to target properties in depth.

10.5. Source Properties

CMake also supports properties on individual source files. These enable fine-grained manipulation of compiler flags on a file-by-file basis rather than for all of a target's sources. They also allow additional information about the source file to be provided to modify how CMake or build tools treat the file. For example, they may indicate whether the file is generated as

part of the build, what compiler to use with it, options for non-compiler tools working with the file, and so on.

Projects should rarely need to query or modify source file properties, but for those situations that require it, CMake provides dedicated setter and getter commands to make the task easier. These follow a similar pattern to the other property-specific setter and getter commands:

```
set_source_files_properties(file1 [file2...]
    PROPERTIES
        propertyName1 value1
        [propertyName2 value2] ...
)
get_source_file_property(resultVar sourceFile propertyName)
```

Again, no APPEND functionality is provided for the setter, while the getter is mostly just syntax shorthand for the generic `get_property()` command and offers no new functionality. If asked to retrieve a property on a source file that doesn't exist, or for a property that is not set on the named file, `get_source_file_property()` sets the result variable to NOTFOUND, whereas `get_property()` sets it to an empty string. Note that this behavior is yet another inconsistency compared to how `get_directory_property()` and `get_target_property()` behave.

The following example shows how to set a property on a source file, in this case to prevent it from being combined with other sources in a unity build (discussed in [Section 26.1, “Unity Builds”](#)):

```
add_executable(MyApp small.cpp big.cpp tall.cpp thin.cpp)

set_source_files_properties(big.cpp PROPERTIES
    SKIP_UNITY_BUILD_INCLUSION YES
)
```

With CMake 3.17 and earlier, source properties are only visible to targets defined in the same directory scope. If the setting of a source property occurs in a different directory scope, the target will not see that property change and therefore the compilation, etc. of that source file will not be affected. With CMake 3.18 or later, additional options are available to specify the directory scope in which the source file properties should be searched or applied. The following shows the full set of options available for setting source file properties with CMake 3.18 or later:

```
set_property(SOURCE sources...
    [DIRECTORY dirs...]
    [TARGET_DIRECTORY targets...]
    [APPEND | APPEND_STRING]
    PROPERTY propertyName values...
)

set_source_files_properties(sources...
    [DIRECTORY dirs...]
    [TARGET_DIRECTORY targets...]
    PROPERTIES
        propertyName1 value1
        [propertyName2 value2] ...
)
```

The DIRECTORY option can be used to specify one or more directories in which the source properties should be set. Any

targets created in those directories will be aware of the source properties. These directories must have already been added to the build by an earlier call to `add_subdirectory()`. Any relative paths will be treated as relative to the current source directory.

The `TARGET_DIRECTORY` option is similar, except it is followed by the names of targets. For each target listed, the directory in which that target was created (i.e. its source directory) will be treated as though it had been specified with the `DIRECTORY` option. Note that this means *all* targets defined in that directory will be aware of the `source` property, not just the target specified.

```
add_executable(MyApp ...)  
add_subdirectory(gen_source)  
  
# gen_source/CMakeLists.txt  
# Logic to generate .../src.cpp omitted for brevity ①  
  
# This adds the generated source to the MyApp target ②  
target_sources(MyApp PRIVATE  
    ${CMAKE_CURRENT_BINARY_DIR}/src.cpp  
)  
  
# We need to set source file properties in the scope of  
# the target the source file is added to  
set_source_files_properties(  
    ${CMAKE_CURRENT_BINARY_DIR}/src.cpp  
    TARGET_DIRECTORY MyApp  
    PROPERTIES  
        SKIP_LINTING YES  
        SKIP_PRECOMPILE_HEADERS YES  
)
```

① See [Section 20.3, “Commands That Generate Files”](#).

② See [Section 16.2.6, “Source Files”](#).

CMake 3.18 also added analogous options for retrieving source file properties:

```
get_property(resultVar SOURCE source
    [DIRECTORY dir | TARGET_DIRECTORY target]
    PROPERTY propertyName
    [DEFINED | SET | BRIEF_DOCS | FULL_DOCS]
)

get_source_file_property(resultVar source
    [DIRECTORY dir | TARGET_DIRECTORY target]
    propertyName
)
```

When retrieving source file properties, at most one target or directory can be listed to identify the directory scope from which to retrieve the property. The current source directory is assumed if neither DIRECTORY nor TARGET_DIRECTORY is given.

Whether DIRECTORY or TARGET_DIRECTORY options are specified or not, note that it is possible for a source file to be compiled into multiple targets. Therefore, in each of the directory scopes where the source properties are set, the properties should make sense for all targets using those files.

Developers should be aware of an implementation detail which may present a strong deterrent to their use in some situations. For some CMake generators (notably the Unix Makefiles generator), the dependencies between sources and source

properties are stronger than one might expect. If source properties are used to modify the compiler flags for specific source files rather than for a whole target, changing the source's compiler flags will still result in all of the target's sources being rebuilt, not just the affected source file. This is a limitation of how the dependency details are handled in the Makefile, where testing whether each source file's compiler flags have changed brings with it a prohibitively big performance hit. The relevant Makefile dependencies were implemented at the target level instead to avoid that problem.

A typical scenario where projects may be tempted to use source properties is to pass version details to just one or two sources as compiler definitions. As discussed in [Section 22.2, “Source Code Access To Version Details”](#), there are better alternatives to source properties which do not suffer from the sort of build performance problems mentioned above. Setting some source properties can also reduce build performance by preventing those sources from participating in unity builds (see [Section 26.1, “Unity Builds”](#)).

The Xcode generator also has a limitation in its support for source properties which prevents it from handling configuration-specific property values. See [Section 16.7, “Language-specific Compiler Flags”](#) for a scenario where this limitation can be important.

10.6. Cache Variable Properties

Properties on cache variables are a little different in purpose to other property types. For the most part, cache variable properties are aimed more at how the cache variables are handled in the CMake GUI and the console-based `ccmake` tool rather than affecting the build in any tangible way. There are also no extra commands provided for manipulating them, so the generic `set_property()` and `get_property()` commands must be used with the `CACHE` keyword.

In [Section 6.3, “Cache Variables”](#), a number of aspects of cache variables were discussed which are ultimately reflected in the cache variable properties.

- Each cache variable has a *type*, which must be one of `BOOL`, `FILEPATH`, `PATH`, `STRING`, or `INTERNAL`. This type can be obtained using `get_property()` with the property name `TYPE`. The type affects how the CMake GUI and `ccmake` present that cache variable in the UI and what kind of widget is used for editing its value. Any variable with type `INTERNAL` will not be shown at all.
- A cache variable can be marked as advanced with the `mark_as_advanced()` command, which is really just setting the boolean `ADVANCED` cache variable property. The CMake GUI and the `ccmake` tool both provide an option to show or hide

advanced cache variables. The user can then choose whether to focus on just the main basic variables or to see the full list.

- The help string of a cache variable is typically set as part of a call to the `set()` or `option()` commands, but it can also be modified or read using the `HELPSTRING` cache variable property. This help string is used as the tooltip in the CMake GUI and as a one-line help tip in the `ccmake` tool. IDEs may also show the help string as a tooltip or in other places.
- If a cache variable is of type `STRING`, then CMake GUI will look for a cache variable property named `STRINGS`. If not empty, it is expected to be a list of valid values for the variable, and CMake GUI will then present that variable as a combo box of those values rather than an arbitrary text entry widget. In the case of `ccmake`, pressing enter on that cache variable will cycle through the values provided. Note that CMake does not enforce that the cache variable must be one of the values from the `STRINGS` property, it is only a convenience for the CMake GUI and `ccmake` tools. When CMake runs its configure step, it still treats the cache variable as an arbitrary string, so it is still possible to give the cache variable any value either at the `cmake` command line or via `set()` commands in the project.

In practice, projects rarely manipulate cache variable properties directly with `set_property()`, except for `STRINGS`. All other properties tend to be set by other commands like `mark_as_advanced()`, `set()`, or `option()`. The following sequence

of commands demonstrates all cache variable properties being set for the TRAFFIC_LIGHT cache variable.

```
set(TRAFFIC_LIGHT Green CACHE STRING "Status of something")
set_property(CACHE TRAFFIC_LIGHT PROPERTY STRINGS
    Red Orange Green
)
mark_as_advanced(TRAFFIC_LIGHT)
```

10.7. Test Properties

CMake also supports properties on individual tests, and it provides the usual test-specific versions of the property setter and getter commands:

```
set_tests_properties(test1 [test2...]
    [DIRECTORY dir] # CMake 3.28 or later
    PROPERTIES
        propertyName1 value1
        [propertyName2 value2] ...
)
get_test_property(test propertyName
    [DIRECTORY dir] # CMake 3.28 or later
    resultVar
)
```

Like their equivalent counterparts, these are just slightly more concise versions of the generic commands which lack APPEND functionality, but may be more convenient in some circumstances. Note the different ordering of the arguments for `get_test_property()` compared to the other `get_..._property()` commands. The result variable is the last argument rather than

the first. If the requested property does not exist, `get_test_property()` sets its result to NOTFOUND.

The `DIRECTORY` option, available with CMake 3.28 or later, can be used to set or query a test in a different directory scope (`DIRECTORY` can also be used with `set_property(TEST...)` and `get_property(TEST...)`). Without this option, only tests defined in the current directory scope can be set or queried.

```
add_subdirectory(unit_tests)

get_test_property(checkSomething LABELS labelsNoDir)
get_test_property(checkSomething LABELS
    DIRECTORY unit_tests
    labelsWithDir
)
message("No DIRECTORY : ${labelsNoDir}")
message("With DIRECTORY: ${labelsWithDir}")
```

```
# unit_tests/CMakeLists.txt
add_test(NAME checkSomething COMMAND ...)
set_tests_properties(checkSomething PROPERTIES LABELS Unit)
```

```
No DIRECTORY : NOTFOUND
With DIRECTORY: Unit
```

Tests are discussed in detail in [Chapter 27, *Testing Fundamentals*](#).

10.8. Installed File Properties

The other type of property CMake supports is for installed files. These properties are specific to the type of packaging being used and are typically not needed by most projects. They are mentioned here for completeness, but are not discussed any further in this book.

10.9. Recommended Practices

Properties are a crucial part of CMake. A range of commands can set, modify, or query the various types of properties, some of which have further implications for dependencies between projects.

All but the special global pseudo properties can be fully manipulated using the generic `set_property()` command, making it predictable for developers and offering flexible APPEND functionality where needed. The property-specific setters may be more convenient in some situations, such as allowing multiple properties to be set at once, but their lack of APPEND functionality may steer some projects towards just using `set_property()`. Neither is right or wrong, although a common mistake is to use the property-specific commands to replace a property value instead of appending to it.

For target properties, prefer to use the various `target_...()` commands over manipulating the associated target properties directly. These commands not only manipulate the properties on specific targets, they also set up dependency relationships

between targets so that CMake can propagate some properties automatically. [Chapter 16, *Compiler And Linker Essentials*](#) discusses a range of topics which highlight the strong preference for the target_...() commands.

Source properties offer a fine-grained level of control over compiler options and other behavior, but they also have the potential for undesirable negative impacts on the build behavior of a project. In particular, some CMake generators may rebuild more than should otherwise be necessary when compile options for only a few source files change. The Xcode generator also has limitations which prevent it from supporting configuration-specific source file properties. Projects should consider using other alternatives to source properties where available, such as the techniques given in [Section 22.2, “Source Code Access To Version Details”](#).

11. GENERATOR EXPRESSIONS

When running CMake, developers tend to think of it as a single step which involves reading the project's `CMakeLists.txt` file and producing the relevant set of generator-specific project files (e.g. Visual Studio solution and project files, an Xcode project, Unix Makefiles, or Ninja input files). There are, however, two quite distinct steps involved. When running CMake, the end of the output log typically looks something like this:

```
-- Configuring done (0.1s)
-- Generating done (0.0s)
-- Build files have been written to: /some/path/build
```

When CMake is invoked, it first reads in and processes the `CMakeLists.txt` file at the top of the source tree, including any other files it pulls in. An internal representation of the project is created as the commands are executed. This is called the *configure* step. Most of the output to the console log is produced during this stage, including any content from `message()` commands. At the end of the configure step, CMake prints the - - Configuring done message to the log.

Once CMake has finished reading and processing the `CMakeLists.txt` file, it then performs the *generation* step. This is where the build tool's project files are created using the internal representation built up in the configure step. For the most part, developers tend to ignore the generation step and just think of it as the result of configuration. The console log almost always shows the -- Generating done message immediately after the configure step completes, so this is understandable. But there are situations where understanding the separation into two distinct phases is particularly important.

Consider a project processed for a multi-configuration CMake generator like Xcode, Visual Studio, or Ninja Multi-Config. When the `CMakeLists.txt` files are being read, CMake doesn't know which configuration a target will be built for. It is a multi-configuration setup, so there's more than one choice (Debug, Release, and others). The developer selects the configuration at *build* time, well after CMake has finished. This would seem to present a problem if the `CMakeLists.txt` file wants to do something like copy a file to the same directory as the final executable for a given target, since the location of that directory depends on which configuration is being built. A placeholder is needed to tell CMake "For whichever configuration is being built, use the directory of the final executable".

This is a prime example of the functionality provided by generator expressions. They provide a way to encode some

logic which is not evaluated at configure time, the evaluation is instead delayed until the generation phase when the project files are being written. They can be used to perform conditional logic, output strings providing information about various aspects of the build like directories, names of things, platform details, and more. They can even be used to provide different content based on whether a build or an install is being performed.

Generator expressions cannot be used everywhere, but they are supported in many places. In the CMake reference documentation, if a particular command or property supports generator expressions, the documentation will mention it. The set of properties supporting generator expressions have expanded over time, with some CMake releases also expanding the set of supported expressions. Projects should confirm that for the minimum CMake version they require, the properties being modified do indeed support the generator expressions used.

11.1. Simple Boolean Logic

A generator expression is specified using the syntax `$<...>` where the content between the angle brackets can take a few different forms. As will become clear shortly, an essential feature is the conditional inclusion of content. The most basic generator expressions for this are the following:

```
$<1:...>
$<0:...>
```

For `$<1:...>`, the result of the expression will be the ... part, whereas for `$<0:...>`, the ... part is ignored and the expression results in an empty string. These are basically the true and false conditional expressions, but unlike for variables, the concept of true and false only allows for these two specific values. Anything other than 0 or 1 for a conditional expression is rejected by CMake with a fatal error. Another generator expression can be used to make boolean expression evaluation more flexible and ensure content evaluates to 0 or 1:

```
$<BOOL:...>
```

This evaluates the ... content in the same way that the `if()` command evaluates a boolean constant, so it understands all the usual special strings like OFF, NO, FALSE and so on. A very common pattern is to use it to wrap the evaluation of a variable that is expected to hold a boolean value, but which might not be restricted to 0 or 1 (see the table a little further below for examples).

Logical operations are also supported:

```
$<AND:expr[,expr...]>
$<OR:expr[,expr...]>
$<NOT:expr>
```

Each `expr` is expected to evaluate to either 1 or 0. The AND and OR expressions can take any number of comma-separated arguments and provide the corresponding logic result, while NOT accepts only a single expression and will yield the negation of its argument. Because AND, OR, and NOT require that their expressions evaluate to only 0 or 1, consider wrapping those expressions in a `$<BOOL:...>` to force more tolerant logic of what is considered a true or false expression.

With CMake 3.8 and later, if-then-else logic can also be expressed very conveniently using a dedicated `$<IF:...>` expression:

```
$<IF:expr, val1, val0>
```

As usual, the `expr` must evaluate to 1 or 0. The result is `val1` if `expr` evaluates to 1 and `val0` if `expr` evaluates to 0. Before CMake 3.8, equivalent logic would have to be expressed in the following more verbose way that requires the expression to be given twice:

```
$<expr:val1>$<$<NOT:expr>:val0>
```

Generator expressions can be nested, allowing expressions of arbitrary complexity to be constructed. The above example shows a nested condition, but any part of a generator expression can be nested. The following examples demonstrate the features discussed so far:

Expression	Result
<code>\$<1:foo></code>	foo
<code>\$<0:foo></code>	
<code>\$<true:foo></code>	Error, not a 1 or 0
<code>\$<\$<BOOL:true>:foo></code>	foo
<code>\$<\$<NOT:0>:foo></code>	foo
<code>\$<\$<NOT:1>:foo></code>	
<code>\$<\$<NOT:true>:foo></code>	Error, NOT requires a 1 or 0
<code>\$<\$<AND:1,0>:foo></code>	
<code>\$<\$<OR:1,0>:foo></code>	foo
<code>\$<1:\$<\$<BOOL:false>:foo>></code>	
<code>\$<IF:\$<BOOL:\${foo}>,yes,no></code>	Result will be yes or no depending on \${foo}

Just like for the `if()` command, CMake also provides support for testing strings, numbers, and versions in generator expressions, although the syntax is slightly different. The following all evaluate to 1 if the respective condition is satisfied, or 0 otherwise.

```
$<STREQUAL:string1,string2>
$<EQUAL:number1,number2>
$<VERSION_EQUAL:version1,version2>
```

```
$<VERSION_GREATER:version1,version2>
$<VERSION_LESS:version1,version2>
```

Another very useful conditional expression is testing the build type:

```
$<CONFIG:arg>
```

This will evaluate to 1 if arg corresponds to the build type being built, and 0 for all other build types. The comparison is case-insensitive. Common uses of this would be to provide compiler flags only for debug builds, or to select different implementations for different build types. For example:

```
add_executable(MyApp src1.cpp src2.cpp)

# Before CMake 3.8
target_link_libraries(MyApp PRIVATE
    $<$<CONFIG:Debug>:CheckedAlgo>
    $<$<NOT:$<CONFIG:Debug>>:FastAlgo>
)

# CMake 3.8 or later allows a more concise form
target_link_libraries(MyApp
    PRIVATE $<IF:$<CONFIG:Debug>,CheckedAlgo,FastAlgo>
)
```

The above would link the executable to the CheckedAlgo library for Debug builds and to the FastAlgo library for all other build types. The `$<CONFIG:...>` generator expression is the only way to robustly provide such functionality which works for all CMake project generators, including multi-configuration generators

like Xcode, Visual Studio, or Ninja Multi-Config. This particular topic is covered in more detail in [Section 15.2, “Common Errors”](#).

CMake offers even more conditional tests based on things like platform and compiler details, CMake policy settings, and more. Developers should consult the CMake reference documentation for the full set of supported conditional expressions.

11.2. Target Details

Another common use of generator expressions is to provide information about targets. Any property of a target can be obtained with one of the following two forms:

```
$<TARGET_PROPERTY:target,property>
$<TARGET_PROPERTY:property>
```

The first form provides the value of the named property from the specified target, while the second form will retrieve the property from the target on which the generator expression is being used.

```
add_executable(MyApp ...)

# In a real project, this might be set elsewhere
set_target_properties(MyApp PROPERTIES
    PROTOCOL_VER 2.1
)

# Set a compile definition based on the PROTOCOL_VER
# target property
```

```
target_compile_definitions(MyApp PRIVATE
    MIN_API=$<TARGET_PROPERTY:PROTOCOL_VER>
)

# Write a file to build directory with the protocol version
file(GENERATE OUTPUT version.txt CONTENT
    "Protocol: $<TARGET_PROPERTY:MyApp,PROTOCOL_VER>"
)
```

While TARGET_PROPERTY is a very flexible expression type, it is not always the best way to obtain information about a target. For example, CMake also provides other expressions which give details about the directory and file name of a target's built binary. These more direct expressions take care of extracting out parts of some properties or computing values based on raw properties. The most general of these is the TARGET_FILE set of generator expressions:

TARGET_FILE

This will yield the absolute path and file name of the target's binary, including any file prefix and suffix if relevant for the platform (e.g .exe, .dylib). For Unix-based platforms where shared libraries typically have version details in their file name, these will also be included.

TARGET_FILE_NAME

Same as TARGET_FILE but without the path (i.e. it provides just the file name part).

TARGET_FILE_DIR

Same as TARGET_FILE but without the file name. This is the most robust way to obtain the directory in which the final executable or library is built. Its value is different for different build configurations when using a multi-configuration generator like Xcode, Visual Studio, or Ninja Multi-Config.

The above three TARGET_FILE expressions are especially useful when defining custom build rules for copying files around in post-build steps. [Section 20.2, “Adding Build Steps To An Existing Target”](#) discusses that in more detail. The following is a reduced example from that section, demonstrating how to pass the location of a target’s binary as a command-line argument to another script that runs whenever the target is rebuilt.

```
add_executable(MyExe main.cpp)

add_custom_command(TARGET MyExe
    POST_BUILD
    COMMAND someScript ${TARGET_FILE:MyExe}
)
```

In addition to the TARGET_FILE expressions, CMake also provides some library-specific expressions that have similar roles, except they handle file name prefix and suffix details slightly differently. These expressions have names starting with TARGET_LINKER_FILE and TARGET SONAME FILE, but they tend not to be used as frequently as the TARGET_FILE expressions.

CMake 3.15 added support for additional target-related generator expressions that extract the basename, prefix, and suffix of target-related file names. Projects needing these more fine-grained details should consult the CMake documentation, but such a need should be rare.

Projects supporting the Windows platform can also obtain details about PDB files for a given target. Again, these would mostly find use in custom build tasks, but the need for it should be rare. Expressions starting with `TARGET_PDB_FILE` follow an analogous pattern as for `TARGET_PROPERTY`, providing path and file name details for the PDB file used for the target on which the generator expression is being used.

One other generator expression relating to targets deserves special mention. CMake allows a library target to be defined as an *object library*. It isn't a library in the usual sense, it is just a collection of object files that CMake associates with a target, but it doesn't actually result in a final library file being created. When using CMake 3.11 or earlier, it is not possible to link to an object library. Instead, object libraries have to be added to targets in the same way that *sources* are added. CMake then includes those object files at the link stage just like the object files created by compiling that target's sources. This is done using the `$<TARGET_OBJECTS:>` generator expression. It lists the object files in a form suitable for `add_executable()` or

`add_library()` to consume, as demonstrated by the following example:

```
# Define an object library
add_library(ObjLib OBJECT src1.cpp src2.cpp)

# Define two executables which each have their own source
# file as well as the object files from ObjLib
add_executable(App1 app1.cpp ${TARGET_OBJECTS:ObjLib})
add_executable(App2 app2.cpp ${TARGET_OBJECTS:ObjLib})
```

In the above example, no separate library is created for `ObjLib`, but the `src1.cpp` and `src2.cpp` source files are still only compiled once. This can be more convenient for some builds because it can avoid the build-time cost of creating a static library, or the run-time cost of symbol resolution for a dynamic library, yet still avoid having to compile the same sources multiple times.

From CMake 3.12, it is possible to link directly to an object library instead of using `${TARGET_OBJECTS:...}` as outlined above. There are limitations to such linking, details of which are discussed in [Section 19.2, “Libraries”](#).

11.3. General Information

Generator expressions can provide information about more than just targets. Information can be obtained about the compiler being used, the platform for which the target is being built, the name of the build configuration, and more. These sorts of expressions tend to find use in more advanced

situations, such as handling a custom compiler, or to work around a problem specific to a particular compiler or toolchain. These expressions also invite misuse, since they may appear to provide a way to do things like construct paths to things which could otherwise have been obtained using more robust methods like TARGET_FILE expressions, or other CMake features. Developers should think carefully before relying on the more general information generator expressions as a way to solve a problem. That said, some of these expressions do have valid uses. Some of the more common ones are listed here as a starting point for further reading:

`$<CONFIG>`

Evaluates to the build type. Use this in preference to the `CMAKE_BUILD_TYPE` variable, since that variable is not used on multi-configuration project generators like Xcode, Visual Studio, or Ninja Multi-Config. Earlier versions of CMake used the deprecated `$<CONFIGURATION>` expression for this, but projects should now only use `$<CONFIG>`.

`$<PLATFORM_ID>`

Identifies the platform for which the target is being built. This can be useful in cross-compiling situations, especially where a build may support multiple platforms (e.g. device and simulator builds). This generator expression is closely related to the `CMAKE_SYSTEM_NAME` variable, and projects

should consider whether using that variable would be simpler in their specific situation.

```
$<C_COMPILER_VERSION>, $<CXX_COMPILER_VERSION>
```

In some situations, it may be useful to only add content if the compiler version is older or newer than some particular version. This is achievable with the help of the `$<VERSION_xxx:...>` generator expressions. For example, the following expression could be used to produce the string `OLDCXX` if the C++ compiler version is less than 4.2.0:

```
$<$<VERSION_LESS:$<CXX_COMPILER_VERSION>,4.2.0>:OLDCXX>
```

Such expressions tend to be used only in situations where the type of compiler is known, and a specific behavior of the compiler needs to be handled in some special way by the project. It can be a useful technique in specific situations, but it can reduce the portability of the project if it relies too heavily on such expressions.

11.4. Path Expressions

CMake 3.24 added support for two path-handling expressions:

```
$<PATH_EQUAL:path1,path2>
```

This is the path equivalent of `$<STREQUAL:string1,string2>`. When the two things to be compared are expected to be paths rather than arbitrary strings, `$<PATH_EQUAL:...>` more

clearly expresses that expectation. It has the advantage of comparing each part of the path individually, effectively collapsing multiple consecutive directory separators into a single separator (they are expected to use forward slashes). Paths can be wrapped with `$<PATH:CMAKE_PATH,...>` to ensure they have the required form:

```
$<PATH_EQUAL:$<PATH:CMAKE_PATH, path1>,$<PATH:CMAKE_PATH, path2>>
```

```
$<PATH:subcommand,...>
```

This is essentially the generator expression equivalent of the configure-time `cmake_path()` command (covered in detail in [Section 21.1.1, “`cmake_path\(\)`”](#)). The same set of operations are supported, although the syntax has some differences. The full list of supported subcommands can be found in the generator expressions manual of the official CMake documentation. Some examples are listed below to give a flavor of what is possible.

```
$<PATH:IS_ABSOLUTE,somePath>
$<PATH:IS_PREFIX,NORMALIZE,prefix fullPath>
$<PATH:GET_FILENAME:somePath>
```

With CMake 3.27 or later, the various `$<PATH:subcommand,...>` expressions also accept a list of paths. When given a list of paths, the subcommand applies the operation to each path and produces a list as a result.

11.5. List Expressions

CMake 3.27 added a family of `$<LIST:>` expressions which provide generation-time capabilities similar to the configuration-time capabilities of the `list()` command. The generator expressions require some extra care with regard to quoting, semicolons, and commas to ensure the expression arguments are parsed correctly by CMake. See [Section 6.7, “Lists”](#) or the generator expressions manual in the CMake documentation for the supported list operations. The following examples give a flavor of what is possible:

```
# Add two values to the end of a list  
$<LIST:APPEND,${someValues},specialSauce,secretThing>  
  
# Remove a specific item if it appears in the list  
$<LIST:REMOVE_ITEM,${someValues},iShouldBeRemoved>  
  
# Remove leading and trailing spaces from each list item  
$<LIST:TRANSFORM,${someValues},STRIP>
```

A few other dedicated list-handling generator expressions are supported with earlier CMake versions. The `$<LIST:>` expressions should be used if the project’s minimum CMake version allows, but for older versions, the following can be used instead.

```
$<JOIN:list,...>
```

This generator expression replaces each semicolon in `list` with the `...` content, effectively joining the list items with `...`

between each one. The expression will also silently drop all empty items from the list. If preserving empty items is important, use `$<LIST:JOIN,...>` instead.

Note that like many generator expressions, `$<JOIN:...>` should never be used without quoting the whole expression. This prevents the semicolons in `list` from acting as argument separators for the command in which the generator expression is being used (see [Section 9.8, “Problems With Argument Handling”](#) for a deeper discussion of this particular topic). Quoting is also needed to prevent any spaces in the `...` part from acting as argument separators. The following shows a very common example of this generator expression being used incorrectly:

```
set(dirs here there) # dirs = here;there

# ERROR: space and ; treated as argument separators
set_target_properties(Foo PROPERTIES
    CUSTOM_INC -I$<JOIN:${dirs}, -I>
)

# OK: Whole generator expression is quoted
set_target_properties(Foo PROPERTIES
    CUSTOM_INC "-I$<JOIN:${dirs}, -I>"
)
```

`$<REMOVE_DUPLICATES:list>`

This expression removes all duplicates, keeping just the first instance where duplicates are present. Note that this also applies to empty items in the list. This expression is only

supported with CMake 3.15 or later. If the project uses CMake 3.27 or later as its minimum version, prefer to use `$<LIST:REMOVE_DUPLICATES,list>` instead, as `$<REMOVE_DUPLICATES:>` may be deprecated in a future CMake version.

`$<FILTER:list,INCLUDE,regex>, $<FILTER:list,EXCLUDE,regex>`

Filter a list, keeping just the items that match or do not match the specified `regex` regular expression. It is the same as `$<LIST:FILTER,list,>`, which should be used instead if the project requires CMake 3.27 or later as its minimum version. `$<FILTER:>` is supported with CMake 3.15 or later, but it may be deprecated in a future CMake version.

11.6. Utility Expressions

Some generator expressions modify content or substitute special characters. Below are some of the ones that are more commonly used or are easily misunderstood.

`$<COMMA>`

There can be scenarios where a comma needs to be included in a generator expression, but doing so would interfere with the generator expression syntax itself. To work around such cases, `$<COMMA>` can be used instead to prevent parsing it as part of the expression syntax. The following shows how to safely convert a list to a string of comma-separated values.

```
$<LIST:JOIN,${someValues},$<COMMA>>
```

```
$<SEMICOLON>
```

Similar to the above, a semicolon embedded in a generator expression may be parsed by CMake as a command argument separator. By using `$<SEMICOLON>` instead, argument parsing won't see a raw semicolon character, so such argument splitting will not occur.

```
$<QUOTE>
```

This is another similar case, but only supported with CMake 3.30 or later. The `$<QUOTE>` expression evaluates to a double-quote character (""). It can be useful when text needs to be passed through substitutions or calls that may try to interpret a raw " in some way.

```
$<LOWER_CASE:...>, $<UPPER_CASE:...>
```

Any content can be converted to lower or uppercase via these expressions. This can be especially useful as a step before performing a string comparison. For example:

```
$<STREQUAL:$<UPPER_CASE:${someVar}>,FOOBAR>
```

```
$<GENEX_EVAL:...>, $<TARGET_GENEX_EVAL:target,...>
```

These two generator expressions were introduced in CMake 3.13. In more advanced scenarios, a situation can arise where the evaluation of a generator expression results in content that itself contains generator expressions. One

example is when evaluating a target property using `$<TARGET_PROPERTY:...>` and that property value contains another generator expression. Normally, the retrieved property is not evaluated further to expand any generator expressions it contains, but expansion can be forced using `$<GENEX_EVAL:...>` or `$<TARGET_GENEX_EVAL:...>`:

```
# Evaluate in current context  
$<GENEX_EVAL:$<TARGET_PROPERTY:MY_PROP>>  
  
# Evaluate for a specific target "foo"  
$<TARGET_GENEX_EVAL:foo,$<TARGET_PROPERTY:foo,MY_PROP>>
```

Projects should rarely need to use these two generator expressions. The above example demonstrates the primary motivation for why they were added to CMake, but that scenario should not typically arise in most projects.

11.7. Recommended Practices

Compared to other functionality, generator expressions are a more recently added CMake feature. Because of this, much of the material online and elsewhere about CMake tends not to use them. This is unfortunate, since generator expressions are typically more robust and provide more generality than older methods. There are some common examples where well-intentioned guidance leads to logic which only works for a subset of supported project generators or platforms, but where the use of suitable generator expressions instead would result

in no such limitations. This is particularly true in relation to project logic that tries to do different things for different build types (Debug, Release, and so on). Therefore, developers should become familiar with the capabilities that generator expressions provide. Those expressions mentioned above are only a subset of what CMake supports, but they form a good foundation for covering the majority of situations most developers are likely to face.

Used judiciously, generator expressions can result in more succinct `CMakeLists.txt` files. For example, conditionally including a source file depending on the build type can be done relatively concisely, as the example given earlier for `$<CONFIG:...>` showed. Such uses reduce the amount of if-then-else logic, resulting in better readability as long as the generator expressions are not too complex. Generator expressions are also a perfect fit for handling content that changes depending on the target or the build type. No other mechanism in CMake offers the same degree of flexibility and generality for handling the multitude of factors which may contribute to the final content needed for a particular target property.

Conversely, it is all too easy to go overboard and try to make everything a generator expression. This can lead to overly complex expressions which ultimately obscure the logic, and which can be difficult to debug ([Section 14.5, “Debugging Generator Expressions”](#) provides some techniques to help with

that). As always, developers should favor clarity over cleverness, and this is especially true with generator expressions. Consider first whether CMake already provides a dedicated facility to achieve the same result. Various CMake modules provide more targeted functionality aimed at a particular third party package, or for carrying out certain specific tasks. There are also a range of variables and properties that could simplify or replace the need for generator expressions altogether. A few minutes spent consulting the CMake reference documentation can save many hours of unnecessary work constructing complex generator expressions which were not really needed.

If the project specifies CMake 3.27 or later as its minimum version, prefer to use the more general `$<LIST:>` expressions rather than the older and more specific `$<JOIN:>`, `$<REMOVE_DUPLICATES:>`, or `$<FILTER:>` expressions. Those older expressions may eventually be deprecated. Projects will have greater longevity if they use the `$<LIST:>` expressions instead.

12. MODULES

The preceding chapters have focused mostly on the core aspects of CMake. Variables, properties, flow control, generator expressions, functions, etc. are all part of what could be considered the CMake language. In contrast, CMake modules are pre-built chunks of CMake code built on top of the core language features. They provide a rich set of functionality through which projects can satisfy a wide variety of goals. Being written and packaged as ordinary CMake code and therefore being human-readable, CMake modules can also be a useful resource for learning more about how to get things done in CMake.

CMake modules are collected together and provided in a single directory as part of a CMake release. Projects employ CMake modules in one of two ways, either directly or as part of finding an external package. The more direct method of employing CMake modules uses the `include()` command to essentially inject the module code into the current scope. This works just like the behavior already discussed back in [Section 8.2, “`include\(\)`”](#), except that only the base name of the module needs

to be given to the `include()` command, not the full path or file extension. All the options to `include()` work exactly as before.

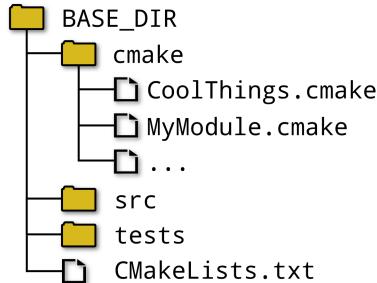
```
include(module
    [OPTIONAL]
    [RESULT_VARIABLE myVar]
    [NO_POLICY_SCOPE]
)
```

When given a module name, the `include()` command will look in a well-defined set of locations for a file whose name is the name of the module (case-sensitive) with `.cmake` appended. For example, `include(FooBar)` would result in CMake looking for a file called `FooBar.cmake`. On case-sensitive systems like Linux, file names like `foobar.cmake` would not match.

When looking for a CMake module's file, CMake first consults the variable `CMAKE_MODULE_PATH`. This is assumed to be a list of directories, and CMake will search each of these in order. The first matching file will be used, or if no matching file is found or if `CMAKE_MODULE_PATH` is empty or undefined, CMake will then search in its own internal module directory. This search order allows projects to add their own CMake modules seamlessly by adding directories to `CMAKE_MODULE_PATH`.

A useful pattern is to collect together a project's CMake module files in a single directory and add it to the `CMAKE_MODULE_PATH` somewhere near the beginning of the top level `CMakeLists.txt`

file. The following directory structure shows such an arrangement:



The corresponding `CMakeLists.txt` file then only needs to add the `cmake` directory to the `CMAKE_MODULE_PATH` and it can then call `include()` using just the base file name when loading each CMake module.

`CMakeLists.txt`:

```
cmake_minimum_required(VERSION 3.0)
project(Example)

list(APPEND CMAKE_MODULE_PATH
"${CMAKE_CURRENT_SOURCE_DIR}/cmake"
)

# Inject code from project-provided modules
include(CoolThings)
include(MyModule)
```

There is one exception to the search order used by CMake to find a CMake module. If the file calling `include()` is itself inside CMake's own internal module directory, then the internal module directory will be searched first *before* consulting `CMAKE_MODULE_PATH`. This prevents project code from accidentally

(or deliberately) replacing an official CMake module with one of their own and changing the documented behavior.

The other way to employ CMake modules is with the `find_package()` command. This is discussed in detail in [Section 34.4, “Finding Packages”](#), but for the moment, a simplified form of that command without any of the optional keywords demonstrates its basic usage:

```
find_package(PackageName)
```

When used in this way, the behavior is very similar to `include()`, except CMake will search for a file called `FindPackageName.cmake` rather than `PackageName.cmake`. This is how details about an external package are often brought into the build, including things like imported targets, variables defining locations of relevant files, libraries or programs, information about optional components, version details, and so on. The set of options and features associated with `find_package()` is considerably richer than what is provided for `include()`, and [Chapter 34, *Finding Things*](#) is dedicated to covering the topic in detail.

The remainder of this chapter introduces a number of interesting modules that are included as part of a CMake release. This is by no means a comprehensive set, but they do give a flavor of the functionality that is available. Other modules are introduced in later chapters where their

functionality is closely related to the topic of discussion. The CMake documentation provides a complete list of all available modules, each with its own help section explaining what the module provides and how it can be used. Be forewarned though that the quality of the documentation does vary widely from one module to another.

12.1. Checking Existence And Support

One of the more comprehensive areas covered by CMake's modules is checking for the existence of or support for various things. This family of modules all work in fundamentally the same way. They write a short amount of test code, and then attempt to compile and possibly link and run the resultant executable to confirm whether what is being tested in the code is supported. All of these modules have a name beginning with Check.

Some of the more fundamental Check... modules are those that compile and link a short test file into an executable and return a success/fail result. With CMake 3.19 or later, the CheckSourceCompiles module provides this capability. It defines the `check_source_compiles()` command:

```
include(CheckSourceCompiles)
check_source_compiles(lang code resultVar
    [FAIL_REGEX regexes...]
    [SRC_EXT extension]
)
```

The `lang` would be one of the languages CMake supports, such as C, CXX, CUDA, and so on. With earlier CMake versions, separate per-language modules provide the same capabilities, but the set of supported languages is much smaller. These modules have names of the form `Check<LANG>SourceCompiles` and each one provides an associated command that performs the test:

```
include(CheckCSourceCompiles)
check_c_source_compiles(code resultVar
    [FAIL_REGEX regexes...]
)

include(CheckCXXSourceCompiles)
check_cxx_source_compiles(code resultVar
    [FAIL_REGEX regexes...]
)

include(CheckFortranSourceCompiles)
check_fortran_source_compiles(code resultVar
    [FAIL_REGEX regexes...]
    [SRC_EXT extension]
)
```

For all of these commands, the `code` argument is expected to be a string containing source code that should produce an executable for the corresponding language. The result of an attempt to compile and link the code is stored in `resultVar` as a cache variable, with `true` indicating success. After the test has been performed once, subsequent CMake runs will use the cached result rather than performing the test again. This is the case even if the code being tested is changed. To force re-

evaluation, the variable has to be manually removed from the cache.

If the FAIL_REGEX option is specified, then additional criteria apply. If the output of the test compilation and linking matches any of the specified regexes (a list of regular expressions), the check will be deemed to have failed, even if the code compiles and links successfully.

```
include(CheckSourceCompiles)
check_c_source_compiles("int main() { int myVar; }"
    unusedNotDetected
    FAIL_REGEX "[Ww]arn"
)
if(unusedNotDetected)
    message("Unused variables do not generate warnings")
endif()
```

In the case of Fortran, the file extension can affect how compilers treat source files, so the file extension can be explicitly specified with the SRC_EXT option to obtain the expected behavior. There is no equivalent option for the C or C++ cases when using the older Check<LANG>SourceCompiles modules, but the newer CheckSourceCompiles module supports it for all languages.

A number of variables of the form CMAKE_REQUIRED_... can be set before calling any of the compilation test commands to influence how they compile the code:

CMAKE_REQUIRED_FLAGS

Additional flags to pass to the compiler command line after the contents of the relevant `CMAKE_<LANG>_FLAGS` and `CMAKE_<LANG>_FLAGS_<CONFIG>` variables (see [Section 16.6, “Compiler And Linker Variables”](#)). This must be a single string with multiple flags being separated by spaces, unlike all the other variables below which are CMake lists.

`CMAKE_REQUIRED_DEFINITIONS`

A CMake list of compiler definitions, each one specified in the form `-DFOO` or `-DFOO=bar`.

`CMAKE_REQUIRED_INCLUDES`

Specifies directories to search for headers. Multiple paths must be specified as a CMake list, with spaces being treated as part of a path.

`CMAKE_REQUIRED_LIBRARIES`

A CMake list of libraries to add to the linking stage. Do not prefix the library names with any `-l` option or similar, provide just the library name or the name of a CMake imported target (discussed in [Chapter 19, Target Types](#)).

`CMAKE_REQUIRED_LINK_OPTIONS`

A CMake list of options to be passed to the linker if building an executable, or to the archiver if building a static library. Support for this variable is only available with CMake 3.14 or later.

CMAKE_REQUIRED_LINK_DIRECTORIES

A CMake list of search paths to be passed to the linker if building an executable. Projects should avoid using this if at all possible. Prefer to pass an absolute path to libraries to be linked instead, which is more robust. Support for this variable is only available with CMake 3.31 or later.

CMAKE_REQUIRED_QUIET

If this option is present, the command will not print any status messages.

These variables are used to construct arguments to the `try_compile()` call made internally to perform the check. They are also supported by various other `check_...()` commands provided by CMake modules. See the end of this section for an example of their use. The CMake documentation for `try_compile()` discusses additional variables which may affect the checks. Other aspects of `try_compile()` behavior relating to toolchain selection and the type of target to build are covered in [Section 24.5, “Compiler Checks”](#).

In addition to checking whether code can be built, CMake also provides modules that test whether the built executable can be run successfully. Success is measured by the exit code of the executable created from the source provided, with 0 being treated as success and all other values indicating failure. With

CMake 3.19 or later, a single module provides a command for all languages:

```
include(CheckSourceRuns)
check_source_runs(lang code resultVar
    [SRC_EXT extension]
)
```

Again, with earlier CMake versions, separate per-language modules provide the same capabilities, but with fewer supported languages:

```
# Supported by all CMake versions
include(CheckCSourceRuns)
check_c_source_runs(code resultVar)

include(CheckCXXSourceRuns)
check_cxx_source_runs(code resultVar)

# Requires CMake 3.14 or later
include(CheckFortranSourceRuns)
check_fortran_source_runs(code resultVar
    [SRC_EXT extension]
)
```

There is no FAIL_REGEX option for these commands, as success or failure is determined purely by the exit code of the test process. If the code cannot be built, this is also treated as a failure. All the same variables that affect how the code is built for `check_source_compiles()` or `check_<lang>_source_compiles()` also have the same effect for these modules' commands as well.

For builds that are cross-compiling to a different target platform, the `check_source_runs()` and `check_<lang>_source_runs()` commands behave quite differently. They may run the code under a simulator if the necessary details have been provided, which would likely slow down the CMake configure step considerably. If simulator details have not been provided, the commands will instead expect a predetermined result to be provided through a set of variables and will not try to run anything. This fairly advanced topic is covered in CMake's documentation for the `try_run()` command, which is what the module commands use internally to perform the checks.

Certain categories of checks are so common that CMake provides dedicated modules for them. These remove much of the boilerplate of defining the test code and allow projects to specify a minimal amount of information for the check. These are typically just wrappers around the commands provided by one of the modules mentioned above, so the same set of variables used for customizing how the test code is built still apply. These more specialized modules check compiler flags, pre-processor symbols, functions, variables, header files, and more.

Just as for the modules above, CMake 3.19 or later provides a single module and command for all supported languages. For

earlier CMake versions, a set of per-language modules must be used instead.

```
# Requires CMake 3.19 or later
include(CheckCompilerFlag)
check_compiler_flag(lang flag resultVar)
```

```
# Supported by all CMake versions
include(CheckCCompilerFlag)
check_c_compiler_flag(flag resultVar)
include(CheckCXXCompilerFlag)
check_cxx_compiler_flag(flag resultVar)
```

```
# Requires CMake 3.3 or later
include(CheckFortranCompilerFlag)
check_fortran_compiler_flag(flag resultVar)
```

The flag-checking commands update the `CMAKE_REQUIRED_DEFINITIONS` variable internally to include flag in a call to `check_source_compiles()` with a trivial test file. An internal set of failure regular expressions is also passed as the `FAIL_REGEX` option, testing whether the flag results in a diagnostic message being issued or not. The result of the call will be true if no matching diagnostic message is issued. This means any flag resulting in a compiler warning but successful compilation will still be deemed to have failed the check. Also be aware that these commands assume any flags already present in the relevant `CMAKE_<LANG>_FLAGS` variables (see [Section 16.6, “Compiler And Linker Variables”](#)) do not themselves generate any compiler warnings. If they do, the

logic for each of these flag-testing commands will be defeated and the result of all such checks will be failure.

CMake 3.18 also introduced the `CheckLinkerFlag` module. It provides the command `check_linker_flag()`, which is mostly just a convenience wrapper around `check_source_compiles()`. It supports the same variables as previously discussed, except it takes over handling the `CMAKE_REQUIRED_LINK_OPTIONS` variable.

```
include(CheckLinkerFlag)
check_linker_flag(language flag resultVar)
```

The specified `flag` is not passed directly to the linker. The linker is invoked via the compiler, which internally adds extra language-specific flags, libraries, etc. needed to successfully link for the specified language. A raw linker flag will usually not work, it typically needs some sort of prefix like `-Wl,...` or `-Xlinker` to tell the compiler to pass it through to the linker. This prefix is compiler-specific, but the special prefix `LINKER:` can be used and CMake will substitute the correct compiler-specific prefix automatically. See [Section 16.1.2, “Linker Flags”](#) and the `target_link_options()` command in [Section 16.2, “Target Property Commands”](#) for related discussions.

```
include(CheckLinkerFlag)
check_linker_flag(CXX LINKER:-stats LINKER_STATS_SUPPORTED)
```

Two other notable modules are `CheckSymbolExists` and `CheckCXXSymbolExists`. The former provides a command which

builds a test C executable and the latter does the same as a C++ executable. Both check whether a particular symbol exists as either a pre-processor symbol (something that can be tested via an `#ifdef` statement), a function, or a variable.

```
include(CheckSymbolExists)
check_symbol_exists(symbol headers resultVar)

include(CheckCXXSymbolExists)
check_cxx_symbol_exists(symbol headers resultVar)
```

For each of the items specified in `headers` (a CMake list if more than one header needs to be given), a corresponding `#include` will be added to the test source code. In most cases, the symbol being checked will be defined by one of these headers. The result of the test is stored in the `resultVar` cache variable in the usual way.

In the case of functions and variables, the symbol needs to resolve to something that is part of the test executable. If the function or variable is provided by a library, that library must be linked as part of the test, which can be done using the `CMAKE_REQUIRED_LIBRARIES` variable.

```
include(CheckSymbolExists)
check_symbol_exists(sprintf stdio.h HAVE_SPRINTF)

include(CheckCXXSymbolExists)
set(CMAKE_REQUIRED_LIBRARIES SomeCxxSDK)
check_cxx_symbol_exists(SomeCxxInitFunc
    somecxxsdk.h)
```

```
HAVE_SOME_CXX_SDK  
)
```

There are limitations on the sort of functions and variables that can be checked by these commands. With CMake 3.15 and older, only those symbols that satisfy the naming requirements for a preprocessor symbol can be used. The implications are stronger for `check_cxx_symbol_exists()`, since it means only non-template functions or variables in the global namespace can be checked because any scoping (:) or template markers (<>) would not be valid for a preprocessor symbol. CMake 3.16 and later bypasses checking for a preprocessor symbol if the name is not a valid macro name, which allows the name to be checked as other symbol types. With any CMake version, it is also impossible to distinguish between different overloads of the same function, so existence of those cannot be checked at all.

There are other modules that aim to provide functionality similar to or a subset of that covered by `CheckSymbolExists`. These other modules are either from earlier versions of CMake, or are for a language other than C or C++. The `CheckFunctionExists` module is already documented as being deprecated, and the `CheckVariableExists` module offers nothing that `CheckSymbolExists` doesn't already provide. The `CheckFortranFunctionExists` module may be useful for those projects working with Fortran, but note that there is no

`CheckFortranVariableExists` module. Fortran projects may want to use `CheckFortranSourceCompiles` for consistency instead.

Other modules provide more detailed checks. For example, struct members can be tested with `CheckStructHasMember`, specific C or C++ function prototypes can be tested with `CheckPrototypeDefinition`, and the size of non-user types can be tested with `CheckTypeSize`. Other higher level checks are also possible, as provided by `CheckLanguage`, `CheckLibraryExists`, and the various `CheckIncludeFile...` modules. Further check modules continue to be added to CMake as it evolves, so consult the CMake module documentation to see the full set of available functionality.

In situations where multiple checks are being made or where the effects of performing the checks need to be isolated from each other or from the rest of the current scope, it can be cumbersome to manually save and restore the state before and after the checks. In particular, the various `CMAKE_REQUIRED_...` variables often need to be saved and restored. To help with this, CMake provides the `CMakePushCheckState` module which defines the following three commands:

```
include(CMakePushCheckState)
cmake_push_check_state([RESET])
cmake_pop_check_state()
cmake_reset_check_state()
```

These commands allow the various `CMAKE_REQUIRED_...` variables to be treated as a set and to have their state pushed and popped to and from a virtual stack. Each time `cmake_push_check_state()` is called, it effectively begins a new virtual variable scope for just the `CMAKE_REQUIRED_...` variables (and also the `CMAKE_EXTRA_INCLUDE_FILES` variable which is only used by the `CheckTypeSize` module). `cmake_pop_check_state()` is the opposite, it discards the current values of the `CMAKE_REQUIRED_...` variables and restores them to the previous stack level's values. The `cmake_reset_check_state()` command is a convenience for clearing all the `CMAKE_REQUIRED_...` variables and the `RESET` option to `cmake_push_check_state()` is also just a convenience for clearing the variables as part of the push. Note, however, that a bug existed prior to CMake 3.10 which resulted in the `RESET` option being ignored, so for projects that need to work with versions before 3.10, it is better to use a separate call to `cmake_reset_check_state()` instead.

```
# Start with a known state we can modify and undo later
include(CMakePushCheckState)
cmake_push_check_state()
cmake_reset_check_state()

set(CMAKE_REQUIRED_FLAGS -Wall)
include(CheckSymbolExists)
check_symbol_exists(FOO_VERSION foo/version.h HAVE_FOO)

if(HAVE_FOO)
    # Preserve -Wall and add more things for extra checks
    cmake_push_check_state()
    set(CMAKE_REQUIRED_INCLUDES foo/inc.h foo/more.h)
```

```

set(CMAKE_REQUIRED_DEFINITIONS -DFOOBXX=1)
check_symbol_exists(FOOBAR "" HAVE_FOOBAR)
check_symbol_exists(FOOBAZ "" HAVE_FOOBAZ)
check_symbol_exists(FOOBBOO "" HAVE_FOOBBOO)
cmake_pop_check_state()
# Now back to just -Wall
endif()

# Clear CMAKE_REQUIRED_... variables for this last check
cmake_reset_check_state()
check_symbol_exists(__TIME__ "" HAVE_PPTIME)

# Restore all CMAKE_REQUIRED_... variables to their
# original values from the top of this example
cmake_pop_check_state()

```

12.2. Other Modules

CMake has excellent built-in support for some languages, especially C and C++. It also includes a number of modules which provide support for languages in a more extensible and configurable way. These modules allow aspects of some languages or language-related packages to be made available to projects by defining relevant commands, variables, and properties. Many of these modules are provided as part of the support for `find_package()` calls (see [Section 34.4, “Finding Packages”](#)), while others are intended to be used more directly via `include()` to bring things into the current scope. The following module list should give a taste of the language support available:

- `CSharpUtilities`

- `FindCUDAToolkit` (CUDA is supported as a first-class language since CMake 3.8)
- `FindJava`, `FindJNI`, `UseJava`
- `FindLua`
- `FindMatlab`
- `FindPerl`, `FindPerlLibs`
- `FindPython`
- `FindPHP4`
- `FindRuby`
- `FindSWIG`, `UseSWIG`
- `FindTCL`
- `FortranCInterface`

In addition, modules are also provided for interacting with external data and projects (see [Chapter 38, *ExternalProject*](#) and [Chapter 39, *FetchContent*](#)). A number of modules are also provided to facilitate various aspects of testing and packaging. These have a close relationship with the `CTest` and `CPack` tools distributed as part of the CMake suite and are covered in depth in [Part IV, “Testing And Analysis”](#) and [Chapter 36, *Packaging*](#). Debugging assistance is also provided by the `CMakePrintHelpers` module (see [Section 14.3, “Print Helpers”](#)).

12.3. Recommended Practices

CMake's collection of modules provides a wealth of functionality built on top of the core CMake language. A project can easily extend the set of available functionality by adding their own custom modules under a particular directory, and then adding that path to the `CMAKE_MODULE_PATH` variable. The use of `CMAKE_MODULE_PATH` should be preferred over hard-coding absolute or relative paths across complex directory structures in `include()` calls, since this will encourage generic CMake logic to be decoupled from the places where that logic may be applied. This in turn makes it easier to relocate CMake modules to different directories as a project evolves, or to re-use the logic across different projects. Indeed, it is not unusual for an organization to build up its own collection of modules, perhaps even storing them in their own separate repository. By setting `CMAKE_MODULE_PATH` appropriately in each project, those reusable CMake building blocks are then made available for use as widely as needed.

Over time, a developer will typically be exposed to an increasing number of interesting scenarios for which a CMake module may provide useful shortcuts or ready-made solutions. Sometimes a quick scan of the available modules can yield an unexpected hidden gem, or a new module may offer a better maintained implementation of something a project has been implementing in an inferior way up to that point. CMake's modules have the benefit of many developers and projects using them across a diverse set of platforms and situations, so

they may offer a more compelling alternative to projects doing their own manual logic in many cases. The quality does vary from one module to another though. Some modules began their life quite early on in CMake’s existence, and these can sometimes become less useful if not kept up to date with changes to CMake, or to the areas those modules relate to. This can be particularly true of Find... modules, which may not track newer versions of the packages they are finding as closely as one might like. On the other hand, modules are just ordinary CMake code, so anyone can inspect them, learn from them, improve or update them without having to learn much beyond what is needed for basic CMake use in a project. In fact, they are an excellent starting point for developers wishing to get involved with working on CMake itself.

The abundance of different Check... modules provided by CMake can be a mixed blessing. Developers can be tempted to get too over-zealous with checking all manner of things, which can result in slowing down the configure stage for sometimes questionable gains. It is common to see the commands related to these checks dominate the profiling results of a CMake run (see [Section 14.6, “Profiling CMake Calls”](#)). Consider whether the benefits outweigh the costs in terms of time to implement and maintain the checks, and the complexity of the project. Sometimes a few judicious checks are enough for covering the most useful cases, or to catch a subtle problem that might otherwise cause hard to trace problems later. Furthermore, if

using any of the Check... modules, aim to isolate the checking logic from the scope in which it may be invoked. Use of the CMakePushCheckState module is highly recommended, but avoid using the RESET option to `cmake_push_check_state()` if support for CMake versions before 3.10 is important.

When the minimum CMake version can be set to 3.20 or later, avoid using the relatively popular but now deprecated TestBigEndian module. That module was deprecated in CMake 3.20 in favor of a new `CMAKE_<LANG>_BYTE_ORDER` variable, which was also introduced in the same CMake release. Projects that are using TestBigEndian should transition to the new variable where possible.

13. POLICIES

CMake has evolved over a long period, introducing new functionality, fixing bugs, and changing the behavior of certain features to address shortcomings or introduce improvements. While the introduction of new capabilities is unlikely to cause problems for existing projects built with CMake, any change in behavior has the potential to break projects if they are relying on the old behavior. For this reason, the CMake developers are careful to ensure that changes are implemented in such a way as to preserve backward compatibility, and to provide a straightforward, controlled migration path for projects to update to the new behavior.

This control over whether old or new behavior should be used is done through CMake's policy mechanisms. In general, policies are not something that developers are exposed to all that often, mostly just when CMake issues a warning about the project relying on an older version's behavior. When developers move to a more recent CMake release, the newer CMake version will sometimes issue such warnings to highlight how the project should be updated to use a new behavior.

13.1. Policy Control By Version

CMake's policy functionality is closely tied to the `cmake_minimum_required()` command, which was introduced back in [Chapter 3, A Minimal Project](#). Not only does this command specify the minimum CMake version a project requires, it also sets CMake's behavior to match that of the version given. Thus, when a project starts with `cmake_minimum_required(VERSION 3.24)`, it says that at least CMake 3.24 is needed and also that the project expects CMake to behave like the 3.24 release. This gives projects confidence that developers should be able to update to a newer version of CMake at their convenience, and the project will still build as it did before.

But sometimes a project may want more fine-grained control than what the `cmake_minimum_required()` command provides. Consider the following scenarios:

- A project wants to set a low minimum CMake version, but it also wants to take advantage of newer behavior if it is available.
- A part of the project cannot be modified (it might come from an external read-only code repository), and it relies on old behavior which has been changed in newer CMake versions. But the rest of the project wants to move to the new behavior.

- A project relies heavily on some old behavior, and it would require a non-trivial amount of work to update. Some parts of the project want to make use of recent CMake features, but the old behavior for that particular change needs to be preserved until time can be set aside to update the project.

These are some common examples where the high-level control provided by the `cmake_minimum_required()` command alone is not enough. More specific control over policies is enabled through the `cmake_policy()` command, which has a number of forms acting at different degrees of granularity. The form acting at the coarsest level is a close relative to `cmake_minimum_required()`:

```
cmake_policy(VERSION major[.minor[.patch[.tweak]]])
```

In this form, the command changes CMake's behavior to match that of the specified version. The `cmake_minimum_required()` command implicitly calls this form to set CMake's behavior. The two are largely interchangeable, except for the top of the project where a call to `cmake_minimum_required()` is mandatory to enforce a minimum CMake version. Apart from the start of the top level `CMakeLists.txt` file, using `cmake_policy()` generally communicates the intent more clearly when a project needs to enforce a particular version's behavior for a section of the project, as demonstrated by the following example:

```
cmake_minimum_required(VERSION 3.31)
project(WithLegacy)

# Uses recent CMake features
add_subdirectory(modernDir)

# Imported from another project, relies on older behavior
cmake_policy(VERSION 3.24)
add_subdirectory(legacyDir)
```

13.2. Policy Control By Version Range

Starting with CMake 3.12, projects can specify a version *range* to either `cmake_minimum_required()` or `cmake_policy(VERSION)`, not just a single version. The range is specified using three dots ... between the minimum and maximum version with no spaces. The range indicates that the CMake version in use must be at least the minimum, and the behavior should match the lowest of the specified maximum and the running CMake version. This allows the project to effectively say "I need at least CMake X, but I am safe to use with policies from up to CMake Y".

The following example shows two ways for a project to require only CMake 3.7, but still support the newer behavior for all policies up to CMake 3.31 if the running CMake version supports them:

```
cmake_minimum_required(VERSION 3.7...3.31)
cmake_policy(VERSION 3.7...3.31)
```

Even though version ranges were only added in CMake 3.12, the version range syntax still provides a degree of backward compatibility with earlier CMake versions. CMake versions before 3.12 effectively see just a single version number. They ignore the ...X.Y.Z part and still enforce the bottom of the range.

13.3. Controlling Individual Policies

CMake also provides the ability to control each behavior change individually with the `cmake_policy(SET)` form:

```
cmake_policy(SET CMPxxxx NEW)
cmake_policy(SET CMPxxxx OLD)
```

Each behavior change is given its own policy number of the form `CMPxxxx`, where `xxxx` is always four digits. By specifying `NEW` or `OLD`, a project tells CMake to use the new or old behavior for that particular policy. The CMake documentation provides the full list of policies in its [cmake-policies\(7\)](#) manual, along with an explanation of the `OLD` and `NEW` behavior for each one.

As an example, before version 3.0, CMake allowed a project to call `get_target_property()` with the name of a target that didn't exist. In such a case, the value of the property was returned as `<varName>-NOTFOUND` rather than issuing an error. But in all likelihood, the project logic was probably incorrect. Therefore, from version 3.0 onward, CMake halts with an error if such a

situation is encountered. In the event that a project was relying on the old behavior, it could continue to do so using policy CMP0045 with CMake versions up to CMake 3.31 like so:

```
# Allow non-existent target with get_target_property()
cmake_policy(SET CMP0045 OLD)

# Would halt with an error without the above policy change
get_target_property(outVar notExist COMPILE_DEFINITIONS)
```

There is a limit to how long projects can expect the OLD behavior of a policy to be supported. [Section 13.6, “Policy Removal”](#) discusses the policy warning and removal process.

The need for setting a policy to NEW is less common. One situation is where a project wants to set a low minimum CMake version, but still take advantage of specific later features if a later version is used. For example, in CMake 3.2, policy CMP0055 was introduced to provide strict checking on usage of the break() command. If the project still wanted to support being built with earlier CMake versions, then the additional checks would have to be explicitly enabled when run with later CMake versions.

```
cmake_minimum_required(VERSION 3.0)
project(PolicyExample)

if(CMAKE_VERSION VERSION_GREATER 3.1)
    # Enable stronger checking of break() command usage
    cmake_policy(SET CMP0055 NEW)
endif()
```

Testing the `CMAKE_VERSION` variable is one way of determining whether a policy is available, but the `if()` command provides a more direct way using the `if(POLICY...)` form. The above could instead be implemented like so:

```
cmake_minimum_required(VERSION 3.0)
project(PolicyExample)

# Only set the policy if the version of CMake being used
# knows about that policy number
if(POLICY CMP0055)
    cmake_policy(SET CMP0055 NEW)
endif()
```

In practice, support for version ranges with CMake 3.12 and later has made the above methods for setting policies to NEW mostly unnecessary.

It is also possible to get the current state of a particular policy. The main situation where the current policy setting may need to be read is in a module file, which may be one provided by CMake itself or by the project. It would be unusual for a project module to change its behavior based on a policy setting.

```
cmake_policy(GET CMPxxxx outVar)
```

The value stored in `outVar` will be OLD, NEW, or an empty string. The `cmake_minimum_required(VERSION...)` and `cmake_policy(VERSION...)` commands reset the state of all policies. Those policies introduced at the specified CMake version or

earlier are reset to NEW. Those policies that were added after the specified version will effectively be reset to empty.

13.4. Policy Scope

Sometimes a policy setting only needs to be applied to a specific section of a file. Rather than requiring a project to manually save the existing value of any policies it wants to change temporarily, CMake provides a policy stack which can be used to simplify this process. Pushing onto the policy stack essentially creates a copy of the current settings and allows the project to operate on that copy. Popping the stack discards the current policy settings and reverts to the previous settings on the stack.

Two methods are available for saving and restoring (pushing and popping) the policy stack:

```
# Requires CMake 3.25 or later
block(SCOPE_FOR_POLICIES)
    # Make changes to policies here. Policy settings outside
    # the block are not affected.
endblock()
```

```
# Works with any CMake version
cmake_policy(PUSH)
    # Make changes to policies here. Policy changes apply
    # up until the policy stack is popped (see below).
cmake_policy(POP)
```

Of the two methods, the first using `block()` is more robust. Regardless of how control flow leaves the block, the policies are restored to their previous state from before the block was entered. This means commands like `return()`, `break()`, and `continue()` can be used freely within the block.

The second method using `cmake_policy()` is more fragile. It relies on the project calling `cmake_policy(POP)` exactly once for each `cmake_policy(PUSH)`. This can be challenging when pushing and popping policy state across many lines. A common error is pushing policies at the start of a long file and popping at the end, but returning early somewhere in the middle without popping the policy stack. This often happens when the file originally had no `return()` statements when the policy push-pop was added, but a `return()` is added later. Module files are a common place where the policy stack might be manipulated like this and where this sort of error frequently occurs.

```
cmake_policy(PUSH)
cmake_policy(SET CMP0085 NEW)

# ...

if("Foo" IN_LIST SomeList)
    # ERROR: Returns without popping the policy stack
    return()
endif()

# ...

cmake_policy(POP)
```

Replacing the above with `block()` instead avoids the problem:

```
block(SCOPE_FOR_POLICIES)
cmake_policy(SET CMP0085 NEW)

# ...

if("Foo" IN_LIST SomeList)
    # OK: No manual policy pop needed
    return()
endif()

# ...

endblock()
```

Some commands implicitly push a new policy state onto the stack and pop it again before returning to the caller. The `add_subdirectory()`, `include()`, and `find_package()` commands are important examples of this. The `include()` and `find_package()` commands also support a `NO_POLICY_SCOPE` option which prevents the automatic push-pop of the policy stack (`add_subdirectory()` has no such option). In very early versions of CMake, `include()` and `find_package()` did not automatically push and pop an entry on the policy stack. The `NO_POLICY_SCOPE` option was added as a way for projects using later CMake versions to revert to the old behavior for specific parts of the project, but its use is discouraged and should be unnecessary for new projects.

13.5. Overriding Policy Defaults And Warnings

If CMake detects that the project is doing something that either relies on the old behavior, conflicts with the new behavior, or whose behavior is ambiguous, it may warn if the relevant policy is unset. These warnings are the most common way developers are exposed to CMake’s policy functionality. They are designed to be noisy and informative, encouraging developers to update the project to the new behavior. For policies that have been around for some time, a warning may be issued even if the policy has been explicitly set (see [Section 13.6, “Policy Removal”](#)).

Sometimes the policy warnings cannot be addressed immediately, but the warnings could be undesirable. The preferred way to handle this is to explicitly set the policy to the desired behavior (OLD or NEW), which stops the warning. This isn’t always possible though, such as when a deeper part of the project issues its own call to `cmake_minimum_required(VERSION...)` or `cmake_policy(VERSION...)`, thereby resetting the policy states.

As a temporary way to work around such situations, CMake provides the `CMAKE_POLICY_DEFAULT_CMPxxxx` and `CMAKE_POLICY_WARNING_CMPxxxx` variables, where `xxxx` is the usual four-digit policy number. These are not intended to be set by the project, but rather by the developer, usually via a `-D` option when invoking CMake.

Enable NEW FetchContent behavior by default

```
cmake -DCMAKE_POLICY_DEFAULT_CMP0168:STRING=NEW ...
```

Ultimately, the better long-term solution is to address the underlying problem highlighted by the warning, or to update the project to use the NEW behavior through appropriate `cmake_minimum_required()` or `cmake_policy()` calls.

CMake 4.0 also added the ability to override the project's minimum CMake version without having to modify the project. A `CMAKE_POLICY_VERSION_MINIMUM` cache variable can be set on the `cmake` command line, or alternatively an environment variable of the same name can be set.

```
cmake -DCMAKE_POLICY_VERSION_MINIMUM:STRING=3.24 ...
```

This feature should only be used when the project cannot be modified or where a short-term workaround is needed until a project can be updated. This situation most often arises when public CI systems like GitHub update their default build environment to a new CMake release. If projects haven't been updating their policy settings for some time, or they need to continue building old branches, they can be caught off-guard and suddenly start seeing build failures. Projects may temporarily set the `CMAKE_POLICY_VERSION_MINIMUM` environment variable in the project's CI settings until the maintainers have the opportunity to update the project. But projects are still better off regularly updating their policy settings in anticipation

of new CMake releases, not reacting when forced to do so as OLD policy behaviors are deprecated or removed.

13.6. Policy Removal

The OLD policy setting shouldn't be treated as a way to avoid updating a project for the behavior change. The OLD setting exists only to help projects transition to the new behavior. Policies follow a set of steps over a series of CMake releases, culminating in their OLD behavior being completely removed and only the NEW behavior being available.

At some point at least two years after a policy is introduced, CMake may start issuing a deprecation warning if a project uses OLD behavior. This warning cannot be silenced, even if the project explicitly sets the policy to OLD. The next CMake major version released at least six years after a policy is introduced will most likely remove the OLD behavior altogether.

CMake 4.0 was the first release to completely remove OLD policy behaviors. All policies up to CMP0065 then only provide the NEW behavior. Any attempt to use the OLD behavior results in a fatal error. It is worth noting that when CMake 4.0 was released, many projects experienced broken builds, which was a consequence of those projects not being updated to new behaviors over a long period.

13.7. Recommended Practices

Where possible, projects should prefer to work with policies at the CMake version level rather than manipulating specific policies. Setting policies to match a particular CMake release's behavior makes the project easier to understand and update. Changes to individual policies can be harder to trace through multiple directory levels, especially because of their interaction with version-level policy changes where they are always reset.

When choosing how to specify the CMake version to conform to, the choice between `cmake_minimum_required(VERSION)` and `cmake_policy(VERSION)` would usually fall to the latter. The two main exceptions to this are at the start of the project's top level `CMakeLists.txt` file and at the top of a module file that could be re-used across multiple projects. For the latter case, it is preferable to use `cmake_minimum_required(VERSION)` because the projects using the module may enforce their own minimum CMake version, but the module may have specific minimum version requirements of its own. Aside from these cases, `cmake_policy(VERSION)` usually expresses the intent more clearly, but both commands will effectively achieve the same thing from a policy perspective.

In cases where a project does need to manipulate a specific policy, it should check whether the policy is available using `if(POLICY...)` rather than testing the `CMAKE_VERSION` variable. This leads to greater consistency of the code. Compare the following

two ways of setting policy behavior and note how the check and the enforcement use a consistent approach:

```
# Version-level policy enforcement
if(NOT CMAKE_VERSION VERSION_LESS 3.4)
    cmake_policy(VERSION 3.4)
endif()

# Individual policy-level enforcement
if(POLICY CMP0055)
    cmake_policy(SET CMP0055 NEW)
endif()
```

If a project needs to manipulate multiple individual policies locally, surround that section with calls to `block(SCOPE_FOR_POLICIES)` and `endblock()`. If CMake 3.24 or earlier must be supported, use `cmake_policy(PUSH)` and `cmake_policy(POP)` instead. Surrounding the code with either command pair ensures that the rest of the scope is isolated from the changes. If using `cmake_policy()` to define these regions, pay special attention to any possible `return()`, `break()`, or `continue()` statements that exit that section of code, and ensure no push is left without a corresponding pop.

Note also that `add_subdirectory()`, `include()`, and `find_package()` all push and pop an entry on the policy stack automatically. No explicit `block` or `push-pop` is needed to isolate their policy changes from the calling scope. Projects should avoid the `NO_POLICY_SCOPE` keyword of these commands, as it is intended

only for addressing a change in behavior of very early CMake versions. `NO_POLICY_SCOPE` is rarely appropriate for new projects.

Aim to avoid modifying policy settings inside a function unless using an appropriate `block()` or `cmake_policy()` push-pop within the function body. Since functions do not introduce a new policy scope, a policy change can affect the caller if the change is not properly isolated using the appropriate logic. Furthermore, the policy settings for the function implementation are taken from the scope in which the function was *defined*, not the one from which it is called. Therefore, prefer to adjust any policy settings in the scope that defines the function rather than within the function itself.

As a last resort, the `CMAKE_POLICY_DEFAULT_CMPxxxx` and `CMAKE_POLICY_WARNING_CMPxxxx` variables may allow a developer to work around some specific policy-related situations. Developers may use these to temporarily change the default for a specific policy setting, or to prevent warnings about a particular policy. Projects should generally avoid setting these variables so that developers have control locally. Nonetheless, in certain situations, they can be used to ensure the behavior or warning about a particular policy persists even through calls to `cmake_minimum_required()` or `cmake_policy(VERSION)`. Where possible, projects should instead try to update to the newer behavior rather than relying on these variables.

Projects should ensure they do not rely on OLD policy behavior for any policy added seven or more CMake feature releases before the latest release. Developers using the latest CMake release may start seeing unsilenceable warnings for those OLD policy settings. As a guide, this means projects should remain no more than roughly two years behind the latest CMake release for their policy settings. This doesn't mean they can't support older CMake releases, only that they should enable newer policy settings when they are available. Using version ranges is a convenient way to achieve that. Smaller, more frequent updates to policy settings are also typically much easier to make than large jumps every couple of years.

14. DEBUGGING AND DIAGNOSTICS



This chapter discusses debugging CMake logic. For debugging executables built by the project, see [Chapter 44, *Debugging Executables*](#).

When a build is behaving well, users tend not to pay much attention to the output generated by CMake. But for developers working on a project, diagnostic output and debugging capabilities are essential. CMake has always provided basic printing functionality, but enhancements added in versions 3.15 to 3.18 significantly extended the available capabilities.

14.1. Log Messages

CMake has always supported logging arbitrary text using the `message()` command, which was introduced briefly back in [Section 6.5, “Printing Variable Values”](#). The more general form of that command is:

```
message([mode] msg1 [msg2]...)
```

If more than one `msg` is specified, they will be joined into a single string with no separators. To preserve spaces, semicolons, or newlines, surround the message with quotes (see [Section 9.8, “Problems With Argument Handling”](#) for a detailed explanation of why).

The message output can be affected by the optional `mode` argument, `cmake` command-line options, and the value of a few variables at the time of the call. The next few subsections cover these in detail.

14.1.1. Log Levels

The `message()` command accepts an optional `mode` keyword which provides information about the type of message being provided. It affects how and where the message is output, whether it is output at all, and in some cases can halt further processing for that CMake run. Recognized `mode` values in order of importance are:

`FATAL_ERROR`

Denotes a hard error. Processing will stop immediately after the message is printed and the log will also normally record the location of the fatal `message()` command.

`SEND_ERROR`

Like `FATAL_ERROR` except processing will continue until the configure stage completes, but generation will not be

performed. This can be quite confusing for users, so projects should avoid this mode and prefer to use FATAL_ERROR instead.

WARNING

Denotes a warning. The log will also normally record the location of the `message()` command raising the warning. Processing will continue.

AUTHOR_WARNING

Like WARNING, but only shown if developer warnings are enabled (use the `-Wno-dev` option on the `cmake` command line to disable them). Projects rarely use this particular type of message. They are usually generated by CMake's own modules.

DEPRECATION

Special category used to log a deprecation message. If the `CMAKE_ERROR_DEPRECATED` variable is set to true, the message will be treated as an error. If the `CMAKE_WARN_DEPRECATED` variable is set to true, the message will be treated as a warning. If neither variable is set, the message will be shown for CMake 3.5 or later and hidden for earlier versions.

NOTICE

This keyword is only recognized with CMake 3.15 or later, but for all versions, this is the default log level when no

mode keyword is provided. The keyword was added for consistency and to allow projects to be clearer about the meaning of such messages. Avoid using this log level if the message doesn't require any action from the user (see further below).

STATUS

Concise status information, generally expected to be a single line. Prefer to use this message mode rather than NOTICE for purely informational messages.

VERBOSE

(CMake 3.15 or later only) More detailed information that wouldn't normally be of interest, but could be helpful to project users when seeking a deeper understanding of what is happening.

DEBUG

(CMake 3.15 or later only) Not intended for project users, but rather for developers working on the project itself. These may record internal implementation details that would not be of interest to those simply wanting to build the project.

TRACE

(CMake 3.15 or later only) Very low level details, used almost exclusively for temporary messages during project development.

Messages of STATUS through to TRACE level will be printed to `stdout`, whereas NOTICE and above are printed to `stderr`. This can result in messages of different log levels sometimes appearing out of order in the output. Furthermore, messages on `stderr` usually imply a problem or something that the user should investigate, so NOTICE is generally a poor choice for purely informational messages that don't require follow-up. Use STATUS or below for such messages.

Messages of STATUS through to TRACE may also have two hyphens and a space automatically prepended. The CMake GUI application and the `ccmake` tool do not prepend this prefix, whereas the current version of the `cmake` tool will. Future CMake versions may drop this prefix completely, so do not rely on it being present. No such prefix is prepended for messages of NOTICE level and above.

CMake 3.15 also added the ability to set a minimum logging level with the `--loglevel=...` command-line option. This option was renamed to `--log-level` in CMake 3.16 for consistency reasons, but `--loglevel` is still accepted for backward compatibility. The option specifies the desired log level, and only messages of that level or higher will be shown. When no `--log-level` option is given, only messages of STATUS level or higher will be recorded.

```
cmake --log-level=VERBOSE ...
```

CMake 3.17 added the ability to specify the default log level with the `CMAKE_MESSAGE_LOG_LEVEL` variable. It is overridden by the `--log-level` command line option if both are present. The cache variable is intended for developer use only, projects should not try to read or modify it.

If a project wants to perform some action only at certain log levels, there is no way to robustly do that with CMake 3.24 or earlier. The `CMAKE_MESSAGE_LOG_LEVEL` variable is not a reliable indicator of the current log level. The `--log-level` option could have been passed on the `cmake` command line, and it overrides the variable when both are given (the variable value is not updated to reflect the command line setting). With CMake 3.25 or later, the current log level can be reliably obtained using `cmake_language(GET_MESSAGE_LOG_LEVEL)`. This accounts for both the variable and the command line option, returning the active log level at the time of the call. Patterns like the following can then be implemented:

```
# Requires CMake 3.25 or later
cmake_language(GET_MESSAGE_LOG_LEVEL topLevel)

# Only do the time-consuming operation at VERBOSE or lower
if(logLevel MATCHES "VERBOSE|DEBUG|TRACE")
    doTimeConsumingDiagnostics()
endif()
```

14.1.2. Message Indenting

When a project logs a non-trivial amount of output, adding some structure can help the user better understand which parts of the project each message relates to. One way to do that is to make use of the `CMAKE_MESSAGE_INDENT` variable. When using CMake 3.16 or later, the contents of this variable at the time of the call to `message()` will be concatenated and prepended to the message for log levels of `NOTICE` and below. If the message contains embedded newlines, the indentation contents will be prepended to each line of the output.

```
# Don't do this, see below
set(CMAKE_MESSAGE_INDENT aa bb)

message("First line\nSecond line")
```

```
aabbFirst line
aabbSecond line
```

While the above example demonstrates how the feature works, it has problems. The general expectation is that the list elements in `CMAKE_MESSAGE_INDENT` will only contain whitespace, typically two spaces each. This isn't a requirement, but deviating from it will likely be annoying for users. Projects should also never `set()` the variable, they should only append to it, typically by calling `list(APPEND)`. This avoids any assumption about the contents of the variable and always preserves the existing indenting. This is especially important for the output of hierarchical projects (discussed in detail in

[Chapter 39, *FetchContent*](#)) or when using indenting within function calls.

The following example demonstrates the above guidelines and how they can be applied in practice.

```
function(funcA)
    list(APPEND CMAKE_MESSAGE_INDENT " ")
    message("${CMAKE_CURRENT_FUNCTION}")
endfunction()

function(funcB)
    list(APPEND CMAKE_MESSAGE_INDENT " ")
    message("${CMAKE_CURRENT_FUNCTION}")
    funcA()
endfunction()

function(funcC)
    list(APPEND CMAKE_MESSAGE_INDENT " ")
    message("${CMAKE_CURRENT_FUNCTION}")
    funcB()
endfunction()

message("Top level")
funcA()
funcB()
funcC()
```

```
Top level
funcA
funcB
    funcA
funcC
    funcB
        funcA
```

Note how the indenting of output from both `funcA()` and `funcB()` varies depending on the call stack. Another feature of the example is that because functions introduce their own variable scope, it is not necessary to pop the indent off the end of the list before returning. The caller has its own separate copy of the `CMAKE_MESSAGE_INDENT` variable, so from its perspective, the value of the variable doesn't change as a result of the function call.

Projects can add support for indenting even if their minimum CMake version is less than 3.16. Older CMake versions will simply ignore the indenting and output will be unchanged.

14.1.3. Message Contexts

CMake 3.17 extended the support for message metadata even further. In the same way that `CMAKE_MESSAGE_INDENT` can be used to provide indenting, the `CMAKE_MESSAGE_CONTEXT` variable can be used to provide information about the context in which each message is generated. This can be used to record things like the project name or some logical part within the project, for example. Users can then instruct CMake to print context information with each message by including the `--log-context` option on the `cmake` command line.

When the `--log-context` option is given and `CMAKE_MESSAGE_CONTEXT` is not empty, a prefix is generated for each line of output from a call to `message()`. This prefix will be the concatenation of the items in `CMAKE_MESSAGE_CONTEXT`, with

each item separated by a dot. The result of that will be enclosed in square brackets and a space added to the end of the prefix. For messages logged at STATUS level or below, the context follows after any leading hyphens that may be added by cmake.

CMakeLists.txt:

```
cmake_minimum_required(VERSION 3.17)
list(APPEND CMAKE_MESSAGE_CONTEXT Coolio)
project(Coolio LANGUAGES CXX)

message("Adding features\nHere we go:")

add_subdirectory(networking)
add_subdirectory(graphics)

message("All done")
```

networking/CMakeLists.txt:

```
list(APPEND CMAKE_MESSAGE_CONTEXT net)
message("Doing something")
```

graphics/CMakeLists.txt:

```
list(APPEND CMAKE_MESSAGE_CONTEXT graphics)
message("Doing something else")
```

Running cmake --log-context on the above would result in output like the following:

```
-- [Coolio] The CXX compiler identification is GNU 9.3.0
-- [Coolio] Detecting CXX compiler ABI info
-- [Coolio] Detecting CXX compiler ABI info - done
-- [Coolio] Check for working CXX compiler: /.../c++ - skipped
-- [Coolio] Detecting CXX compile features
-- [Coolio] Detecting CXX compile features - done
```

```
[Coolio] Adding features
[Coolio] Here we go:
[Coolio.net] Doing something
[Coolio.graphics] Doing something else
[Coolio] All done
-- Configuring done
-- Generating done
-- Build files have been written to: /...
```

Compiler feature checks are triggered by the call to `project()`, so `Coolio` is appended to `CMAKE_MESSAGE_CONTEXT` before that call to ensure that the check output includes context information. The final few lines at the end of the output which record the completion of the different run stages will always have no context.

The general expectation is that when the output of context information is enabled, that output is going to undergo further post-processing of some sort rather than being shown directly to the user. For example, an IDE tool might use this to understand the structure of the output and offer filtering capabilities to the user. The IDE might support the user expanding and collapsing or showing and hiding parts of the `cmake` output according to their interest.

Another use case would be scripted builds. These might use Unix commands like `tee` and `awk` to save an annotated log to a file, but still show the output without context details to allow it to be monitored in real time. The saved file can then be searched later to find specific lines of interest. The following is

one way of doing this within a bash shell on a Unix-like system (it also strips off any leading hyphen prefix along with the context information):

```
cmake . --log-context |& \
    tee out.log | \
    awk 'sub("^((-- )?(\\"[^\\\"]]*\\") )?", "")'
```

One could then extract just the messages associated with networking from the saved log file using a tool like grep:

```
grep -E '^(-- )?\[.*Coolio\.net\]' out.log
```

CMake places certain restrictions on what a project may use as context names. Valid context names (each item in the CMAKE_MESSAGE_CONTEXT list) are those that could be used as the name of a CMake variable. For the most part, this essentially means letters, numbers, and underscores. In addition, CMake considers context names that begin with cmake_ or a leading underscore to be reserved for its own use.

Message contexts are particularly effective when message() calls specify appropriate log levels. For example, projects may provide more detailed information using a VERBOSE log level, but only fairly minimal output at STATUS level or higher. That would make the default output uncluttered, but using a --log-level of VERBOSE would provide extra detail when needed. Users could

then focus in on just the details they want by searching for the message context(s) of interest.

14.1.4. Check Messages

Another useful feature available with CMake 3.17 or later is support for messages that record the status of some form of check. The syntax is essentially the same as the main form of the `message()` command, but the meaning of the first argument is different:

```
message(checkState msg1 [msg2]...)
```

The `checkState` argument is expected to be one of the following values:

`CHECK_START`

Signifies the start of the check. The message should be short, ideally not more than a few words. It will be repeated as part of the pass or fail message at the end of the check.

`CHECK_PASS`

The check completed successfully.

`CHECK_FAIL`

The check completed with a failure.

Start, pass, and fail messages are always output with a `STATUS` log level. The meaning of success or failure is up to the project,

and failure does not necessarily imply an error. For example, the project may want to check for a number of related things and stop upon the first successful one it finds.

Upon completion of the check (pass or fail), the `message()` command will repeat the message from the most recent `CHECK_START` and then "forget" that message. Output from nested checks then works intuitively with minimal effort. When combined with appropriate indenting using `CMAKE_MESSAGE_INDENT`, the readability and consistency of the output is particularly good.

```
# Functions just to demonstrate pass/fail behavior
function(checkSomething resultVar)
    set(${resultVar} YES PARENT_SCOPE)
endfunction()

function(checkSomethingElse resultVar)
    set(${resultVar} NO PARENT_SCOPE)
endfunction()

# Outer check starts here
message(CHECK_START "Checking things")
list(APPEND CMAKE_MESSAGE_INDENT " ")

# Inner check 1
message(CHECK_START "Checking support for something")
checkSomething(successVar1)
if(successVar1)
    message(CHECK_PASS "supported")
else()
    message(CHECK_FAIL "not supported")
endif()

# Inner check 2
```

```

message(CHECK_START "Checking support for something else")
checkSomethingElse(successVar2)
if(successVar2)
    message(CHECK_PASS "supported")
else()
    message(CHECK_FAIL "not supported")
endif()

# Outer check finishes here
list(POP_BACK CMAKE_MESSAGE_INDENT)
if(successVar1 OR successVar2)
    message(CHECK_PASS "ok")
else()
    message(CHECK_FAIL "failed")
endif()

```

Output from the above would contain lines like the following:

```

-- Checking things
--   Checking support for something
--     Checking support for something - supported
--     Checking support for something else
--       Checking support for something else - not supported
--   Checking things - ok

```

Starting with CMake 3.26, internal messages from various checks are recorded in a central "configure log". This is a file in YAML format intended to be readable by both humans and automated tooling. The file's name and location may change with future CMake versions, but at least for now, it can be found at `<buildDir>/CMakeFiles/CMakeConfigureLog.yaml`. In most cases, developers shouldn't need to know about this file, but it can be used to help investigate problems when checks don't behave as expected. The `message()` command can write entries

to that log file using the form `message(CONFIGURE_LOG "...")`. This should rarely be needed and is only intended for cases where a project is implementing a special kind of check not based on `try_compile()` or `try_run()`. Consult the official documentation of the `message()` command for guidance on how and when to use this special form.

14.2. Color Diagnostics

Some compilers support showing their warning and error messages with colored text. When the build output is long, or where custom tasks generate a lot of less interesting output, having warnings and errors shown in different colors helps draw attention to the more important information. This can be of great assistance to developers in their day-to-day work.

Colorized output is usually done by inserting ANSI formatting codes in the output. These codes are then interpreted by the consumer, applying the colorizing instructions they represent rather than showing the raw characters. The conventions for ANSI codes are very old and well-established, but they are not supported in all scenarios. Compilers that offer such functionality usually try to auto-detect whether the calling environment supports them, adding the ANSI codes only if safe to do so. Unfortunately, this auto-detection is frequently defeated by the way the compiler is invoked. Compiler output may be piped between processes, it may be buffered by the

build tool, or IDEs may capture the output and show it in a UI component. In scenarios like these, the compiler has no terminal to query for its capabilities, so color output will usually be disabled.

Compilers typically offer the ability to override the auto-detection, but the command line flags are compiler-specific. With CMake 3.24 or later, the `CMAKE_COLOR_DIAGNOSTICS` variable can be set to specify the behavior in a compiler-independent way. Setting this variable to true will enable color output for compilers that support it, while setting it to false will disable color output (useful if the compiler's auto-detection incorrectly decides that color output is supported). If the variable is not set, the compiler's auto-detection will be used, matching the behavior of CMake 3.23 and older.

If the `CMAKE_COLOR_DIAGNOSTICS` variable is undefined the first time CMake is run in a build directory, it is initialized from the environment variable of the same name, if set. This is primarily intended for IDEs so they can turn on color diagnostics by default for CMake invocations they initiate.

The `CMAKE_COLOR_DIAGNOSTICS` variable may also enable colorized output of some build tools. It replaces the much older `CMAKE_COLOR_MAKEFILE` variable, which should no longer be needed. `CMAKE_COLOR_DIAGNOSTICS` is more general and controls color diagnostics for a broader range of tools.

14.3. Print Helpers

The `CMakePrintHelpers` module provides two macros which make printing the values of properties and variables more convenient during development. They are not intended for permanent use, but are more aimed at helping developers quickly and easily log information temporarily to help investigate problems in the project.

```
cmake_print_properties(  
    [TARGETS target1 [target2...]]  
    [SOURCES source1 [source2...]]  
    [DIRECTORIES dir1 [dir2...]]  
    [TESTS test1 [test2...]]  
    [CACHE_ENTRIES var1 [var2...]]  
    PROPERTIES property1 [property2...]  
)
```

This command essentially combines `get_property()` with `message()` into a single call. Exactly one of the property types must be specified and each of the named properties will be printed for each entity listed. It is particularly convenient for logging values of multiple entities or properties.

```
add_executable(MyApp main.c)  
add_executable(MyAlias ALIAS MyApp)  
add_library(MyLib STATIC src.cpp)  
  
include(CMakePrintHelpers)  
cmake_print_properties(TARGETS MyApp MyLib MyAlias  
    PROPERTIES TYPE ALIASED_TARGET  
)
```

```
Properties for TARGET MyApp:  
  MyApp.TYPE = "EXECUTABLE"  
  MyApp.ALIASED_TARGET = <NOTFOUND>  
Properties for TARGET MyLib:  
  MyLib.TYPE = "STATIC_LIBRARY"  
  MyLib.ALIASED_TARGET = <NOTFOUND>  
Properties for TARGET MyAlias:  
  MyAlias.TYPE = "EXECUTABLE"  
  MyAlias.ALIASED_TARGET = "MyApp"
```

The module also provides a similar function for logging the value of one or more variables:

```
cmake_print_variables(var1 [var2...])
```

This works for all variables regardless of whether they have been explicitly set by the project, are automatically set by CMake, or have not been set at all.

```
set(foo "My variable")  
unset(bar)  
  
include(CMakePrintHelpers)  
cmake_print_variables(foo bar CMAKE_VERSION)
```

```
foo="My variable" ; bar="" ; CMAKE_VERSION="3.8.2"
```

14.4. Tracing Variable Access

Another mechanism provided for debugging variable use is the `variable_watch()` command. This is intended for more complex projects where it may not be clear how a variable ended up

with a particular value. When a variable is watched, all attempts to read or modify it are logged.

```
variable_watch(myVar [command])
```

For the vast majority of cases, listing the variable to be watched without the optional command is sufficient, as it logs all accesses to the nominated variable. For a more customized degree of control, a command can be given which will be executed every time the variable is read or modified. The command is expected to be the name of a CMake function or macro, which will receive a number of arguments (detailed in the CMake documentation for the `variable_watch()` command). The following example shows how such a command can be defined and used to only log changes to a variable, ignoring any read-only accesses:

```
function(watchChanges varName access value file listFileStack)
    if(access MATCHES "MODIFIED")
        message(NOTICE
            "Watched variable: ${varName}\n"
            "  value: '${value}'\n"
            "  accessed from file: '${file}'\n"
            "  list file stack: ${listFileStack}"
        )
    endif()
endfunction()

variable_watch(someVar watchChanges)
```

In practice, specifying a command with `variable_watch()` would be very uncommon. The default message is usually enough to

help diagnose the situations where `variable_watch()` is typically used. The default message also contains more detail in the call stack than is available in the last argument passed to a custom watcher command.

14.5. Debugging Generator Expressions

Generator expressions can quickly become complicated, making it difficult to confirm their correctness. Because they are only evaluated at generation time, their results are not available during the configure stage and therefore cannot be printed using the `message()` command.

One way to debug the value of a generator expression is to use the `file(GENERATE)` command, which is covered in [Section 21.3, “Reading And Writing Files Directly”](#). The generator expression can be written to a temporary file and inspected when CMake finishes execution. For example:

```
add_executable(someTarget ...)  
target_include_directories(someTarget ...)  
  
set(incDirs  
    ${TARGET_PROPERTY:someTarget,INCLUDE_DIRECTORIES}  
)  
set(genex "-I${JOIN:${incDirs}, -I}")  
  
file(GENERATE OUTPUT genex.txt CONTENT "${genex}\n")
```

Another approach is to create a temporary custom build target whose command prints the value of the generator expression

(see [Section 20.1, “Custom Targets”](#)). Building that target then prints the result of the expression.

```
add_custom_target(printGenex
    COMMENT "Result of generator expression:"
    COMMAND ${CMAKE_COMMAND} -E echo "${genex}"
    VERBATIM
)
```

Building that target and some representative output might look like this:

```
cmake --build . --target printGenex
[1/1] Result of generator expression:
-I/some/path -I/some/other/path
```

This technique is especially useful for configuration-specific generator expressions and when using multi-config generators like Xcode, Visual Studio, and Ninja Multi-Config:

```
set(genex "$<IF:$<CONFIG:Debug>,is debug,not debug>")

add_custom_target(printGenex
    COMMENT "Result of generator expression:"
    COMMAND ${CMAKE_COMMAND} -E echo "${genex}"
    VERBATIM
)
```

For multi-configuration generators, the configuration can be specified with the build command:

```
cmake --build . --target printGenex --config Release
[1/1] Result of generator expression:
not debug
```

```
cmake --build . --target printGenex --config Debug  
[1/1] Result of generator expression:  
is debug
```

14.6. Profiling CMake Calls

CMake 3.18 added the ability to profile CMake's own processing of a project. For large, complicated projects where the configure stage takes a long time, this can provide valuable insights into where time is being spent. When profiling is enabled, every CMake command invocation is recorded in the profiling output.

Both of the following command line options need to be provided on the `cmake` command line to enable profiling:

`--profiling-format=fmt`

This specifies the format of the profiling data. Currently, the only supported value for `fmt` is `google-trace`.

`--profiling-output=fileName`

The profiling data will be written to the specified `fileName`. The `google-trace` format is written as JSON, so use a `.json` file extension to make it easier to find and load the file into tools that understand the format.

For the `google-trace` format, the output file can be loaded directly into a web browser (<https://ui.perfetto.dev>) or some IDEs (e.g. CLion, Qt Creator). Some Chrome-based browsers also provide a legacy viewer using the URL `about:tracing`.



The profiling results often show calls like `try_compile()` and `execute_process()` as consuming the majority of the execution time. Rather than focusing on those two calls specifically, inspect the call stacks that led up to those commands. There may be opportunities for reducing how often these two commands are called by avoiding unnecessary or overly pessimistic logic higher in the call stack.

14.7. Discarding Previous Results

When trying to track down unexpected behavior in the CMake logic of a project, a recommended debugging step is to discard any cached results from an existing build directory and then confirm whether the problem still persists. For small projects, deleting the whole build directory is often the easiest way to achieve that. For very large projects, the loss of all the compiled object files and other build artifacts may be unacceptable. A more surgical approach may be needed to remove a smaller subset of the files and directories.

The `CMakeCache.txt` file in the top of the build directory is the primary place where information is cached. In some scenarios,

the developer may need to delete this file so that cached information is recomputed, or manual changes discarded. Examples where the file should be removed include:

- A dependency may have been updated or removed.
- A cache variable the developer added or modified temporarily might no longer be needed and the defaults should be used instead.
- The compiler or other tools associated with the toolchain might have been updated or changed.
- The developer wants to switch to a different CMake generator.

If anything about the toolchain changes, the `CMakeFiles` directory should also be removed. This is where CMake caches toolchain information after performing various checks on the first run.

With CMake 3.24 or later, the `--fresh` option can be passed on the `cmake` command line. This option tells CMake to delete both the `CMakeCache.txt` file and the `CMakeFiles` directory. It is mostly a convenience for developers, with the added advantage that the details of where CMake caches things don't need to be remembered. The same functionality has also been available in the CMake GUI application for much earlier CMake versions. It can be found in the **File** menu as the **Delete Cache...** action.

14.8. Interactive Debugging

CMake 3.27 added support for connecting CMake's configuration step to a debugger using the standard Debug Adapter Protocol. This feature is aimed at IDEs, which can provide an interactive debugging experience similar to traditional debuggers for languages like C and C++. Such debuggers can step through a project's `CMakeLists.txt` file as it is processed during the configure step. Variables and properties are available, breakpoints can be set, and so on.

As this is a relatively new CMake feature, it will take some time for IDEs to develop and stabilize their support for it. There are already some IDEs with initial support, but one should expect gaps in functionality and bugs until that support matures.

Note that interactive CMake debugging only covers the configure phase of CMake. It cannot do things like evaluate generator expressions, since those can only be reliably expanded once the configure phase has been completed. See [Section 14.5, “Debugging Generator Expressions”](#) for techniques covering those scenarios.

14.9. Recommended Practices

A common problem with many projects is that they log an excessive amount of output during the configure step. This tends to train users to ignore the output, which in turn means

that important messages and warnings are easily missed. When the output is fairly minimal and a warning does occur, users tend to take note and investigate the cause. Therefore, aim to minimize the amount of output at the STATUS log level, saving more detailed output for a log level of VERBOSE or lower. If supporting CMake versions older than 3.15 where log levels below STATUS are not available, consider putting detailed logging behind a project-specific cache option, which should be off by default.

For log messages intended to remain as part of the build, aim to always specify a log level as the first argument to the `message()` command. If the message is of a general informational nature, prefer to use STATUS rather than no keyword at all so that message output does not appear out of order in the build log. Temporary debugging messages frequently omit specifying a log level for convenience, but if they are likely to remain part of the project for any length of time, it is better that they too specify a log level.

For non-trivial projects, consider adding message context information to allow users to filter log output and focus on just those messages that are of interest to them. Never discard existing contents of the `CMAKE_MESSAGE_CONTEXT` variable, always use `list(APPEND)` when starting a new message context. If the message context should end before the end of the current variable scope, use `list(POP_BACK)`. Make no assumptions about

what the variable contains other than that this append / pop back pattern can be used. Consider appending the project name as a message context immediately before the first `project()` call in the top level `CMakeLists.txt` file so that compiler feature checks also have a message context.

In a similar manner, also consider using the `CMAKE_MESSAGE_INDENT` variable to provide some logical structure to the message output. Prefer to append two spaces for an indent. While other indents are permitted, following this convention will make the output more consistent, especially in hierarchical projects that make use of external dependencies. Use `list(APPEND)` to add to the existing indent, never replace or discard the existing contents of the `CMAKE_MESSAGE_INDENT` variable. If required, `list(POP_BACK)` can be used to reduce the indent again before the end of the current variable scope.

Both the `CMAKE_MESSAGE_CONTEXT` and `CMAKE_MESSAGE_INDENT` variables can be populated by the project regardless of the minimum supported CMake version. When using an earlier CMake version that doesn't know about these variables, it will simply ignore them and the output will be unaffected. Therefore, consider using these features even if the project needs to support earlier CMake versions. Note that the `list(POP_BACK)` command requires CMake 3.15 or later, so if the project needs to support versions earlier than that, it must use alternative commands to achieve the same effect where that is

needed. But in most cases, a new message context or indentation level will apply through to the end of the current variable scope, so popping the last value from the end of the list variable won't be necessary.

Consider using the `CHECK_START`, `CHECK_PASS`, and `CHECK_FAIL` form of the `message()` command to record details of checks. This reduces duplication of messages and provides improved readability. It is especially effective when used in conjunction with the indenting support provided by the `CMAKE_MESSAGE_INDENT` variable.

If the configure stage of a project takes a long time to complete, consider running `cmake` with the `--profiling-output` and `--profiling-format` options to investigate where the time is being spent. Available with CMake 3.18 or later, these options enable the generation of command-level profiling information, which can be viewed with tools like Perfetto (<https://ui.perfetto.dev>), the Chrome web browser, or IDEs like Qt Creator and CLion.

[Section 34.6, “Debugging `find_...\(\)` Calls”](#) also discusses further debugging features added in CMake 3.17 and later. Those features relate to finding files, packages, and other things, which is covered in detail in [Chapter 34, *Finding Things*](#).

15. BUILD TYPE

This chapter and the next cover two closely related topics. The build type (also known as the build configuration or build scheme in some IDE tools) is a high level control that selects different sets of compiler and linker behavior. Manipulation of the build type is the subject of this chapter, while the next chapter presents more specific details for controlling compiler and linker options. Together, these chapters cover material every CMake developer will typically use for all but the most trivial projects.

15.1. Build Type Basics

The build type has the potential to affect almost everything about the build in one way or another. While it primarily has a direct effect on the compiler and linker behavior, it also affects the directory structure used for a project. This can in turn influence how a developer sets up their own local development environment, so the effects of the build type can be quite far-reaching.

Developers commonly think of builds as being one of two arrangements: debug or release. For a debug build, compiler flags are used to enable the recording of information that debuggers can use to associate machine instructions with the source code. Optimizations are frequently disabled in such builds so that the mapping from machine instruction to source code location is direct and easy to follow when stepping through program execution. A release build, on the other hand, generally has full optimizations enabled and no debug information generated.

These are examples of what CMake refers to as the *build type*. While projects are able to define whatever build types they want, the default build types provided by CMake are usually good enough for most projects:

Debug

With no optimizations and full debug information, this is commonly used during development and debugging, as it typically gives the fastest build times and the best interactive debugging experience.

Release

This build type typically provides full optimizations for speed and no debug information, although some platforms may still generate debug symbols in certain circumstances. It

is generally the build type used when building software for final production releases.

RelWithDebInfo

This is somewhat of a compromise of the previous two. It aims to give performance close to a Release build, but still allow some level of debugging. Most optimizations for speed are typically applied, but most debug functionality is also enabled. This build type is therefore most useful when the performance of a Debug build is not acceptable even for a debugging session. Note that the default settings for RelWithDebInfo will disable assertions.

MinSizeRel

This build type is typically only used for constrained resource environments such as embedded devices. The code is optimized for size rather than speed, and no debug information is created.

Each build type results in a different set of compiler and linker flags. It may also change other behaviors, such as altering which source files get compiled or what libraries to link to. These details are covered in the next few sections. But before launching into those discussions, it is essential to understand how to select the build type and how to avoid some common problems.

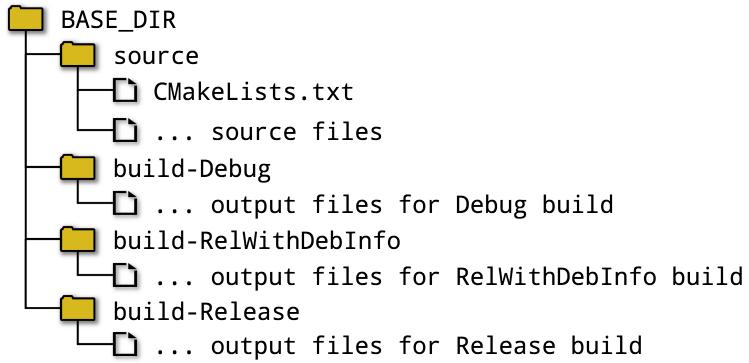
15.1.1. Single Configuration Generators

Back in [Section 2.3, “Generating Project Files”](#), the different types of project generators were introduced. Some, like Makefiles and Ninja, support only a single build type per build directory. For these generators, the build type is chosen by setting the `CMAKE_BUILD_TYPE` cache variable. For example, to configure and then build a project with Ninja, one might use commands like this:

```
cmake -G Ninja -DCMAKE_BUILD_TYPE:STRING=Debug -B build  
cmake --build build
```

The `CMAKE_BUILD_TYPE` cache variable can also be changed in the CMake GUI application instead of from the command line, but the end effect is the same. With CMake 3.22 or later, if the `CMAKE_BUILD_TYPE` cache variable is not set, it will be initialized from the `CMAKE_BUILD_TYPE` environment variable (if defined).

Rather than switching between different build types in the same build directory, an alternative strategy is to set up separate build directories for each build type, all still using the same sources. Such a directory structure might look something like this:



If frequently switching between build types, this arrangement avoids having to constantly recompile the same sources just because compiler flags change. It also allows a single-configuration generator to effectively act like a multi-configuration generator. IDE environments like Qt Creator support switching between build directories just as easily as Xcode or Visual Studio allow switching between build schemes or configurations.

15.1.2. Multiple Configuration Generators

Some generators, notably Xcode and Visual Studio, support multiple configurations in a single build directory. From CMake 3.17, the Ninja Multi-Config generator is also available. These multi-config generators ignore the `CMAKE_BUILD_TYPE` cache variable and instead require the developer to choose the build type within the IDE or with a command line option at build time. Configuring and building such projects would typically look something like this:

```

cmake -G Xcode -B build
cmake --build build --config Debug

```

When building within the Xcode IDE, the build type is controlled by the build scheme, while within the Visual Studio IDE, the current solution configuration controls the build type. Both environments keep separate directories for the different build types, so switching between builds doesn't cause constant rebuilds. In effect, the same thing is being done as the multiple build directory arrangement described above for single-configuration generators, it's just that the IDE is handling the directory structure on the developer's behalf.

For command-line builds, the Ninja Multi-Config generator has a little more flexibility compared to the other multi-config generators. The `CMAKE_DEFAULT_BUILD_TYPE` cache variable can be used to change the default configuration to use when no configuration is specified on the build command line. The Xcode and Visual Studio generators have their own fixed logic for determining the default configuration in this scenario. The Ninja Multi-Config generator also supports advanced features that allow custom commands to execute as one configuration, but other targets to be built with one or more other configurations. Most projects would not typically need or benefit from these more advanced features, but the CMake documentation for the Ninja Multi-Config generator provides the essential details, with examples.

15.2. Common Errors

Note how for single-configuration generators, the build type is specified at *configure* time, whereas for multi-configuration generators, the build type is specified at *build* time. This distinction is critical, as it means the build type is not always known when CMake is processing a project's `CMakeLists.txt` file. Consider the following piece of CMake code, which unfortunately is rather common, but demonstrates an incorrect pattern:

```
# WARNING: Do not do this!
if(CMAKE_BUILD_TYPE STREQUAL "Debug")
    add_compile_definitions(MYPROJ_DEBUG)    ①
endif()
```

① See [Section 16.4, “Directory Properties And Commands”](#) for an explanation of the `add_compile_definitions()` command.

The above would work fine for Makefile-based generators and Ninja, but not for Xcode, Visual Studio, or Ninja Multi-Config. In practice, just about any logic based on `CMAKE_BUILD_TYPE` within a project is questionable, unless it is protected by a check to confirm a single-configuration generator is being used. For multi-configuration generators, this variable is likely to be empty, and even if it isn't, its value should be considered unreliable because the build will ignore it. Rather than referring to `CMAKE_BUILD_TYPE` in the `CMakeLists.txt` file, projects should instead use other more robust alternative techniques, such as generator expressions based on `$<CONFIG:...>`. The

following shows a more robust way of implementing the previous example:

```
add_compile_definitions($<$<CONFIG:Debug>:MYPROJ_DEBUG>)
```

When scripting builds, another common deficiency is to assume a particular CMake generator is used, or to not properly account for differences between single- and multi-configuration generators. Developers should ideally be able to change the generator in one place, and the rest of the script should still function correctly. Conveniently, single-configuration generators will ignore any build-time specification, and multi-configuration generators will ignore the `CMAKE_BUILD_TYPE` variable, so by specifying both, a script can account for both cases. For example:

```
cmake -G Ninja -DCMAKE_BUILD_TYPE=Release -B build  
cmake --build build --config Release
```

With the above example, a developer could change the generator name given to the `-G` parameter and the rest of the script would work unchanged.

Not explicitly setting the `CMAKE_BUILD_TYPE` for single-configuration generators is also common, but usually not what the developer intended. A behavior unique to single-configuration generators is that if `CMAKE_BUILD_TYPE` is not set, the build type will usually be empty. This can lead to the

misunderstanding that an empty build type is equivalent to Debug, but this is not so. An empty build type is its own unique, nameless build type. In such cases, no configuration-specific compiler or linker flags are used, which often results in invoking the compiler and linker with minimal flags. The behavior is then determined by the compiler's and linker's own defaults. While this may often be similar to the Debug build type's behavior, it is by no means guaranteed.

Using the Visual Studio compilers with a single-configuration generator is somewhat of a special case. For that toolchain, there are different runtime libraries for debug and non-debug builds. An empty build type would make it unclear which runtime should be used. To avoid this ambiguity, the build type will default to Debug for this combination.

15.3. Custom Build Types

Sometimes a project may want to limit the set of build types to a subset of the defaults, or it may want to add other custom build types with a special set of compiler and linker flags. A good example of the latter is adding a build type for profiling or code coverage, both of which require specific compiler and linker settings.

There are two main places where a developer may see the set of build types. When using IDE environments for multi-configuration generators like Xcode and Visual Studio, the IDE

provides a drop-down list or similar from which the developer selects the configuration they wish to build. For single-configuration generators like Makefiles or Ninja, the build type is entered directly for the `CMAKE_BUILD_TYPE` cache variable, but the CMake GUI application can be made to present a combo box of valid choices instead of a simple text edit field. The mechanisms behind these two cases are different, so they must be handled separately.

The set of build types known to multi-configuration generators is controlled by the `CMAKE_CONFIGURATION_TYPES` cache variable, or more accurately, by the value of this variable at the end of processing the top level `CMakeLists.txt` file. The first encountered `project()` command populates the cache variable if it has not already been defined. With CMake 3.22 or later, a `CMAKE_CONFIGURATION_TYPES` environment variable can provide the default value. If that environment variable isn't set, or an earlier CMake version is used, the default value will be (possibly a subset of) the four standard configurations mentioned in [Section 15.1, “Build Type Basics”](#) (Debug, Release, `RelWithDebInfo`, and `MinSizeRel`).

Projects may modify the `CMAKE_CONFIGURATION_TYPES` variable after the first `project()` command, but only in the top level `CMakeLists.txt` file. Some CMake generators rely on this variable having a consistent value throughout the whole project. Custom build types can be defined by adding them to

`CMAKE_CONFIGURATION_TYPES`, and unwanted build types can be removed from that list. Note that only the non-cache variable should be modified, as changing the cache variable may discard changes made by the developer.

Care needs to be taken to avoid setting `CMAKE_CONFIGURATION_TYPES` if it is not already defined. Prior to CMake 3.9, a very common approach for determining whether a multi-configuration generator was being used was to check if `CMAKE_CONFIGURATION_TYPES` was non-empty. Even parts of CMake itself did this prior to 3.11. While this method is usually accurate, it is not unusual to see projects unilaterally set `CMAKE_CONFIGURATION_TYPES` even if using a single-configuration generator. This can lead to wrong decisions being made regarding the type of generator in use. To address this, CMake 3.9 added a new `GENERATOR_IS_MULTI_CONFIG` global property which is set to true when a multi-configuration generator is being used. This provides a definitive way to obtain that information instead of relying on inferring it from `CMAKE_CONFIGURATION_TYPES`. Even so, checking `CMAKE_CONFIGURATION_TYPES` is still a relatively common pattern among older projects, so only modify the variable if it exists, and never create it otherwise.

It should also be noted that prior to CMake 3.11, adding custom build types to `CMAKE_CONFIGURATION_TYPES` was not safe. Certain parts of CMake only accounted for the default build types.

However, projects may still be able to usefully define custom build types with earlier CMake versions, depending on how they are going to be used. That said, for better robustness, it is recommended that at least CMake 3.11 be used if custom build types are going to be defined.

Another aspect of this issue is that developers may add their own types to the `CMAKE_CONFIGURATION_TYPES` cache variable, or remove those they are not interested in. Projects should therefore not make any assumptions about what configuration types are or are not defined.

Taking the above points into account, the following pattern shows the preferred way for projects to add their own custom build types for multi-configuration generators:

```
cmake_minimum_required(3.11)
project(Foo)

# Only make changes if we are the top level project
if(CMAKE_SOURCE_DIR STREQUAL CMAKE_CURRENT_SOURCE_DIR)
    get_property(isMultiConfig GLOBAL
        PROPERTY GENERATOR_IS_MULTI_CONFIG
    )
    if(isMultiConfig)
        if(NOT "Profile" IN_LIST CMAKE_CONFIGURATION_TYPES)
            list(APPEND CMAKE_CONFIGURATION_TYPES Profile)
        endif()
    endif()
    # Set Profile-specific flag variables as needed...
endif()
```

For single-configuration generators, there is only one build type. This is specified by the `CMAKE_BUILD_TYPE` cache variable, which is a string. In the CMake GUI, this is normally presented as a text edit field, so the developer can edit it to contain whatever arbitrary content they wish. As discussed back in [Section 10.6, “Cache Variable Properties”](#), cache variables can have their `STRINGS` property defined to hold a set of valid values. The CMake GUI application will then present that variable as a combo box containing the valid values instead of as a text edit field.

```
set_property(CACHE CMAKE_BUILD_TYPE PROPERTY
    STRINGS Debug Release Profile
)
```

Properties can only be changed from within the project’s `CMakeLists.txt` files, so they can safely set the `STRINGS` property without having to worry about preserving any developer changes. But note that setting the `STRINGS` property of a cache variable does not guarantee that the cache variable will hold one of the defined values, it only controls how the variable is presented in the CMake GUI application. Developers can still set `CMAKE_BUILD_TYPE` to any value at the `cmake` command line or edit the `CMakeCache.txt` file manually.

Projects should not generally try to restrict the developer to a set of hard-coded choices for the build type. The developer may want to define their own build type with custom flags. As a

special case, a project might want to require a non-empty build type for single-configuration generators, since such a choice will normally not give the developer what they expected. This is most easily handled by setting `CMAKE_BUILD_TYPE` as a cache variable before the first `project()` command using a non-empty default value.

Putting together the above techniques for multi- and single-configuration generators, the final result would look something like this:

```
cmake_minimum_required(3.11)

# Ensure non-empty default build type for single-config
get_property(isMultiConfig GLOBAL
    PROPERTY GENERATOR_IS_MULTI_CONFIG
)
if(NOT isMultiConfig)
    set(CMAKE_BUILD_TYPE Debug CACHE STRING "Build type")
endif()

project(Foo)

# Only modify config details if the top level project
if(CMAKE_SOURCE_DIR STREQUAL CMAKE_CURRENT_SOURCE_DIR)
    if(NOT isMultiConfig)
        set_property(CACHE CMAKE_BUILD_TYPE PROPERTY
            STRINGS Debug Release Profile
        )
    elseif(NOT "Profile" IN_LIST CMAKE_CONFIGURATION_TYPES)
        list(APPEND CMAKE_CONFIGURATION_TYPES Profile)
    endif()
endif()

# Set Profile-specific flag variables (see below)...
endif()
```

The above techniques enable *Selecting* a custom build type, but they don't *define* anything about that build type. Selecting a build type specifies which configuration-specific variables to use. It also affects any generator expressions whose logic depends on the current configuration (`$<CONFIG>` and `$<CONFIG:...>`). These variables and generator expressions are discussed in [Section 16.6, “Compiler And Linker Variables”](#) and in [Section 24.3, “Tool Selection”](#). For now, the following families of variables are of primary interest.

- `CMAKE_<LANG>_FLAGS_<CONFIG>`
- `CMAKE_<TARGETTYPE>_LINKER_FLAGS_<CONFIG>`

The flags specified in these variables are added to the default set provided by the same-named variables without the `_<CONFIG>` suffix. A custom Profile build type might be defined like so:

```
set(CMAKE_C_FLAGS_PROFILE           "-fprofile-generate")
set(CMAKE_CXX_FLAGS_PROFILE         "-fprofile-generate")
set(CMAKE_EXE_LINKER_FLAGS_PROFILE  "-fprofile-generate")
set(CMAKE_SHARED_LINKER_FLAGS_PROFILE "-fprofile-generate")
set(CMAKE_STATIC_LINKER_FLAGS_PROFILE "")
set(CMAKE_MODULE_LINKER_FLAGS_PROFILE "-fprofile-generate")
```

The above assumes a GCC-compatible compiler to keep the example simple. It turns on profiling as well as enabling debugging symbols and most optimizations. An alternative is to base the compiler and linker flags on one of the default build

types and add the extra flags needed. This can be done as long as it comes after the `project()` command, since that command populates the default compiler and linker flag variables. For profiling, the `RelWithDebInfo` default build type is a good choice for the base configuration, since it enables both debugging and most optimizations:

```
set(CMAKE_C_FLAGS_PROFILE
    "${CMAKE_C_FLAGS_RELWITHDEBINFO} -p"
)
set(CMAKE_CXX_FLAGS_PROFILE
    "${CMAKE_CXX_FLAGS_RELWITHDEBINFO} -p"
)
set(CMAKE_EXE_LINKER_FLAGS_PROFILE
    "${CMAKE_EXE_LINKER_FLAGS_RELWITHDEBINFO} -p"
)
set(CMAKE_SHARED_LINKER_FLAGS_PROFILE
    "${CMAKE_SHARED_LINKER_FLAGS_RELWITHDEBINFO} -p"
)
set(CMAKE_STATIC_LINKER_FLAGS_PROFILE
    "${CMAKE_STATIC_LINKER_FLAGS_RELWITHDEBINFO}"
)
set(CMAKE_MODULE_LINKER_FLAGS_PROFILE
    "${CMAKE_MODULE_LINKER_FLAGS_RELWITHDEBINFO} -p"
)
```

Each custom configuration should have the associated compiler and linker flag variables defined. For some multi-configuration generator types, CMake will check that the required variables exist and will fail with an error if they are not set.

Defining a custom build type in the project's `CMakeLists.txt` file has its drawbacks. By hard-coding the compiler and linker flags,

the developer is unable to override them without modifying the project. Using cache variables instead of regular non-cache variables may seem like a good solution, but projects cannot implement this robustly for all scenarios. Better alternatives would be to define the cache variables in CMake presets or toolchain files, both of which the developer has full control over. See [Chapter 42, Presets](#) and [Section 24.1, “Toolchain Files”](#) for discussion of these features.

Another variable which may sometimes be defined for a custom build type is `CMAKE_<CONFIG>_POSTFIX`. It is used to initialize the `<CONFIG>_POSTFIX` property of each library target, with its value being appended to the file name of such targets when built for the specified configuration. This allows libraries from multiple build types to be put in the same directory without overwriting each other. `CMAKE_DEBUG_POSTFIX` is often set to values like `d` or `_debug`, especially for Visual Studio builds where different runtime DLLs must be used for Debug and non-Debug builds. Packages may need to include libraries for both build types if they want their consumers to be able to build both Debug and non-Debug configurations.

In the case of the custom Profile build type defined above, an example of a suitable postfix would be:

```
set(CMAKE_PROFILE_POSTFIX _profile)
```

If creating packages that contain multiple build types, setting `CMAKE_<CONFIG>_POSTFIX` for each build type is highly recommended. By convention, the postfix for Release builds is typically empty. Note though that the `<CONFIG>_POSTFIX` target property is ignored on Apple platforms.

For historical reasons, the items passed to the `target_link_libraries()` command can be prefixed with the `debug` or `optimized` keywords to indicate that the named item should only be linked in for debug or non-debug builds respectively. A build type is considered to be a debug build if it is listed in the `DEBUG_CONFIGURATIONS` global property, otherwise it is considered to be optimized. For custom build types, they should have their name added to this global property if they should be treated as a debug build in this scenario. As an example, if a project defines its own custom build type called `StrictChecker`, and that build type should be considered a non-optimized debug build type, it can (and should) make this clear like so:

```
set_property(GLOBAL APPEND PROPERTY
    DEBUG_CONFIGURATIONS StrictChecker
)
```

New projects should normally prefer to use generator expressions instead of the `debug` and `optimized` keywords with the `target_link_libraries()` command. The next chapter discusses this area in more detail.

15.4. Recommended Practices

Developers should not assume a particular CMake generator is being used to build their project. Another developer on the same project may prefer to use a different generator because it integrates better with their IDE tool. Or a future version of CMake may add support for a new generator type which might bring other benefits. Certain build tools may contain bugs which a project may later be affected by, so it can be useful to have alternative generators to fall back on until such bugs are fixed. Expanding a project's set of supported platforms can also be hindered if a particular CMake generator has been assumed.

When using single-configuration generators like Makefiles or Ninja, consider using multiple build directories, one for each build type of interest. This allows switching between build types without forcing a complete recompile each time. This provides similar behavior to that inherently offered by multi-configuration generators, and it can be a useful way to enable IDE tools like Qt Creator to simulate multi-configuration functionality.

For single-configuration generators, consider setting `CMAKE_BUILD_TYPE` to a better default value if it is empty. While an empty build type is technically valid, it is also often misunderstood by developers to mean a Debug build rather than its own distinct build type. Furthermore, avoid creating logic based on `CMAKE_BUILD_TYPE` unless it is first confirmed that

a single-configuration generator is being used. Even then, such logic is likely to be fragile and could probably be better expressed with more generality and robustness using generator expressions like `$<CONFIG:...>` and `$<CONFIG>`.

Only consider modifying the `CMAKE_CONFIGURATION_TYPES` variable if it is known that a multi-configuration generator is being used, or if the variable already exists. If adding a custom build type or removing one of the default build types, do not modify the cache variable. Instead, change the regular variable of the same name, which will take precedence over the cache variable. Also, when modifying one of the default build types, prefer to add and remove individual items rather than completely replacing the list. These measures will help avoid interfering with changes made to the cache variable by the developer. Only make such changes in the top level `CMakeLists.txt` file.

If requiring CMake 3.9 or later, use the `GENERATOR_IS_MULTI_CONFIG` global property to definitively query the generator type instead of relying on the existence of `CMAKE_CONFIGURATION_TYPES` to perform a less robust check.

A common but incorrect practice is to query the `LOCATION` target property to work out a target's output file name. A related error is to assume a particular build output directory structure in custom commands (see [Chapter 20, *Custom Tasks*](#)). These

methods do not work for all build types, since LOCATION is not known at configure time for multi-configuration generators, and the build output directory structure is typically different across the various CMake generator types. Generator expressions like `$<TARGET_FILE:...>` should be used instead, as they robustly provide the required path for all generators, both single- and multi-configuration.

16. COMPILER AND LINKER ESSENTIALS

The previous chapter discussed the build type and how it relates to selecting a particular set of compiler and linker behavior. This chapter discusses the fundamentals of how that compiler and linker behavior is controlled. The material presented here covers some of the most important topics and techniques with which every CMake developer should become familiar.

As CMake has evolved, the available methods for controlling the compiler and linker behavior have also improved. The focus has shifted from a more build-global view to one where the requirements of each individual target can be controlled, along with how those requirements should or should not be applied to other targets that depend on it. This is an important shift in thinking, as it affects how a project can most effectively define the way targets should be built. CMake's more mature features can be used to control behavior at a coarse level, at the expense of losing the ability to define relationships between targets. The more recent target-focused features should be preferred

instead, since they greatly improve the robustness of the build and offer much more precise control over compiler and linker behavior. The newer features also tend to be more consistent in their behavior and the way they are meant to be used.

16.1. Target Properties

Within CMake’s property system, the target properties form the primary mechanism by which compiler and linker flags are controlled. Some properties provide the ability to specify any arbitrary flag, whereas others focus on a specific capability so they can abstract away platform or compiler differences. This chapter focuses on the more commonly used and general purpose properties, with later chapters covering a number of the more specific ones.

It should be noted that the target properties discussed in the following sections are not usually modified directly. CMake provides dedicated commands which are generally more convenient and more robust than direct property manipulation. [Section 16.2, “Target Property Commands”](#) discusses those commands in detail, with examples. However, an awareness of the underlying properties involved will help with understanding the features and restrictions of those commands.

16.1.1. Compiler Flags

The most fundamental target properties for controlling compiler flags are the following, each of which hold a list of items:

INCLUDE_DIRECTORIES

This is a list of directories to be used as header search paths, all of which must be absolute paths. CMake will add a compiler flag for each path with an appropriate prefix prepended (typically `-I` or `/I`). When a target is created, the initial value of this target property is taken from the directory property of the same name.

COMPILE_DEFINITIONS

This holds a list of definitions to be set on the compile command line. A definition has the form `VAR` or `VAR=VALUE`, which CMake will convert to the appropriate form for the compiler being used (typically `-DVAR...` or `/DVAR...`). When a target is created, the initial value of this target property will be empty. There is a directory property of the same name, but it is *not* used to provide an initial value for this target property. Rather, the directory and target properties are *combined* in the final compiler command line.

COMPILE_OPTIONS

Any compiler flags that are neither header search paths nor symbol definitions are provided in this property. When a target is created, the initial value of this target property is

taken from the directory property of the same name. Note that this property is also subject to de-duplication (see [Section 16.5, “De-duplicating Options”](#) for further details).



An older and now deprecated target property with the name `COMPILE_FLAGS` used to serve a similar purpose as `COMPILE_OPTIONS`. The `COMPILE_FLAGS` property is treated as a single string included directly on the compiler command line. As a result, it may require manual escaping, whereas `COMPILE_OPTIONS` is a list and CMake performs any required escaping or quoting automatically.

The `INCLUDE_DIRECTORIES` and `COMPILE_DEFINITIONS` properties are really just conveniences, taking care of the compiler-specific flags for the most common things projects often want to set. All remaining compiler-specific flags are then provided in the `COMPILE_OPTIONS` property.

The three target properties above have related target properties of the same name with `INTERFACE_` prepended. These interface properties do the same thing as their non-`INTERFACE` counterparts, except instead of applying to the target itself, they apply to targets that link directly to it. In other words, they specify compiler flags that *consuming* targets inherit. For this reason, they are often referred to as *usage requirements*, in contrast to the non-`INTERFACE` properties which are sometimes called *build requirements*. Two special library types `IMPORTED`

and INTERFACE are discussed later in [Chapter 19, Target Types](#). These special library types support only the INTERFACE_... target properties and not the non-INTERFACE_... properties. [Section 16.8.2, “System Header Search Paths”](#) discusses additional functionality related to how INTERFACE_INCLUDE_DIRECTORIES is used.

Unlike their non-interface counterparts, none of the above INTERFACE_... properties are initialized from directory properties. Instead, they all start out empty, since only the project has knowledge of what header search paths, defines, and compiler flags should propagate to consuming targets.

All the above target properties except COMPILE_FLAGS support generator expressions. Generator expressions are particularly useful for the COMPILE_OPTIONS property, since they enable adding a particular flag only if some condition is met, such as only for one particular compiler or language. Generator expressions are also frequently used with INTERFACE_INCLUDE_DIRECTORIES to control how information propagates to consumers (see [Section 16.3.1, “Building, Installing, And Exporting”](#)).

If compiler flags need to be manipulated at the individual source file level, target properties are not granular enough. For such cases, CMake provides the COMPILE_DEFINITIONS, COMPILE_FLAGS, and COMPILE_OPTIONS source file properties (the

`COMPILE_OPTIONS` source file property was only added in CMake 3.11). These are each analogous to their same-named target properties except that they apply only to the specific source file on which they are set. Note that their support for generator expressions has lagged behind that of the target properties, with the `COMPILE_DEFINITIONS` source file property gaining generator expression support in CMake 3.8 and the others in 3.11. Furthermore, the Xcode project file format does not support configuration-specific source file properties at all, so if targeting Apple platforms, `$<CONFIG>` or `$<CONFIG:...>` should not be used in source file properties. Also keep in mind the warnings discussed back in [Section 10.5, “Source Properties”](#) regarding implementation details leading to performance issues when source file properties are used.

16.1.2. Linker Flags

The target properties associated with linker flags have similarities to those for compiler flags, but some were only added in more recent CMake versions. CMake 3.13, in particular, added a number of improvements for linker control. Also note that only some of the linker-related properties have an associated interface property and that not all properties support generator expressions.

`LINK_LIBRARIES`

This target property holds a list of all libraries the target should link to directly. It is initially empty when the target is created, and it supports generator expressions. An associated interface property `INTERFACE_LINK_LIBRARIES` is supported. Each library listed can be one of the following:

- A path to a library, usually specified as an absolute path.
- Just the library name without a path, usually also without any platform-specific file name prefix (e.g. `lib`) or suffix (e.g. `.a`, `.so`, `.dll`).
- The name of a CMake library target. CMake will convert this to a path to the built library when generating the linker command, including supplying any prefix or suffix to the file name as appropriate for the platform. Because CMake handles all the various platform differences and paths on the project's behalf, using a CMake target name is generally the preferred method.

CMake will use the appropriate linker flags to link each item listed in the `LINK_LIBRARIES` property. In some circumstances, linker flags may also be present in this property, but the other target properties below are generally preferred for holding such options.

`LINK_OPTIONS`

Support for this property was added in CMake 3.13. It holds a list of flags to be passed to the linker for targets that are

executables, shared libraries, or module libraries. It is ignored for targets being built as a static library. This property is intended for general linker flags, not those flags which specify other libraries to link to. When a target is created, the initial value of this target property is taken from the `directory` property of the same name. Generator expressions are supported, and the property is also subject to de-duplication (see [Section 16.5, “De-duplicating Options”](#) for further details).

An associated interface property `INTERFACE_LINK_OPTIONS` is also supported. Note that the contents of this interface property will be applied to consuming targets even if the target on which `INTERFACE_LINK_OPTIONS` is set is a static library. This is because the interface property is specifying linker flags that the *consumer* should use, so the type of the library being consumed is not a factor.

`LINK_FLAGS`

This property serves a similar purpose to `LINK_OPTIONS`, but there are a number of differences. The first key difference is that it holds a single string that will be placed directly on the linker command line rather than a list of linker flags. Another difference is that it does not support generator expressions. Furthermore, there is no associated interface property and it is initialized to an empty value when the target is created. In general, `LINK_OPTIONS` is more robust and

offers a broader set of features, so only use `LINK_FLAGS` if CMake versions earlier than 3.13 must be supported.

`STATIC_LIBRARY_OPTIONS`

This is the counterpart to `LINK_OPTIONS`. It only has meaning for targets being built as a static library, and it will be used for the librarian or archiver tool. It holds a list of options, generator expressions are supported, and it is subject to de-duplication (see [Section 16.5, “De-duplicating Options”](#)). Like `LINK_OPTIONS`, support for `STATIC_LIBRARY_OPTIONS` was only added in CMake 3.13, but note that there is no associated interface property. A target cannot dictate librarian/archiver flags of its consumers, only linker flags (see the comments regarding `INTERFACE_LINK_OPTIONS` above).

`STATIC_LIBRARY_FLAGS`

This is the counterpart to `LINK_FLAGS` and should only be used if CMake versions earlier than 3.13 must be supported. It is a single string rather than a list, and it does not support generator expressions. There is no associated interface property.

In some older projects, one may occasionally encounter a target property named `LINK_INTERFACE_LIBRARIES`, which is an older version of `INTERFACE_LINK_LIBRARIES`. This older property has been deprecated since CMake 2.8.12, but policy `CMP0022` can be

used to give the old property precedence if needed. New projects should prefer to use INTERFACE_LINK_LIBRARIES instead.

The LINK_FLAGS and STATIC_LIBRARY_FLAGS properties do not support generator expressions, but they do have related configuration-specific properties:

- LINK_FLAGS_<CONFIG>
- STATIC_LIBRARY_FLAGS_<CONFIG>

These flags will be used in addition to the non-configuration-specific flags when the <CONFIG> matches the configuration being built. These should only be used if the project must support CMake versions earlier than 3.13. For 3.13 or later, prefer to use LINK_OPTIONS and STATIC_LIBRARY_OPTIONS, and express configuration-specific content using generator expressions.

One of the difficulties of passing flags to the linker is that the linker is usually invoked via the compiler front end, and each compiler has its own syntax for how to pass through linker options. For example, invoking the ld linker via gcc requires specifying linker flags using the form -Wl,..., whereas clang expects the form -Xlinker With CMake 3.13 or later, this difference can be handled automatically by adding a LINKER: prefix to each linker flag in the LINK_OPTIONS and INTERFACE_LINK_OPTIONS properties (CMake 4.0 extended support

for LINKER: to LINK_LIBRARIES and INTERFACE_LINK_LIBRARIES as well). This will result in the linker flag being transformed into the required form for the compiler front end being used. For example:

```
set_property(TARGET Algo APPEND PROPERTY
    LINK_OPTIONS LINKER:-stats
)
```

Using the `gcc` compiler, this would add `-Wl,-stats`, whereas with `clang` it would add `-Xlinker -stats`.

With CMake 4.0 or later, a similar feature is available for the STATIC_LIBRARY_OPTIONS target property. An ARCHIVER: prefix can be used to pass options to the underlying archiver tool without having to deal with the toolchain-specific way it is invoked. This is similar to what the LINKER: prefix does in LINK_OPTIONS. The use of LINKER: is relatively common, but projects should rarely need to use an ARCHIVER: prefix.

Both LINKER: and ARCHIVER: are subject to de-duplication. See [Section 16.5, “De-duplicating Options”](#) for an important discussion of this topic.

16.1.3. Sources

The sources associated with a target follow a similar pattern to the compiler and linker flags. A SOURCES property lists all sources for a target that will be considered for compilation. This

includes not just files like `.cpp` or `.c` files, it may also include headers, resources, and other files for which no compilation should be performed. It may seem of limited use to list files as sources if they won't be compiled, but there are situations where it is desirable. If any files are generated by the build, having them listed as sources makes them dependencies of the target and ensures the files are generated when the target is built. This is especially useful for generated headers (see [Section 20.3, “Commands That Generate Files”](#)). Listing non-compiled files as sources is also a common technique for making them show up in file lists of some IDE tools.

A target's `INTERFACE_SOURCES` property lists sources to be added to consumers of that target. In practice, it would be very unusual for any file in this property to be a compilable source. The more typical use case is for listing headers of an interface library (see [Section 19.2.4, “Interface Libraries”](#)). Another potential use case might be to add resources that need to be part of the same translation unit to work, but such situations are uncommon.

Both `SOURCES` and `INTERFACE_SOURCES` support generator expressions. Common examples of their use include specifying sources that should only be compiled for certain configurations, platforms, or compilers. Another common example is the `$<TARGET_OBJECTS:targetName>` generator expression. Before CMake's support for object libraries matured (see [Section 19.2.2,](#)

“Object Libraries”), it was not possible to link directly to an object library. Instead, the project had to add that object library’s objects directly to the consuming target’s SOURCES property using `$<TARGET_OBJECTS:objectLib>`. With CMake 3.14 or later, this is no longer necessary and can be robustly handled by linking directly to the object library instead.

16.2. Target Property Commands

As mentioned earlier, the target properties discussed in this chapter so far are not normally manipulated directly. CMake provides dedicated commands for modifying them in a more convenient and robust manner. These commands also encourage clear specification of dependencies and transitive behavior between targets.

16.2.1. Linking Libraries

Back in [Section 4.3, “Linking Targets”](#), the `target_link_libraries()` command was presented, along with an explanation of how inter-target dependencies are expressed using PRIVATE, PUBLIC, and INTERFACE specifications. That earlier discussion focused on the dependency relationships between targets, but following the discussion of target properties earlier in this chapter, the exact effects of those keywords can now be made more precise.

```
target_link_libraries(targetName  
    <PRIVATE|PUBLIC|INTERFACE> item1 [item2 ...]
```

```
[<PRIVATE|PUBLIC|INTERFACE> item3 [item4 ...]]  
...  
)
```

PRIVATE

Items listed after PRIVATE affect the behavior of `targetName` itself. The items are added to the `LINK_LIBRARIES` target property. Additional behavior applies if `targetName` is a STATIC or OBJECT library, which is discussed further below.

INTERFACE

This is the complement to PRIVATE, with items following the INTERFACE keyword being added to the target's `INTERFACE_LINK_LIBRARIES` property. Any target that links to `targetName` will have these items applied to them as though the items were listed in their own `LINK_LIBRARIES` property.

PUBLIC

This is equivalent to combining the effects of PRIVATE and INTERFACE.

Developers will probably find the explanation in [Section 4.3, “Linking Targets”](#) more intuitive, but the above more precise description explains how the behavior is ultimately implemented under the covers. The above also happens to map very closely to the behavior of other `target_...()` commands that manipulate compiler and linker flags. In fact, they all follow the

same pattern and apply the PRIVATE, PUBLIC, and INTERFACE keywords in the same way.

The effects of the target_link_libraries() command can be more involved than the above basic explanation though. Consider the following example:

```
# Uncomment only one of these and see the difference
add_library(Algo STATIC ...)
#add_library(Algo OBJECT ...)
#add_library(Algo SHARED ...)

add_library(AlgoImpl ...)
add_library(Compute ...)
add_executable(MyApp ...)

target_link_libraries(Algo
    PUBLIC
        Compute
    PRIVATE
        AlgoImpl
)
target_link_libraries(MyApp
    PRIVATE
        Algo
)

include(CMakePrintHelpers)
cmake_print_properties(
    TARGETS Algo MyApp
    PROPERTIES LINK_LIBRARIES INTERFACE_LINK_LIBRARIES
)
```

The relationships expressed in the above example state that Algo uses AlgoImpl in a private way, meaning that consumers of Algo shouldn't need to know anything about AlgoImpl. However,

if Algo is a STATIC or OBJECT library, this isn't quite true. When linking MyApp, the linker will need to resolve symbols needed by Algo, and some of those will come from AlgoImpl. If Algo is a shared library, the linker would already have resolved those symbols when linking Algo itself. But if Algo is STATIC or OBJECT, that responsibility is transferred to the linking of Algo's consumers, which in this case is MyApp. The target_link_libraries() command handles this situation automatically, which can be seen by the output of the above example for the different cases:

With Algo as a STATIC or OBJECT library:

```
Properties for TARGET Algo:  
Algo.LINK_LIBRARIES = "Compute;AlgoImpl"  
AlgoINTERFACE_LINK_LIBRARIES = "Compute;$<LINK_ONLY:AlgoImpl>"  
Properties for TARGET MyApp:  
MyApp.LINK_LIBRARIES = "Algo"  
MyAppINTERFACE_LINK_LIBRARIES = <NOTFOUND>
```

With Algo as a SHARED library:

```
Properties for TARGET Algo:  
Algo.LINK_LIBRARIES = "Compute;AlgoImpl"  
AlgoINTERFACE_LINK_LIBRARIES = "Compute"  
Properties for TARGET MyApp:  
MyApp.LINK_LIBRARIES = "Algo"  
MyAppINTERFACE_LINK_LIBRARIES = <NOTFOUND>
```

When Algo is a STATIC or OBJECT library, target_link_libraries() adds \$<LINK_ONLY:AlgoImpl> to Algo's INTERFACE_LINK_LIBRARIES property. MyApp is a direct consumer of Algo, so MyApp will then

be linked to `AlgoImpl`. With `Algo` as a SHARED library, its `INTERFACE_LINK_LIBRARIES` property no longer mentions `AlgoImpl`, so `MyApp` will link to `Algo`, but not `AlgoImpl`. [Section 23.2, “Linking Static Libraries”](#) also discusses this and other related topics.

The subtle details of the above highlight one of the many reasons to prefer using the target-based commands instead of manipulating the target properties directly. The developer can focus on the relationships between targets and let CMake handle the complex implementation details.

For projects defining a target across multiple directories, older CMake versions have an important restriction. CMake 3.12 and earlier prohibited `target_link_libraries()` from operating on a target defined in a different directory. If a subdirectory needed to make the target link to something, it couldn’t do so from within that subdirectory. The call to `target_link_libraries()` had to be made in the same directory as the `add_executable()` or `add_library()` call. [Section 43.5.1, “Building Up A Target Across Directories”](#) discusses this restriction in more detail. CMake 3.13 removed this limitation.

16.2.2. Linker Options

CMake 3.13 added a dedicated command for specifying linker options. It enables projects to more clearly communicate the intent, and it populates more relevant target properties rather

than abusing `target_link_libraries()` and the `LINK_LIBRARIES` property.

```
target_link_options(targetName [BEFORE]
    <PRIVATE|PUBLIC|INTERFACE> item1 [item2 ...]
    [<PRIVATE|PUBLIC|INTERFACE> item3 [item4 ...]]
    ...
)
```

This populates the `LINK_OPTIONS` target property with the `PRIVATE` items, and the `INTERFACE_LINK_OPTIONS` target property with the `INTERFACE` items. `PUBLIC` items are added to both properties. The properties support generator expressions, so `target_link_options()` does too.

Each time `target_link_options()` is called, it appends the specified items to the relevant target properties. This makes it easy to add multiple options in a natural, progressive manner. If required, the `BEFORE` keyword can be used to prepend the listed options to existing contents of the target properties instead, but that should rarely be needed.

Since `target_link_options()` adds items to the `LINK_OPTIONS` and `INTERFACE_LINK_OPTIONS` properties, the command also supports items being prefixed with `LINKER:` to handle the compiler front end differences. The example in [Section 16.1.2, “Linker Flags”](#) can therefore be better implemented as:

```
target_link_options(Algo PRIVATE LINKER:-stats)
```

`target_link_options()` can be used even if `targetName` is a static library, but note that `PRIVATE` and `PUBLIC` items will populate `LINK_OPTIONS`, not `STATIC_LIBRARY_OPTIONS`. To populate `STATIC_LIBRARY_OPTIONS`, the only choice is to modify the target property directly with `set_property()` or `set_target_properties()`. Using `target_link_options()` to add `INTERFACE` items to a static library target may still be useful, since the contents of `INTERFACE_LINK_OPTIONS` are applied to the *consuming* target. But in practice, needing to modify any sort of linking options for a static library is rare.

16.2.3. Header Search Paths

A number of commands are available for managing a target's compiler-related properties. Adding directories to the compiler's header search path is one of the most common needs. With CMake 3.23 or later, file sets (discussed in [Section 16.2.7, “File Sets”](#) further below) are the recommended way to handle header search paths. For earlier CMake versions, or in situations where file sets are not appropriate, the `target_include_directories()` command can be used instead:

```
target_include_directories(targetName [AFTER|BEFORE] [SYSTEM]
    <PRIVATE|PUBLIC|INTERFACE> dir1 [dir2 ...]
    [<PRIVATE|PUBLIC|INTERFACE> dir3 [dir4 ...]]
    ...
)
```

The `target_include_directories()` command adds header search paths to the `INCLUDE_DIRECTORIES` and `INTERFACE_INCLUDE_DIRECTORIES` target properties. Directories following a `PRIVATE` keyword are added to the `INCLUDE_DIRECTORIES` target property. Directories following an `INTERFACE` keyword are added to the `INTERFACE_INCLUDE_DIRECTORIES` target property. Directories following a `PUBLIC` keyword are added to both the `INTERFACE` and non-`INTERFACE` properties. The `SYSTEM` keyword affects how these search paths are used and is discussed in [Section 16.8.2, “System Header Search Paths”](#).

The `BEFORE` keyword has the same effect as for `target_link_options()`. It causes the specified directories to be prepended to the relevant properties instead of appending. CMake 3.20 added support for the `AFTER` keyword for symmetry, but it doesn't need to be used since appending is the default behavior already.

Since the `target_include_directories()` command is basically just populating the relevant target properties, all the usual features of those properties apply. This means generator expressions can be used, a feature which becomes much more important when installing targets and creating packages. See [Section 16.3.1, “Building, Installing, And Exporting”](#) for discussion of specific generator expressions frequently used with this command and its underlying properties.

The `target_include_directories()` command offers another advantage over manipulating the target properties directly. Projects can specify relative directories too, not just absolute directories. Relative paths will be automatically converted to absolute, treating them as relative to the current source directory. If a path begins with a generator expression, it must expand to an absolute path, as the generator expression prevents automatic detection and conversion of relative paths.

```
add_executable(MyApp ...)

target_include_directories(MyApp
PRIVATE
    include                                # OK
    ${${MSVC}:include/msvc}                 # ERROR
    ${${CMAKE_CURRENT_SOURCE_DIR}/private}   # OK
)
```

In the above example, the first item is `include`, which is a relative path that does not contain any generator expressions. Therefore, `target_include_directories()` will automatically prepend `${CMAKE_CURRENT_SOURCE_DIR}/` before adding it to the `INCLUDE_DIRECTORIES` property of `MyApp`.

The second item will either evaluate to an empty string, which would be fine, or to a relative path if using the MSVC toolchain. Because the item starts with a generator expression, `${CMAKE_CURRENT_SOURCE_DIR}/` will not be automatically prepended. The `INCLUDE_DIRECTORIES` property would then end up containing a relative path, which would lead to a fatal error.

The third item also starts with a generator expression, but it evaluates to an absolute path because \${CMAKE_CURRENT_SOURCE_DIR}/ is explicitly given. No additional transformation is required.

16.2.4. Compiler Defines

Compiler defines for a target also have their own dedicated command, following the usual form:

```
target_compile_definitions(targetName
    <PRIVATE|PUBLIC|INTERFACE> item1 [item2 ...]
    [<PRIVATE|PUBLIC|INTERFACE> item3 [item4 ...]]
    ...
)
```

The `target_compile_definitions()` command is straightforward. Each item has the form VAR or VAR=VALUE. PRIVATE items populate the `COMPILE_DEFINITIONS` target property, INTERFACE items populate the `INTERFACE_COMPILE_DEFINITIONS` target property, and PUBLIC items populate both target properties. Generator expressions can be used.

```
target_compile_definitions(Algo
    PUBLIC
        $<$<CONFIG:Debug>:ALGO_DEBUG>
    PRIVATE
        STRATEGY=2
        ENABLE_SECRET_SAUCE
)
```

16.2.5. Compiler Options

Adding compiler options other than defines should be done with the `target_compile_options()` command. It follows the usual pattern with PRIVATE items populating the `COMPILE_OPTIONS` target property, INTERFACE items populate the `INTERFACE_COMPILE_OPTIONS` target property, and PUBLIC items populate both. Items are appended to existing target property values by default, but a BEFORE keyword is provided to prepend instead. Generator expressions are supported.

```
target_compile_options(targetName [BEFORE]
    <PRIVATE|PUBLIC|INTERFACE> item1 [item2 ...]
    [<PRIVATE|PUBLIC|INTERFACE> item3 [item4 ...]]
    ...
)
```

Compiler options are usually compiler-specific, and sometimes they are also language-specific. They should only be added for situations where they will be supported. It is usually clearer to use `if()` for such conditional logic, but some things can only be expressed with generator expressions. The following example uses `if()` to handle the compiler selection, but a generator expression is required to narrow the use of the option further to only C++ source compilation.

```
if(CMAKE_CXX_COMPILER_ID MATCHES "GNU|Clang")
    target_compile_options(Algo
        PRIVATE $<$<COMPILE_LANGUAGE:CXX>:-fconstexpr-depth=1024>
    )
endif()
```

16.2.6. Source Files

The most direct way of adding sources to a target is to list them in the `add_executable()` or `add_library()` call. This adds those files to the `SOURCES` property of the target. With CMake 3.1 or later, the `target_sources()` command can be used to add sources to a target after the target has been defined. This command works just like the other `target_...()` commands and supports the same familiar form ([Section 16.2.7, “File Sets”](#) also discusses a different form):

```
target_sources(targetName
    <PRIVATE|PUBLIC|INTERFACE> file1 [file2 ...]
    [<PRIVATE|PUBLIC|INTERFACE> file3 [file4 ...]]
    ...
)
```

`PRIVATE` sources are added to the `SOURCES` property, `INTERFACE` sources are added to the `INTERFACE_SOURCES` property, and `PUBLIC` sources are added to both properties. The more practical way of thinking of this is that `PRIVATE` sources are compiled into `targetName`, `INTERFACE` sources are added to anything that links to `targetName`, and `PUBLIC` sources are added to both. In practice, anything other than `PRIVATE` would be unusual. [Section 19.2.4, “Interface Libraries”](#) discusses scenarios where listing headers with `INTERFACE` may be justified if supporting CMake 3.18 or earlier.

```
add_executable(MyApp main.cpp)
if(WIN32)
```

```
    target_sources(MyApp PRIVATE eventloop_win.cpp)
else()
    target_sources(MyApp PRIVATE eventloop_generic.cpp)
endif()
```

A peculiarity of the `target_sources()` command prior to CMake 3.13 is that if a source is specified with a relative path, that path is assumed to be relative to the source directory of the target it is being added to. This creates a number of problems.

The first problem is that if a relative source was added with `INTERFACE`, the path would be treated as relative to the consuming target, not the target on which `target_sources()` was called. This could create incorrect paths, so any non-`PRIVATE` source would need to be specified with an absolute path.

The second problem is that relative paths behave non-intuitively when `target_sources()` is called from a directory other than the one in which the target was defined. Consider a modification of the previous example where platform-specific code is separated into different directories:

CMakeLists.txt

```
add_executable(MyApp main.cpp)
if(WIN32)
    add_subdirectory(windows)
else()
    add_subdirectory(generic)
endif()
```

windows/CMakeLists.txt

```
# WARNING: Wrong file paths with CMake 3.12 or earlier
target_sources(MyApp PRIVATE eventloop_win.cpp)
```

generic/CMakeLists.txt

```
# WARNING: Wrong file paths with CMake 3.12 or earlier
target_sources(MyApp PRIVATE eventloop_generic.cpp)
```

In the above example, the calls to `target_sources()` were intended to add sources from the windows or generic subdirectories. But with CMake 3.12 or earlier, they would be interpreted as being relative to the top level directory where the `MyApp` target was defined.

A robust way to address both of these problems is to prefix the files with `${CMAKE_CURRENT_SOURCE_DIR}` or `${CMAKE_CURRENT_LIST_DIR}` to ensure they always use the correct path:

windows/CMakeLists.txt

```
target_sources(MyApp PRIVATE
  ${CMAKE_CURRENT_LIST_DIR}/eventloop_win.cpp
)
```

Having to prefix each source file with `${CMAKE_CURRENT_SOURCE_DIR}` or `${CMAKE_CURRENT_LIST_DIR}` is inconvenient and not particularly intuitive. In recognition of this, the behavior was changed in CMake 3.13 to treat relative paths as being relative to `CMAKE_CURRENT_SOURCE_DIR` at the point where `target_sources()` is called, not the source directory in

which the target was defined. Policy CMP0076 provides backward compatibility for those projects that were relying on the old behavior. If at all possible, projects should set their minimum CMake version to 3.13 or higher and use the new CMP0076 policy behavior instead.

CMake 3.20 added the ability to use `target_sources()` to add sources to custom targets (discussed in detail in [Chapter 20, Custom Tasks](#)). With earlier CMake versions, sources could only be added to custom targets in the `add_custom_target()` call.

16.2.7. File Sets

CMake 3.23 introduced the concept of *file sets*. A file set is a group of files of a particular type, associated with a specific target. They provide additional details which can affect how those files are compiled, or how other sources and targets using those files might be treated. They can affect dependencies between files, compiler flags, install behavior, and more. File sets are defined using a different form of the `target_sources()` command:

```
target_sources(targetName
    <PRIVATE|PUBLIC|INTERFACE>
    FILE_SET setName
    [TYPE fileType]
    [BASE_DIRS dir1 [dir2...]]
    [FILES file1 [file2...]]
    ...
)
```

What differentiates this from the form presented earlier in [Section 16.2.6, “Source Files”](#) is the FILE_SET option, which follows immediately after the PRIVATE, PUBLIC, or INTERFACE keyword. The effects of the PRIVATE, PUBLIC, and INTERFACE keywords are more complex with this form and are discussed further below.

The type of files associated with the file set is given by the TYPE option. With CMake 3.23 to 3.27, the only valid type is HEADERS. The BASE_DIRS option (discussed below) is directly relevant to this type of file set. CMake 3.28 added support for the type CXX_MODULES. Files in a CXX_MODULES file set must be C++ sources, each of which should export an interface module or partition unit. The C++ standard for the target must also be set to 20 or higher for modules to be supported (see [Section 17.3, “Requirements For C++20 Modules”](#)). [Section 23.5.3, “Additional Complications With C++20 Modules”](#) and [Section 35.6, “Installing C++20 Modules”](#) also discuss important aspects of CMake’s support for C++20 modules.

The TYPE must always be given, except for the special case where the setName is the same as the type. If using a different set name, that name is not allowed to begin with a capital letter or underscore. Set names may only use letters, numbers, and underscores.

`BASE_DIRS` and `FILES` are closely related. All files must be located under one of the `BASE_DIRS`. No base directory is allowed to be a subdirectory of one of the other base directories in the set. This means every file has one relative path below exactly one base directory.



A common pattern with continuous integration systems is for the build directory to be a subdirectory of the source tree. If any file from the build directory is added to a file set, do not specify the top of the source tree as a base directory. Doing so would prevent any location in the build directory from being added as a base directory, since it would always be a subdirectory of another base directory.

Any relative path given to `BASE_DIRS` or `FILES` will be interpreted as being relative to `CMAKE_CURRENT_SOURCE_DIR`, unless it starts with a generator expression. It is advisable to ensure any such generator expression evaluates to an absolute path. If `BASE_DIRS` is omitted in the first `target_sources()` call for a given file set, `CMAKE_CURRENT_SOURCE_DIR` is automatically added to that file set as a base directory.

somewhere/CMakeLists.txt

```
target_sources(Colors
  PUBLIC
    FILE_SET HEADERS
    BASE_DIRS
      include
      ${CMAKE_CURRENT_BINARY_DIR}/include
```

```
)  
add_subdirectory(include/Colors)
```

somewhere/include/Colors/CMakeLists.txt

```
include(GenerateExportHeader)  
generate_export_header(Colors)  
  
target_sources(Colors  
    PUBLIC  
        FILE_SET HEADERS  
        FILES  
            colors.h  
            ${CMAKE_CURRENT_BINARY_DIR}/colors_export.h  
)
```

The above example demonstrates a common structure where headers from both the source and build directories are part of a target. The first call to `target_sources()` adds both base directories. The headers could also have been added in that call, but for this example, it is more convenient to generate the `colors_export.h` header down in the `include/Colors` subdirectory. See [Section 23.5.2, “Specifying Individual Symbol Visibilities”](#) for discussion of the `generate_export_header()` command.

For file sets of the `HEADERS` type, each base directory will be added to the header search path of the target, its consumers, or both. `PRIVATE` file sets add each base directory to the target’s `INCLUDE_DIRECTORIES` property, wrapped in a `$<BUILD_INTERFACE:>` generator expression (see [Section 16.3, “Target Property Contexts”](#) for what that expression does). `INTERFACE` file sets add

each base directory to the target's INTERFACE_INCLUDE_DIRECTORIES property instead, again wrapped in a \$<BUILD_INTERFACE:> generator expression. PUBLIC file sets populate both target properties. After a particular setName has been specified once, all subsequent calls to target_sources() for the same setName must use the same PRIVATE, PUBLIC, or INTERFACE keyword.

The example above takes full advantage of this header search path handling. The file set's base directories are automatically added as header search paths. This means target_include_directories() doesn't need to be called to explicitly add them. There are further advantages to using HEADERS file sets. They can be used to verify that headers are not missing #include statements, and they can simplify the installation of headers (see [Section 32.6, “File Sets Header Verification”](#) and [Section 35.5.1, “File Sets”](#) respectively).

One limitation of file sets is that they cannot be used with framework targets. CMake 3.23.1 and later issues a fatal error in such cases. A future CMake release may remove this constraint.

16.3. Target Property Contexts

Many target properties support generator expressions. Some expressions expand to different contents depending on the context in which they are evaluated. For example, some expand to non-empty contents when building, but not when installing,

or vice versa. Others expand to non-empty contents when compiling, but not when linking, or vice versa. These generator expressions are an important part of ensuring the right details are propagated to consumers.

16.3.1. Building, Installing, And Exporting

Most of the discussions so far have focused on the *build context*. Properties like `COMPILE_OPTIONS`, `COMPILE_DEFINITIONS`, and `INCLUDE_DIRECTORIES` affect the compiler command line used when compiling a target's sources. `INTERFACE_...` versions of those properties affect compiler command lines by propagating usage requirements to consumers of a target in the same build (the official CMake documentation sometimes uses the phrase "in the same build system"). An analogous situation exists for linker command lines with the `LINK_OPTIONS` and `LINK_LIBRARIES` properties.

Targets can also be installed for consumption by a separate build with the `install()` command (discussed in detail in [Section 35.2, “Installing Project Targets”](#)). Installing a project provides the built binaries and any supporting files, which can be used without access to the project's sources or build directory. A project may be installed directly, or the installation may be performed as part of producing packages with `cpack` (see [Chapter 36, Packaging](#)).

When installing, target details can be exported to a separate file, which defines imported targets representing the original targets the installed contents were created from (see [Section 35.3, “Installing Exports”](#)). These imported targets define INTERFACE_... properties that propagate details to consumers of the installation, just like what happens in the project’s own build. The generation of these exported targets during installation is referred to as the *install context*.

The \${<BUILD_INTERFACE:>} and \${<INSTALL_INTERFACE:>} generator expressions can be used in target properties to provide values for just the build or just the install context respectively. Consider the following example, which uses target_include_directories() instead of handling header search paths using file sets:

```
add_library(SomeFuncs STATIC ...)
target_include_directories(SomeFuncs
    PUBLIC
        ${CMAKE_CURRENT_BINARY_DIR}/somewhere
        ${MyProject_BINARY_DIR}/anotherDir
)
install(TARGETS SomeFuncs EXPORT Funcs DESTINATION ...)
install(EXPORT Funcs DESTINATION ...)
```

Within the build, anything linking to SomeFuncs will have the absolute paths to somewhere and anotherDir added to its header search path. When SomeFuncs is installed, it may be packaged up and deployed to another machine. Clearly the path to somewhere and anotherDir would no longer make sense, but the above

example would add them to consuming targets' header search path anyway. What is needed is a way to say "Use path xxx when building and path yyy when installing", which is exactly what the `$<BUILD_INTERFACE:>` and `$<INSTALL_INTERFACE:>` generator expressions do:

```
set(somewhere ${CMAKE_CURRENT_BINARY_DIR}/somewhere)
set(anotherDir ${MyProject_BINARY_DIR}/anotherDir)
target_include_directories(SomeFuncs
    PUBLIC
        $<BUILD_INTERFACE:${somewhere}>
        $<BUILD_INTERFACE:${anotherDir}>
        $<INSTALL_INTERFACE:include> # see below
)
```

`$<BUILD_INTERFACE:xxx>` will expand to xxx for the build context, and to nothing when installing. When used in a call to `target_include_directories()`, the expansion takes place after the check for relative paths, so the value must evaluate to an absolute path or CMake will issue an error.

`$<INSTALL_INTERFACE:yyy>` does the opposite, ensuring that yyy is added for the installed target, but not when building the target. In the install context, include directories are not required to be absolute paths. Instead, they are usually provided as relative paths, which are treated as being relative to the base install location. Typically, this relative path would be a directory called `include`, but it is not recommended to hard-code this directly, as done in the above example. [Section 35.1.1, “Relative Layout”](#) discusses variables that should be used instead to provide

greater flexibility, and [Section 35.2, “Installing Project Targets”](#) continues that discussion further.

Somewhat in between these two main scenarios lies a third case. A project can export target details for the current build directory without any installation. This is done with the `export()` command, which is discussed in [Section 35.3, “Installing Exports”](#). A separate project can then consume the exported targets and access them directly from the original build directory. All paths embedded in the exported information still refer to the original build directory, but the exported details otherwise look very similar to those provided when the project is installed.

Exporting a target directly from the build directory rather than as part of an install is considered to be part of both the build *and* install contexts. Thus, when generating the exported files in this case, both `$<BUILD_INTERFACE:zzz>` and `$<INSTALL_INTERFACE:zzz>` will expand to `zzz`. This isn’t always desirable though. A project may want to add flags that should only be used in the local build, but not when the target is exported and consumed by something outside the local build (e.g. special warning flags that shouldn’t be forced onto consumers outside the project). To support such scenarios, CMake 3.26 added support for the `$<BUILD_LOCAL_INTERFACE:zzz>` generator expression. It expands to nothing when generating the exported details, and to `zzz` when used directly in the same

build as the target. The following example demonstrates a commonly used pattern where such flags are collected in an interface library, and where that library shouldn't be exposed to anything outside the project.

```
add_library(SpecialFlags INTERFACE)
target_compile_options(SpecialFlags INTERFACE ...)

add_library(SomeFuncs STATIC ...)
target_link_libraries(SomeFuncs
PRIVATE
$<BUILD_LOCAL_INTERFACE:SpecialFlags>
)
```

In the local build of SomeFuncs, the target links to SpecialFlags and the special flags will be applied. However, when SomeFuncs is exported or installed, the \$<BUILD_LOCAL_INTERFACE:SpecialFlags> expression expands to nothing, so there will be no mention of SpecialFlags in the exported details. Since external consumers never see SpecialFlags, the SpecialFlags target does not need to be exported. Without \$<BUILD_LOCAL_INTERFACE:...>, SomeFuncs would be seen to link to SpecialFlags because SomeFuncs is a static library, and its PRIVATE dependencies are therefore treated as PUBLIC for the purpose of linking (see [Section 23.2, “Linking Static Libraries”](#) for an explanation of this behavior). Since SpecialFlags is now mentioned in the exported details of SomeFuncs, SpecialFlags is no longer hidden from consumers, so it would also need to be exported.

16.3.2. Compiling And Linking

CMake 3.27 and later supports an additional generator expression, `$<COMPILE_ONLY:...>`. This expression can be used to limit the propagation of linking dependencies to consumers. It would typically only be used in `LINK_LIBRARIES` or `INTERFACE_LINK_LIBRARIES` target properties, but in general should rarely be needed. It allows the linking requirements to be ignored (linker options), while still propagating compilation requirements (compiler definitions, options, and header search paths).

```
add_library(ExpensiveThing ...)
add_library(Algo ...)
target_link_libraries(Algo PUBLIC ExpensiveThing)

# It is known that SomeFuncs only uses parts of Algo that
# do not use ExpensiveThing in any way
add_library(SomeFuncs ...)
target_link_libraries(SomeFuncs
    PRIVATE $<COMPILE_ONLY:Algo>
)
```

The above example shows a situation where the developer knows that `SomeFuncs` only uses things from `Algo` headers which don't need anything else to be linked. Specifically, the headers used from `Algo` have fully inlined implementations (or at least the parts of the headers used by `SomeFuncs` are fully inlined), and those inlined implementations do not use `ExpensiveThing`. Therefore, `SomeFuncs` does not need to link to `Algo` or to `ExpensiveThing`. The use of `$<COMPILE_ONLY:...>` here means

`SomeFuncs` can be built without having to also build `Algo` or `ExpensiveThing`, even if the inlined implementations in the headers from `Algo` are being modified. This might significantly reduce the iteration time for the developer if `Algo` or `ExpensiveThing` takes a long time to build.

CMake 3.1 and later also offers a `$<LINK_ONLY:...>` generator expression, which is the logical counterpart to `$<COMPILE_ONLY:...>`. It is used where linking requirements from a target should be applied to the consumer, but compilation requirements should be ignored. Projects generally don't use `$<LINK_ONLY:...>` directly, but it is frequently used by CMake as part of linking or exporting static library targets. [Section 16.2.1, “Linking Libraries”](#) and [Section 23.2, “Linking Static Libraries”](#) both discuss the reason behind that behavior.

16.4. Directory Properties And Commands

With CMake 3.0 and later, target properties are strongly preferred for specifying compiler and linker flags due to their ability to define how they interact with targets that link to one another. In earlier versions of CMake, target properties were much less prominent and properties were often specified at the directory level instead. These directory properties and the commands used to manipulate them lack the consistency of their target-based equivalents, which is another reason projects should generally avoid them. That said, since many online

tutorials and examples still use them, developers should be aware of the directory level properties and commands.

```
include_directories([AFTER | BEFORE] [SYSTEM]
    dir1 [dir2...]
)
```

Simplistically, the `include_directories()` command adds header search paths to targets created in the current directory scope and below. By default, paths are appended to the existing list of directories, but that default can be changed by setting the `CMAKE_INCLUDE_DIRECTORIES_BEFORE` variable to true. It can also be controlled on a per-call basis with the `BEFORE` and `AFTER` options to explicitly direct how the paths for that call should be handled. Projects should be wary about setting `CMAKE_INCLUDE_DIRECTORIES_BEFORE`, as most developers will likely assume that the default behavior of directories being appended will apply. The effect of the `SYSTEM` keyword is discussed in [Section 16.8.2, “System Header Search Paths”](#).

The paths provided to `include_directories()` can be relative or absolute. Relative paths are converted to absolute paths automatically and are treated as relative to the current source directory. Paths may also contain generator expressions.

The details of what `include_directories()` actually does is more complex than the simplistic explanation above. Primarily, there are two main effects of calling `include_directories()`:

- The listed paths are added to the INCLUDE_DIRECTORIES directory property of the current CMakeLists.txt file. This means all targets created in the current directory and below will have the directories added to their INCLUDE_DIRECTORIES target property.
- Any target created in the current CMakeLists.txt file (or more accurately, the current directory scope) will also have the paths added to their INCLUDE_DIRECTORIES target property, even if those targets were created before the call to `include_directories()`. This applies strictly only to the targets created in the current CMakeLists.txt file or other files pulled in via `include()`, but not to any targets created in parent or child directory scopes.

It is the second of the above points that tends to surprise many developers. The following example demonstrates the behavior:

For illustration only, not good practice

```
# This target IS affected by the include_directories() call
add_library(Early ...)

# Targets defined within "first" are NOT affected
add_subdirectory(first)

include_directories(...)

# Targets defined from here onward ARE affected, including
# any defined in the "second" subdirectory
add_library(Later ...)
add_subdirectory(second)
```

To avoid creating situations that may lead to such confusion, if the `include_directories()` command must be used, prefer to call it early in a `CMakeLists.txt` file before any targets have been created or any subdirectories have been pulled in with `include()` or `add_subdirectory()`.

The `add_definitions()` and `remove_definitions()` commands add and remove entries in the `COMPILE_DEFINITIONS` directory property:

```
add_definitions(-DSomeSymbol /DAnotherThing=Value ...)  
remove_definitions(-DSomeSymbol /DAnotherThing=Value ...)
```

Each entry should begin with either `-D` or `/D`, the two most prevalent flag formats used by the vast majority of compilers. CMake strips off this flag prefix before the definition is stored in the `COMPILE_DEFINITIONS` directory property, so it doesn't matter which prefix is used, regardless of the compiler or platform on which the project is built.

Just as for `include_directories()`, these two commands affect all targets created in the current `CMakeLists.txt` file, even those created before the `add_definitions()` or `remove_definitions()` call. Targets created in child directory scopes will only be affected if created *after* the call. This is a direct consequence of how the `COMPILE_DEFINITIONS` directory property is used by CMake.

Although not recommended, it is also possible to specify compiler flags other than definitions with these commands. If CMake does not recognize an item as a compiler definition, it will be added to or removed from an internally tracked set of compiler options rather than the `COMPILE_DEFINITIONS` directory property. It still affects the compiler command line, but in a much less intuitive and less flexible way. This behavior is present for historical reasons, but new projects should avoid relying on it. See the `add_compile_options()` command a little further below for a better alternative.

Since the `COMPILE_DEFINITIONS` directory property supports generator expressions, so do these two commands, with some caveats. Generator expressions should only be used for the value part of a definition, not for the name part (i.e. only after the "`=`" in a `-DVAR=VALUE` item or not at all for a `-DVAR` item). This relates to how CMake parses each item to check if it is a compiler definition or not. Note also that these commands only modify the `COMPILE_DEFINITIONS` directory property, they do not affect the `COMPILE_DEFINITIONS` target property.

The `add_definitions()` command has a number of shortcomings. The requirement to prefix each item with `-D` or `/D` to have it treated as a definition is not consistent with other CMake behavior. The fact that omitting the prefix makes the command treat the item as a generic option instead is also counter-intuitive given the command's name. Furthermore, the

restriction on generator expressions only being supported for the VALUE part of a KEY=VALUE definition is also a direct consequence of the prefix requirement. In recognition of this, CMake 3.12 introduced the `add_compile_definitions()` command as a replacement for `add_definitions()`:

```
add_compile_definitions(SomeSymbol AnotherThing=Value ...)
```

The new command handles only compile definitions. It does not require any prefix on each item, and generator expressions can be used without the VALUE-only restriction. The new command's name and treatment of the definition items is consistent with the analogous `target_compile_definitions()` command. `add_compile_definitions()` still affects all targets created in the same directory scope, regardless of whether those targets are created before or after `add_compile_definitions()` is called. This is a characteristic of the underlying `COMPILE_DEFINITIONS` directory property the command manipulates, not of the command itself.

```
add_compile_options(opt1 [opt2 ...])
```

The `add_compile_options()` command is used to provide arbitrary compiler options. Unlike the `include_directories()`, `add_definitions()`, `remove_definitions()` and `add_compile_definitions()` commands, its behavior is very straightforward and predictable. Each option given to `add_compile_options()` is added to the `COMPILE_OPTIONS` directory

property. Every target subsequently created in the current directory scope and below will then inherit those options in their own `COMPILE_OPTIONS` target property. Any targets created before the call are not affected. This behavior is much closer to what developers would intuitively expect compared to the other directory property commands.

```
# Targets defined here before the call to
# add_compile_options() are NOT affected,
# including any defined in the "first" subdirectory
add_library(Early ...)
add_subdirectory(first)

add_compile_options(...)

# Targets defined from here onward ARE affected, including
# any defined in the "second" subdirectory
add_library(Later ...)
add_subdirectory(second)
```

Generator expressions are also supported by the underlying directory and target properties, so the `add_compile_options()` command also supports them. This is especially useful for applying a consistent set of potentially language-specific warning flags to the whole build, if supported ([Section 16.7, “Language-specific Compiler Flags”](#) discusses cases where it isn’t). Such situations can be common for company projects that must meet certain code quality or certification requirements.

```
add_compile_options(
    -Wall
    ${${COMPILER_LANGUAGE:CXX}:-Wnoexcept}
)
```

In early CMake versions, the next two commands were the primary way to tell CMake to link libraries into other targets, but they should now generally be avoided:

```
link_libraries(item1 [item2 ...]
    [ [debug | optimized | general] item] ...
)
link_directories( [ BEFORE | AFTER ] dir1 [dir2 ...])
```

These commands affect all targets created in the current directory scope and below after the commands are called, but any existing targets remain unaffected, similar to the behavior of `add_compile_options()`. The items specified in the `link_libraries()` command can be CMake targets, library names, full paths to libraries, or even linker flags. The `debug`, `optimized`, and `general` keywords are historical features that projects should no longer use. Generator expressions provide a more flexible and more consistent way to link configuration-specific items.

The directories added by `link_directories()` only have an effect when CMake is given a bare library name to link to. CMake adds the supplied paths to the linker command line and leaves the linker to find such libraries on its own. The directories given should be absolute paths, although relative paths were permitted prior to CMake 3.13 (see policy `CMP0081` which controls whether CMake halts with an error if a relative path is encountered). The `BEFORE` and `AFTER` keywords were added in

CMake 3.13 and have a similar effect as they do for `include_directories()`, including the default behavior being equivalent to `AFTER` if neither keyword is present.

For robustness reasons, if using `link_libraries()`, provide a full path or the name of a CMake target. No linker search directory is necessary for either of those cases, and the exact location of the library will be given to the linker. Once a linker search directory has been added by `link_directories()`, projects have no convenient way to remove that search path if they need to. Therefore, avoid linking a library in a way that requires a linker search directory to be added.

CMake 3.13 also introduced the `add_link_options()` command. It is analogous to the `target_link_options()` command, acting instead on a directory property rather than on target properties.

```
add_link_options(item1 [item2...])
```

This command appends items to the `LINK_OPTIONS` directory property, which is used to initialize the same-named target property of all targets subsequently created in the current directory scope and below. As with other directory level commands, `add_link_options()` should generally be avoided in favor of the target level command.

16.5. De-duplicating Options

When CMake constructs the final compiler and linker command lines, it performs a de-duplication step on the flags. This can greatly reduce the command line length, which has benefits for the implementation and for developers trying to understand the final set of options used. But in some cases, de-duplication will be undesirable. For example, an option might need to be repeated with different second arguments, such as passing multiple linker options with Clang:

```
# This won't work as expected
target_link_options(SomeTarget PRIVATE
    -Xlinker -z
    -Xlinker defs
)
```

After de-duplication, the second `-Xlinker` would be removed, resulting in the incorrect set of command line options `-Xlinker -z` `defs`. A similar case exists for the compiler:

```
# This won't work as expected either
target_compile_options(SomeTarget PRIVATE
    -Xassembler --keep
    -Xassembler --no_esc
)
```

CMake provides the `SHELL:` prefix as a way of preventing groups of options from being split up by de-duplication. It has been supported since CMake 3.12 for compiler options, and 3.13 for linker options. To force two or more options to be treated as a group that should not be split, they should be prefixed by `SHELL:`

and given as a single quoted string, with options separated by spaces.

```
target_link_options(SomeTarget PRIVATE
    "SHELL:-Xlinker -z"
    "SHELL:-Xlinker defs"
)
target_compile_options(SomeTarget PRIVATE
    "SHELL:-Xassembler --keep"
    "SHELL:-Xassembler --no_esc"
)
```

For linker options, the LINKER: prefix is expanded after de-duplication. It can also be combined with SHELL:. Either of the following would be equivalent:

```
target_link_options(SomeTarget PRIVATE
    "LINKER:-z,defs"
)
target_link_options(SomeTarget PRIVATE
    "LINKER:SHELL:-z defs"
)
```

When using Clang, "LINKER:-z,defs" and "LINKER:SHELL:-z defs" both expand to -Xlinker -z -Xlinker defs. The -Xlinker part is not de-duplicated.

The SHELL:, LINKER:, and ARCHIVER: prefixes all operate at the target property level. This means they can be used with any of the commands that manipulate the relevant target properties. LINKER: is supported by LINK_OPTIONS and INTERFACE_LINK_OPTIONS, and also by LINK_LIBRARIES and

INTERFACE_LINK_LIBRARIES since CMake 4.0. The ARCHIVER: prefix is similar to LINKER:, except it is only supported by the STATIC_LIBRARY_OPTIONS property. All of these properties also support SHELL:. The COMPILE_OPTIONS and INTERFACE_COMPILE_OPTIONS target properties only support SHELL:. Since all of these target properties are initialized from directory properties of the same names, those directory properties can also use the prefixes.

16.6. Compiler And Linker Variables

Properties are the main way that projects should seek to influence compiler and linker flags. End users cannot manipulate properties directly, so the project is in full control of how the properties are set. There are situations, however, where the user will want to add their own compiler or linker flags. They may wish to add more warning options, turn on special compiler features such as sanitizers or debugging switches, and so on. For these situations, variables are more appropriate.

CMake provides a set of variables that specify compiler and linker flags to be merged with those provided by the various directory, target, and source file properties. They are normally cache variables to allow the developer to easily view and modify them. CMake gives the cache variables suitable default values the first time it runs in a build directory, and the project

should not normally set or modify them. They are intended primarily as developer controls.

The primary variables directly affecting the compiler flags have the form `CMAKE_<LANG>_FLAGS` and `CMAKE_<LANG>_FLAGS_<CONFIG>`. `<LANG>` corresponds to the language being compiled, with typical values being C, CXX, Fortran, Swift, and so on. The `<CONFIG>` part is an uppercase string corresponding to one of the build types, such as DEBUG, RELEASE, RELWITHDEBINFO, or MINSIZEREL.

`CMAKE_<LANG>_FLAGS` will be applied to all build types, including single configuration generators with an empty `CMAKE_BUILD_TYPE`. `CMAKE_<LANG>_FLAGS_<CONFIG>` is only applied to the build type specified by `<CONFIG>`. Thus, a C++ file being built with a Debug configuration would have compiler flags from both `CMAKE_CXX_FLAGS` and `CMAKE_CXX_FLAGS_DEBUG`.

The first `project()` command encountered will create cache variables for these if they don't already exist (this is a bit of a simplification, a more complete explanation is given in [Chapter 24, Toolchains And Cross Compiling](#)). Therefore, after the first time CMake has been run, their values are easy to check in the CMake GUI application. As an example, for one particular compiler, the following variables for the C++ language are defined by default:

`CMAKE_CXX_FLAGS`

CMAKE_CXX_FLAGS_DEBUG	-g -O0
CMAKE_CXX_FLAGS_RELEASE	-O3 -DNDEBUG
CMAKE_CXX_FLAGS_RELWITHDEBINFO	-O2 -g -DNDEBUG
CMAKE_CXX_FLAGS_MINSIZEREL	-Os -DNDEBUG

The handling of linker flags is similar. They are controlled by the `CMAKE_<TARGETTYPE>_LINKER_FLAGS` and `CMAKE_<TARGETTYPE>_LINKER_FLAGS_<CONFIG>` family of variables. These are specific to a particular type of target, each of which was introduced back in [Chapter 4, Building Simple Targets](#). The `<TARGETTYPE>` part of the variable name must be one of the following:

EXE

Targets created with `add_executable()`.

SHARED

Targets created with `add_library(name SHARED ...)` or equivalent, such as omitting the `SHARED` keyword but with the `BUILD_SHARED_LIBS` variable set to true.

STATIC

Targets created with `add_library(name STATIC ...)` or equivalent, such as omitting the `STATIC` keyword but with the `BUILD_SHARED_LIBS` variable set to false or not defined.

MODULE

Targets created with `add_library(name MODULE ...)`.

Just like for the compiler flags, the `CMAKE_<TARGETTYPE>_LINKER_FLAGS` are used when linking any build configuration, whereas the `CMAKE_<TARGETTYPE>_LINKER_FLAGS_<CONFIG>` flags are only added for the corresponding `CONFIG`. It is common on some platforms for some or all of the linker flags to be empty strings.

CMake tutorials and example code frequently use the above variables to control the compiler and linker flags. This was fairly common practice in the CMake 2.x era, but with the focus shifting to a target-centric model with CMake 3.0 and later, such examples are no longer a good model to follow. They often lead to a number of common mistakes, with some of the more prevalent ones presented below.

16.6.1. Compiler And Linker Variables Are Single Strings, Not Lists

If multiple compiler flags need to be set, they need to be specified as a single string, not as a list. CMake will not properly handle flag variables if their contents contain semicolons, which is what a list would be turned into if specified by the project.

```

# Wrong, list used instead of a string
set(CMAKE_CXX_FLAGS -Wall -Wextra)

# Correct, but see later sections for why appending
# would be preferred
set(CMAKE_CXX_FLAGS "-Wall -Wextra")

# Appending to existing flags the correct way
# (two methods)
set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -Wall -Wextra")
string(APPEND CMAKE_CXX_FLAGS " -Wall -Wextra")

```

16.6.2. Distinguish Between Cache And Non-cache Variables

All the variables mentioned above are *cache* variables. Non-cache variables of the same name can be defined, and they will override the cache variables for the current directory scope and its children (i.e. those created by `add_subdirectory()`). But problems can arise when a project tries to force updating the cache variable instead of a local variable. Code like the following tends to make projects harder to work with. It can lead to developers feeling like they are fighting the project when they want to change flags for their own build through the CMake GUI application or with `-D` options on a `cmake` command line:

```

# Case 1: Only has an effect if the variable isn't
#         already in the cache
set(CMAKE_CXX_FLAGS "-Wall -Wextra"
    CACHE STRING "C++ flags"
)

```

```
# Case 2: Using FORCE to always update the cache
#           variable, but this overwrites any changes
#           a developer might make to the cache
set(CMAKE_CXX_FLAGS "-Wall -Wextra"
    CACHE STRING "C++ flags" FORCE
)

# Case 3: FORCE + append = recipe for disaster
#           (see discussion below)
set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -Wall -Wextra"
    CACHE STRING "C++ flags" FORCE
)
```

The first case above highlights a common oversight made by developers new to CMake. Without the `FORCE` keyword, the `set()` command only updates a cache variable if it is not already defined. The first run of CMake may appear to do what the developer intended (if placed before any `project()` command), but if the line is ever changed to specify something else for the flags, that change won't be applied to an existing build because the variable will already be in the cache.

The usual reaction to discovering this is to then use `FORCE` to ensure the cache variable is always updated, as shown in the second case, but this then creates another problem. The cache is a primary means for developers to change variables locally without having to edit project files. If a project uses `FORCE` to unilaterally set cache variables in this manner, any change made by the developer to that cache variable will be lost.

The third case is even more problematic because every time CMake is run, the flags will be appended again, leading to an ever growing and repeating set of flags. Using FORCE to update the cache like this for compiler and linker flags is rarely a good idea.

Rather than simply removing the FORCE keyword, the correct behavior is to set a non-cache variable rather than the cache variable. It is then safe to append flags to the current value because the cache variable is left untouched. Every CMake run will start with the same set of flags from the cache variable, regardless of how often CMake is invoked. Any changes the developer chooses to make to the cache variable will also be preserved.

```
# Preserves the cache variable contents, appends new
# flags safely
set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -Wall -Wextra")
```

16.6.3. Prefer Appending Over Replacing Flags

As touched on above, developers are sometimes tempted to unilaterally set compiler flags in their `CMakeLists.txt` files like so:

```
# Not ideal, discards any developer settings from cache
set(CMAKE_CXX_FLAGS "-Wall -Wextra")
```

Because this discards any value set by the cache variable, developers lose their ability to easily inject their own flags. This forces developers to go hunting through the project to find and modify the offending lines. For a complex project with many subdirectories, this can be tedious. Where possible, in situations where these variables must be manipulated, prefer to append flags to the existing value.

One reasonable exception to this guideline may be if a project is required to enforce a mandated set of compiler or linker flags. In such cases, a workable compromise may be to set the variable values in the top level `CMakeLists.txt` file as early as possible, ideally at the very top just after the `cmake_minimum_required()` command (or even better, in the toolchain file if one is being used - see [Chapter 24, Toolchains And Cross Compiling](#) for further details). Keep in mind though that over time, the project may itself become a child of another project. At that point, it would no longer be the top level of the build, and the suitability of this compromise may be reduced.

16.6.4. Understand When Variable Values Are Used

One of the more obscure aspects of the compiler and linker flag variables is the point in the build process at which their value actually gets used. One might reasonably expect the following code to behave as noted in the inline comments:

```
# Save the original set of flags so we can
# restore them later
set(oldCxxFlags "${CMAKE_CXX_FLAGS}")

# This library has stringent build requirements, so
# enforce them just for it alone.
# WARNING: This doesn't do what it may appear to do!
set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -Wall -Wextra")
add_library(StrictReq STATIC ...)

# Less strict requirements from here, so restore the
# original set of compiler flags
set(CMAKE_CXX_FLAGS "${oldCxxFlags}")
add_library(RelaxedReq STATIC ...)
```

It may be surprising to learn that with the arrangement above, the `StrictReq` library will *not* be built with `-Wall -Wextra` flags. Intuitively, one may expect that the variable's value at the time of the call to `add_library()` is what CMake uses, but in fact it is the variable's value at the end of processing for that directory scope that gets used. In other words, what matters is the value the variable holds at the end of the `CMakeLists.txt` file for that directory. This can lead to unexpected results in a variety of situations for the unaware.

A common way developers get caught by this behavior is by treating compiler and linker variables as though they are applied to targets as they are created. Another related trap is when an `include()` is used after targets have been created and the included file(s) modify the compiler or linker variables. This alters the compiler and linker flags for targets already defined

in the current directory scope. This delayed nature of compiler and linker variables makes them fragile to work with. If a project must modify these variables, it should ideally only modify them early in the top level CMakeLists.txt file. This minimizes opportunities for misuse and developer surprise.

16.7. Language-specific Compiler Flags

There are limitations to be aware of when it comes to setting compiler flags that should only apply for specific languages. It is possible to set language-specific compiler flags for a particular target using generator expressions, as the following example shows (for simplicity, the compiler is assumed to support the -fno-exceptions option):

```
target_compile_options(Algo PRIVATE
    $<$<COMPILE_LANGUAGE:CXX>:-fno-exceptions>
)
```

Unfortunately, this will not work as expected for Visual Studio or for Xcode. Those generators' implementations do not support setting different flags for different languages at the target level. Instead, they evaluate generator expressions with the target language assumed to be C++ if the target has any C++ sources, or as C otherwise. This applies not just to compile options, but also to compile definitions and include directories. This limitation is a result of a compromise needed to avoid considerably degrading the build performance. If projects are willing to

accept slower builds, compiler flags can be applied using source file properties instead. For example:

```
add_executable(MyApp src1.c src2.cpp)

set_property(SOURCE src2.cpp APPEND PROPERTY
    COMPILE_OPTIONS -fno-exceptions
)
```

Source file properties also have their own limitations, as discussed in [Section 10.5, “Source Properties”](#). In particular, the Xcode generator cannot support configuration-specific source file properties, so generator expressions like `$<CONFIG>` need to be avoided.

A better way to work around these limitations is to split out the different languages to their own separate targets, not combine them in the same target. The compiler flags can then be applied to the whole target, which will work for all CMake generators and will not degrade build performance.

```
add_library(MyApp_c src1.c)
add_executable(MyApp src2.cpp)

target_link_libraries(MyApp PRIVATE MyApp_c)
target_compile_options(MyApp PRIVATE -fno-exceptions)
```

A less ideal workaround is to use the `CMAKE_<LANG>_FLAGS` variables which are handled correctly by Visual Studio and Xcode, but they will apply indiscriminately to all targets in a

directory scope and should preferably be left alone for developers to manipulate.

16.8. Compiler Option Abstractions

CMake provides abstractions for a variety of different compiler features. Some of these are for features implemented by multiple compilers, others are for making a feature of a specific toolchain easier to use. This section covers some more common, general purpose abstractions. Other chapters cover additional cases that relate to specific topics.

Where CMake provides an abstraction for a particular feature, the project should not mix using that abstraction with explicitly passing compiler flags for that feature. The project should either fully adopt the abstraction, or fully avoid using it. Mixing explicit compiler flags for a feature while also using the abstraction for it can result in unexpected results, or even broken builds. Pay extra attention to dependencies that are part of the build (see [Chapter 39, *FetchContent*](#)), as these need to also use or not use the same abstractions as the rest of the build.

16.8.1. Warnings As Errors

For projects that are expected to build free of warnings, it can be desirable to treat any warnings as errors. This is a common need for continuous integration builds, where a newly introduced warning should result in a build failure. Such a

mechanism encourages the developer to address the warning before their change is merged into the main branch.

For developers building locally, it is less clear-cut whether builds should treat warnings as errors. The developer might be testing out a newer compiler or a different toolchain, which means new warnings may be generated compared to CI builds. If the project hard-coded treating warnings as errors, the developer would have to modify the project to prevent that. If the code causing the warnings is coming from dependencies, and those dependencies are enforcing treating warnings as errors, it may be difficult for the developer to make that change (see [Section 16.8.2, “System Header Search Paths”](#) for a common way of handling such cases).

CMake 3.24 added the `COMPILE_WARNING_AS_ERROR` target property, which can be set to true to treat all compiler warnings for that target as errors. CMake will add the appropriate flag for the compiler, freeing the project from having to work out what flag to add. Not all compilers are supported for this feature, but it is implemented for all the mainstream compilers. The `COMPILE_WARNING_AS_ERROR` property documentation contains a list of the supported compilers.

The `COMPILE_WARNING_AS_ERROR` property is initialized from the `CMAKE_COMPILE_WARNING_AS_ERROR` variable when the target is created. In general, projects should not set the target property directly, and ideally they shouldn’t set the variable either.

Instead, the decision for whether to treat all warnings as errors should be left up to the developer, or a script driving the build. The developer or scripts can set `CMAKE_COMPILE_WARNING_AS_ERROR` as a cache variable without having to modify the project:

```
cmake -DCMAKE_COMPILE_WARNING_AS_ERROR=YES ...
```

If CMake presets are being used (see [Chapter 42, Presets](#)), they are an ideal place to set this variable. This is especially so where presets are used for continuous integration builds.

In certain circumstances, a project may choose to set the `CMAKE_COMPILE_WARNING_AS_ERROR` variable to meet things like certification requirements or company policies. Alternatively, a dependency might hard-code enabling warnings as errors despite the above advice, either through setting individual target properties or the `CMAKE_COMPILE_WARNING_AS_ERROR` variable. When situations like these occur, a developer can still turn off treating warnings as errors by passing the `--compile-no-warning-as-error` option on the `cmake` command line. This command line option forces CMake to ignore the `COMPILE_WARNING_AS_ERROR` target property throughout the whole build.

```
cmake --compile-no-warning-as-error ...
```

If the project is manually adding compiler flags to turn warnings into errors, CMake will not attempt to remove those.

Unless CMake does not implement the warnings as errors feature for the compiler being used, such hard-coded flags should be removed from the project.

CMake 4.0 added analogous features for the linker. The `LINK_WARNING_AS_ERROR` target property achieves for the linker what `COMPILE_WARNING_AS_ERROR` achieves for the compiler. A corresponding `CMAKE_LINK_WARNING_AS_ERROR` variable and a `--link-no-warning-as-error` command line option are also provided. CMake does not implement this support for all linkers, but most mainstream ones are supported. For the rest, the `LINK_WARNING_AS_ERROR` property is silently ignored.

`LINK_WARNING_AS_ERROR` supports more than just boolean true or false values. It also supports a list containing either or both of the values `LINKER` or `DRIVER`. These can be used to differentiate between ways of invoking the linker. For most projects, this more detailed specification is overkill and not all that useful. Sticking to a simple boolean true or false value will generally be clearer and more appropriate.

16.8.2. System Header Search Paths

Most mainstream compilers support specifying *system* header search paths. Historically, these were paths that were in system locations (e.g. `/usr/include` on Unix systems), or part of the toolchain rather than being provided by the project. More

recently, the term is also sometimes used for header search paths that are associated with dependencies of a project.

System header search paths work mostly like regular header search paths, but some compiler-dependent behavior differences may apply. For example:

- The compiler may search all non-system search paths before searching any system ones, even if the system paths appear earlier on the command line.
- When a header is found in a system header location, compilers will often skip warnings coming from that header. Some compilers do this automatically, others provide separate warning flags to achieve the same effect (the Visual Studio toolchain is an example of the latter).
- When the compiler computes dependencies for the file being compiled, it may leave out dependencies on headers in system locations.

CMake's abstraction for system header search paths makes the behavior more consistent between toolchains and CMake generators. The abstraction was progressively improved in the following key CMake versions:

CMake 3.12

System search paths are always placed after non-system ones on the compiler command line. This means the header

search order will be consistent across all toolchains.

CMake 3.22

When using the Visual Studio toolchain (VS 16.10 or later), `/external:W0` is included in the default compiler flags when using one of the Ninja or Makefiles generators. This turns off warnings coming from system headers. Compare this with gcc and clang which always do this by default.

CMake 3.24

When using one of the Visual Studio generators with a Visual Studio toolchain (VS 16.11 or later), system headers are supported. Earlier CMake or Visual Studio toolchain versions would treat such headers as regular non-system headers when using the Visual Studio generators.

CMake treats header search paths defined on imported targets as system search paths by default. [Section 19.2.3, “Imported Libraries”](#) discusses imported targets in more detail, but for now it is sufficient to know that these represent a library provided by something outside the project, usually system libraries or libraries from dependencies. They usually represent a library that already exists on the system, or that is provided at a known location and potentially built in some way external to the project.

If, for some reason, a consumer should not treat header search paths from imported targets as system search paths, one can set

the consumer's `NO_SYSTEM_FROM_IMPORTED` target property to true. Note that this setting does not discriminate between different imported targets, it will apply to *all* imported targets the consumer links to. In practice, use of this setting likely indicates deeper problems in the project or the targets it is linking to. The "systemness" of a target being consumed shouldn't be determined by the thing that consumes it, except perhaps for enforcing strict code quality policies or certification requirements.

CMake 3.25 and later provides a better approach. Targets support a `SYSTEM` property, which CMake uses to decide whether consumers should treat that target's header search paths as system or not. It doesn't affect building the target on which `SYSTEM` is set, only its consumers. For imported targets, `SYSTEM` defaults to true. For non-imported targets, the default value is taken from the `SYSTEM` directory property, or false if that directory property is not set. These defaults give the same behavior as described above for CMake 3.24 and earlier.

Changing the `SYSTEM` property for an imported target is rare. A case where it may be required is an imported target representing something that is part of the project, but built with another build system. Since the imported target is not external to the project, its `SYSTEM` property should be false.

For non-imported targets, it may be appropriate to set the `SYSTEM` property to true in certain situations. One example is where the sources for a third-party dependency are added directly to the project's build (the `FetchContent` module discussed in [Chapter 39, `FetchContent`](#) uses this approach extensively). In this scenario, non-imported targets are created for the dependency, but the main project may still want to treat headers coming from that dependency as system headers.

For the dependency-related scenario just described, it would be tedious to explicitly set the `SYSTEM` property on each target from every dependency individually. A more convenient approach is to use the `SYSTEM` directory property to change the default value for non-imported targets. Rather than modifying that directory property directly, the best way to manipulate it is by adding the `SYSTEM` keyword to the `add_subdirectory()` or `FetchContent_Declare()` call used to bring in the dependency. These both set the `SYSTEM` directory property to true for the subdirectories they add to the build.

```
# Vendored code stored directly in the project
add_subdirectory(third_party/somedep SYSTEM)

# External dependency downloaded and added to the build
include(FetchContent)
FetchContent_Declare(anotherdep
    GIT_REPOSITORY ...
    SYSTEM
)
FetchContent_MakeAvailable(anotherdep)
```

CMake 3.25 also provides control over an installed or exported target's `SYSTEM` property, where it will be represented by an imported target (see [Section 35.2, “Installing Project Targets”](#) and [Section 35.3, “Installing Exports”](#)). As discussed above, the `SYSTEM` property of that imported target defaults to true. Normally, this is the right behavior, but for situations where that imported target should not be treated as system, set the `EXPORT_NO_SYSTEM` property on the original target to true.

```
# This is an ordinary non-imported target during the build
add_library(MyThing ...)
set_target_properties(MyThing PROPERTIES
    EXPORT_NO_SYSTEM TRUE
)

# It becomes an imported target in the installed location.
# Its SYSTEM property will be false when installed.
install(TARGETS MyThing EXPORT MyProj ...)
install(EXPORT MyProj ...)
export(EXPORT MyProj ...)
```

CMake 3.23 added support for an `IMPORTED_NO_SYSTEM` property, but that was deprecated in CMake 3.25. The functionality provided by `IMPORTED_NO_SYSTEM` has been superseded by the `SYSTEM` and `EXPORT_NO_SYSTEM` properties. Therefore, avoid using `IMPORTED_NO_SYSTEM`.

In addition to the methods described above, the `target_include_directories()` and `include_directories()` commands also accept a `SYSTEM` keyword. The effect of that

keyword in these commands is related to the above, but the mechanisms are different.

When `SYSTEM` is used with `include_directories()`, it forces the header search paths listed to be treated as system search paths for the current directory and all its subdirectories. This cannot be disabled, and it is not affected by target properties like `SYSTEM`, `EXPORT_NO_SYSTEM`, or `IMPORTED_NO_SYSTEM`. The `include_directories()` command should generally be avoided in favor of target-based commands, and the use of the `SYSTEM` keyword with `include_directories()` is even more strongly discouraged because of the inability to negate it later if needed.

Use of `SYSTEM` with `target_include_directories()` is only marginally better. The paths are still added to the same target properties, so the `PRIVATE`, `PUBLIC`, and `INTERFACE` keywords still have their usual meanings. However, internally CMake records that those paths are to be treated as system paths. Those listed as `PUBLIC` or `INTERFACE` will be added to the target's `INTERFACE_SYSTEM_INCLUDE_DIRECTORIES` property, but `PRIVATE` paths are not added to any project-readable property. The `SYSTEM` keyword for `target_include_directories()` also has the same problem as `include_directories()` in that it is not affected by target properties like `SYSTEM`, `EXPORT_NO_SYSTEM`, or `IMPORTED_NO_SYSTEM`.

```
add_library(MyThing ...)  
add_executable(Consumer ...)
```

```
target_link_libraries(Consumer PRIVATE MyThing)

target_include_directories(MyThing SYSTEM
    PRIVATE secret
    PUBLIC api
)
```

The above is not a particularly good example of using the `SYSTEM` keyword, but it demonstrates the behavior. CMake will add `api` as a system header search path when building `Consumer`. It will add `secret` and `api` as system header search paths when building `MyThing`. What makes this a relatively poor example is that headers provided by the project should not normally be treated as system headers. Since `MyThing` is built by the project, headers in its `secret` or `api` directory can also be considered part of the project, and therefore shouldn't be treated as system headers.

In practice, projects should rarely need to use the `SYSTEM` keyword with `target_include_directories()` or `include_directories()`. CMake normally makes appropriate choices by default based on whether a consumed target is imported or non-imported. Where the default behavior doesn't fit the needs of the project, it may be appropriate to use the `SYSTEM` keyword with `target_include_directories()` if the project must support older CMake versions where the `SYSTEM` target property is not supported.

16.8.3. Runtime Library Selection

When using compilers that target the MSVC ABI, a runtime library must be selected. The project needs to choose between a statically linked or dynamically linked runtime. It also needs to choose whether to use the debug or non-debug runtime. With CMake 3.15 or later, this choice can be handled through the `MSVC_RUNTIME_LIBRARY` target property. Valid values are:

- `MultiThreaded`
- `MultiThreadedDLL`
- `MultiThreadedDebug`
- `MultiThreadedDebugDLL`

Values ending in `DLL` use the dynamically linked runtime, those without it use the statically linked runtime. And of course, values containing `Debug` use the debug version of the runtime, while those without `Debug` use the non-debug runtime. When `MSVC_RUNTIME_LIBRARY` is set, CMake chooses the appropriate flags for the compiler used. This frees the project from having to know all the different options required for the various toolchains that target the MSVC ABI. If the `MSVC_RUNTIME_LIBRARY` property remains unset, CMake uses the default value equivalent to the generator expression `MultiThreaded$<$<CONFIG:Debug>:Debug>DLL`. The property is initialized from the value of the `CMAKE_MSVC_RUNTIME_LIBRARY` variable, if set.

When using CMake 3.14 or earlier, similar defaults are used for at least some MSVC toolchains. But instead of achieving that through the `MSVC_RUNTIME_LIBRARY` property, raw flags are added using the variables discussed in [Section 16.6, “Compiler And Linker Variables”](#). This makes it much more difficult for the project to change the behavior from the defaults, since it requires knowing the flags used and performing string replacements. This is fairly fragile and much less convenient.

In order for CMake to use the `MSVC_RUNTIME_LIBRARY` property, the project must ensure policy `CMP0091` is set to `NEW` before the very first `project()` command is called. The easiest and most typical way of ensuring that is to require at least CMake 3.15 or higher, with a statement like the following at the beginning of the top level `CMakeLists.txt`:

```
# Need at least CMake 3.15 to use MSVC_RUNTIME_LIBRARY
cmake_minimum_required(VERSION 3.15)
```

If a version older than 3.15 is specified, CMake will ignore the `MSVC_RUNTIME_LIBRARY` property and fall back to the old behavior of encoding raw compiler flags in the flag variables.

The above illustrates how to specify the MSVC runtime, but for most projects, the defaults already give the appropriate behavior. Debug builds will use the debug runtime, and binaries will be dynamically linked. Only if there is a specific need to deviate from these defaults should the property or

variable discussed above be used. Changing from the defaults is often a cause of friction for other projects that need to link to the produced binaries. Therefore, prefer to leave the choice up to a consuming project, and only override the defaults for a top level project where there is a strong need to do so.

In addition to the `MSVC_RUNTIME_LIBRARY` target property, CMake 3.30 and later also supports a `VS_USE_DEBUG_LIBRARIES` target property. When using a Visual Studio generator, this property controls the `UseDebugLibraries` setting for each configuration in the generated `.vcxproj` files. This setting doesn't usually affect the build directly, but it may be used by some tools to influence their behavior. The defaults should be suitable for most projects, unless they define custom configurations (see [Section 15.3, “Custom Build Types”](#)). The property should evaluate to a true or false value, usually expressed as a generator expression of the form `$<CONFIG:Debug,MyCustomConfig>`. The associated `CMAKE_VS_USE_DEBUG_LIBRARIES` variable would normally be the preferred way to control `UseDebugLibraries` consistently across the whole build.

16.8.4. Runtime Checks Selection

When using the Visual Studio toolchain, runtime checks can be enabled using compiler flags of the form `/RTC....`. With CMake 3.31 and earlier, the `/RTC1` flag was added to the `CMAKE_<LANG>_FLAGS_DEBUG` variables by default. This can be

inconvenient if a project wants to enable a different combination of runtime checks, forcing the use of fragile string substitutions to achieve the desired outcome.

CMake 4.0 added a new abstraction to address this shortcoming. Like for the runtime library selection, there are two parts to using the new abstraction. The first is to set a new policy `CMP0184` to `NEW` before the first `project()` call. This enables the abstraction for the entire project. The second part is to set the `MSVC_RUNTIME_CHECKS` property on each target. Following CMake's usual pattern, the property is initialized by a `CMAKE_MSVC_RUNTIME_CHECKS` variable, if set. This variable would normally be set before any targets have been created.

The `MSVC_RUNTIME_CHECKS` property expects a list of values, and generator expressions can be used. After generator expressions have been expanded, each list value must be one of the following:

PossibleDataLoss

Enable checks for assigning a value too large for the variable's data type. This corresponds to the `/RTCc` flag.

StackFrameErrorCheck

Enable checks associated with the local stack. Effects include initializing local variables to a non-zero value, detecting overruns and underruns in local array variables, and

mismatched calling conventions. This corresponds to the /RTC_s flag.

UninitializedVariable

Enable checks for use of an uninitialized variable. This corresponds to the /RTC_u flag. Note that this check can be easily defeated, such as by simply taking the address of the variable. For more rigorous checks, consider using the Undefined Behavior Sanitizer (see [Section 33.1, “Sanitizers”](#)).

The /RTC₁ flag used by default in CMake 3.31 and earlier corresponds to the combination of /RTC_{cu}, which is equivalent to enabling the PossibleDataLoss and UninitializedVariable checks. When CMP0184 is set to NEW, the defaults for MSVC_RUNTIME_CHECKS also enable those two checks for Debug builds. These checks should never be enabled in production code, so they will usually be defined using a \$<\$<CONFIG:Debug>: ...> generator expression to limit them to only Debug builds.

The following example shows how a project might enable the new abstraction and also enable all three of the runtime checks for Debug builds only:

```
# Ensure policy CMP0184 is set to NEW
cmake_minimum_required(VERSION 4.0)

project(msvc_example)

# Runtime checks to enable for all targets defined below
set(runtime_checks
```

```
PossibleDataLoss
StackFrameErrorCheck
UninitializedVariable
)
set(CMAKE_MSVC_RUNTIME_CHECKS
"${$<$<CONFIG:Debug>:${runtime_checks}>"}
)

# Add targets with add_executable() and add_library()...
```

16.8.5. Debug Information Format Selection

CMake's default compiler flags may include options that affect the debug information format. For example, when using the MSVC toolchain, flags like /Z7, /Zi, or /ZI change both where debug information is stored and aspects of the debugging experience in Visual Studio. With CMake 3.24 and earlier, these flags are specified in the `CMAKE_<LANG>_FLAGS_<CONFIG>` family of variables discussed in [Section 16.6, “Compiler And Linker Variables”](#). When a developer or the project needs something different from the defaults, string-based search-and-replace has to be performed on these variables. This is inconvenient for a number of reasons:

- String-based replacements can be fragile.
- It has to be done separately for each combination of language and configuration.
- It requires knowing all possible flags for any version of the toolchain.

CMake 3.25 added an abstraction for handling debug information when using a toolchain that targets the MSVC ABI. The abstraction uses a `MSVC_DEBUG_INFORMATION_FORMAT` target property to determine what flags to add for the debug information for that target, but only if policy `CMP0141` is set to `NEW` at the first `project()` call. If the policy is unset or set to `OLD`, the default values of the various `CMAKE_<LANG>_FLAGS_<CONFIG>` variables will contain debug-related flags just as they did with CMake 3.24 and earlier, and the `MSVC_DEBUG_INFORMATION_FORMAT` property will be ignored.

When `CMP0141` is set to `NEW`, the `MSVC_DEBUG_INFORMATION_FORMAT` target property must evaluate to one of the following values or an empty string. Generator expressions are supported, so different flags can be used for different configurations.

Embedded

The compiler will include debug information directly in each object file. For the MSVC toolchain, this corresponds to the `/Z7` flag.

ProgramDatabase

The compiler collects debug information in a separate file (the program database). For the MSVC toolchain, this corresponds to the `/Zi` flag, with the debug information being stored in a PDB file.

EditAndContinue

This is like `ProgramDatabase`, except the program database supports the Visual Studio "edit and continue" functionality. For the MSVC toolchain, this corresponds to the `/ZI` flag.

For non-MSVC toolchains that target the MSVC ABI, not all of the above are supported. It is the developer's responsibility to ensure that the requested behavior is supported by the toolchain used. For example, when using a Clang toolchain that targets the MSVC ABI, the only supported value is `Embedded`.

With `CMP0141` set to `NEW`, if `MSVC_DEBUG_INFORMATION_FORMAT` evaluates to an empty string, no debug-related flags are added for that target. This allows generator expressions to be used to provide debug-related flags for some configurations and not others.

```
# NOTE: Setting this property directly is discouraged.  
set_target_properties(SomeTarget PROPERTIES  
    CMAKE_MSVC_DEBUG_INFORMATION_FORMAT  
    ${$<CONFIG:Debug,RelWithDebInfo>:Embedded}  
)
```

Projects wouldn't typically manipulate the `MSVC_DEBUG_INFORMATION_FORMAT` target property directly like in the above example. The initial value of that property is taken from the `CMAKE_MSVC_DEBUG_INFORMATION_FORMAT` variable. This variable should not typically be set by the project, it should be under the developer's control to allow them to select the type of debugging support they need.

When `CMAKE_MSVC_DEBUG_INFORMATION_FORMAT` is not set and `CMP0141` is set to `NEW`, CMake will use a default that gives the same end result as the `OLD` behavior. Where the toolchain supports `ProgramDatabase`, that will be the default value for the `Debug` and `RelWithDebInfo` configurations. For toolchains that target the MSVC ABI but do not support `ProgramDatabase`, the default value for those configurations will be `Embedded` instead.

`CMAKE_MSVC_DEBUG_INFORMATION_FORMAT` can be explicitly set to an empty string. With `CMP0141` set to `NEW`, this results in no debug-related flags being added for any configuration when using a toolchain that targets the MSVC ABI. An example scenario where this may be needed is when using a toolchain file (see [Section 24.1, “Toolchain Files”](#)), and the projects it will be used with may set `CMP0141` to `OLD` or `NEW`, or CMake 3.24 or older needs to be supported. In such cases, for the toolchain file to work as intended in all situations, it will need to override the default compiler flag variables and explicitly set the debug-related flags. `CMAKE_MSVC_DEBUG_INFORMATION_FORMAT` then has to be set to an empty string to prevent CMake from adding debug-related flags as well. [Appendix A, Full Compiler Cache Example](#) shows another situation where both `OLD` and `NEW` behavior of `CMP0141` must be accounted for.

16.9. Recommended Practices

This chapter has covered areas of CMake that have undergone some of the most significant improvements since earlier versions. The reader should expect to encounter plenty of examples and tutorials that still recommend patterns and approaches employing the older methods using variables and directory property commands. It should be understood that the target_...() commands should be the preferred approach in CMake projects today.

Projects should seek to define all dependencies between targets with the target_link_libraries() command. This clearly expresses the nature of the relationships between targets, and it communicates unambiguously to all project developers how targets are related. The target_link_libraries() command should be preferred over link_libraries() or manipulating target or directory properties directly. Similarly, the other target_...() commands offer a cleaner, more consistent, and more robust way to manipulate compiler and linker flags than variables, directory property commands, or direct manipulation of properties.

CMake 3.13 introduced a number of new commands and properties related to linker options, some of which were added for consistency reasons or to address specific use cases. Projects should generally avoid the new add_link_options() directory level command and prefer to use the new target_link_options() command instead. CMake 3.13 also

introduced a new target level command `target_link_directories()`, which is a complement to the existing directory level `link_directories()` command. Both of these link directory commands should be avoided for robustness reasons. Projects are advised to link to target names or use absolute paths to libraries where those libraries are not in directories expected to be on the default linker search path. The `LINK_LIBRARIES_ONLY_TARGETS` target property supported with CMake 3.23 or later may be helpful in enforcing this (see [Section 18.1, “Require Targets For Linking”](#)).

The following guide may help determine which methods are appropriate for a given situation:

- Where possible, prefer to use the `target_...()` commands to describe relationships between targets and to modify compiler and linker behavior.
- Prefer to avoid the directory property commands. While they can be convenient in some circumstances, consistent use of the `target_...()` commands instead will establish clear patterns for project developers to follow. If directory property commands must be used, do so as early in the `CMakeLists.txt` file as possible to avoid less intuitive behavior.
- Avoid direct manipulation of the target and directory properties that affect compiler and linker behavior. Understand what the properties do and how the different commands manipulate them, but prefer to use the more

specialized target- and directory-specific commands where possible. Querying the target properties can, however, be useful from time to time when investigating unexpected compiler or linker command line flags.

- Where CMake provides an abstraction for a compiler or linker feature, prefer to use that instead of adding raw compiler or linker flags. Ensure the abstraction is used instead of the raw flags consistently throughout the whole build, including any dependencies built from sources.
- Prefer to avoid modifying the various `CMAKE_..._FLAGS` variables and their configuration-specific counterparts. Consider these to be reserved for the developer, who may wish to change them locally at will. If changes need to be applied on a whole-of-project basis, consider using a few strategic directory property commands at the top level of the project instead, but consider whether such settings really should be unilaterally applied. A partial exception to this is in toolchain files where initial defaults may be defined (see [Chapter 24, Toolchains And Cross Compiling](#) for a detailed discussion of this area).

Developers should become familiar with the concepts of PRIVATE, PUBLIC, and INTERFACE relationships. They are a critical part of the `target_...()` command set, and they become even more important for the install and packaging stages of a project. Think of PRIVATE as meaning for the target itself, INTERFACE for things that link against the target, and PUBLIC as meaning both

behaviors combined. While it may be tempting to just mark everything as PUBLIC, this may unnecessarily expose dependencies out beyond targets they need to. Build times can be impacted, and private dependencies can be forced onto other targets which should not have to know about them. This in turn has a strong impact on other areas such as symbol visibility (discussed in detail in [Section 23.5, “Symbol Visibility”](#)). Therefore, prefer to start with a dependency as PRIVATE and only make it PUBLIC when it is clear that the dependency is needed by those linking to the target.

The INTERFACE keyword is used mostly for imported or interface library targets. Another less common use is to add missing requirements to a target defined in a part of the project the developer may not be allowed to change directly. Examples include parts written for older CMake versions and that don't use the `target_...()` commands, or external libraries with imported targets that omit important flags needed by targets linking to them. CMake 3.13 removed the restriction that `target_link_libraries()` could not be called to operate on a target defined in a different directory scope. For all other `target_...()` commands, there was no such restriction previously, so they can always be used to extend the interface properties of targets defined elsewhere in the project. [Section 43.5.1, “Building Up A Target Across Directories”](#) revisits this topic, demonstrating how these capabilities can also be used to promote a more modular project structure.

Prefer to put all headers owned by a target into one or more file sets. Use the PRIVATE, PUBLIC, and INTERFACE keywords appropriately so that it is clear which headers are intended for use outside that target, and which are not. Using file sets appropriately should mean that `target_include_directories()` does not need to be called to add any header search paths, since all such paths should be handled by the `BASE_DIRS` of the target's file sets. Defining file sets also greatly simplifies installing a target's headers (see [Section 35.5.1, “File Sets”](#)).

Avoid hard-coding turning warnings into errors. Let the choice be determined by the `CMAKE_COMPILE_WARNING_AS_ERROR` (CMake 3.24 or later) and `CMAKE_LINK_WARNING_AS_ERROR` (CMake 4.0 or later) variables. Projects shouldn't set these variables, they are meant as developer controls, to be set either on the command line or in a CMake preset (see [Chapter 42, *Presets*](#)). If supporting CMake versions from before these variables were supported, do not hard-code raw compiler or linker flags like `-Werror` or `/WX` to force warnings to be treated as errors.

Developers are sometimes tempted to use the `SYSTEM` target property or the `SYSTEM` keyword with `target_include_directories()` or `include_directories()` to silence warnings coming from headers instead of addressing those warnings directly. If such headers are part of the project, `SYSTEM` is not typically an appropriate feature to use. In general,

`SYSTEM` is intended for paths outside the project (e.g. for dependencies).

III: BUILDS IN DEPTH

In the preceding chapters, the most fundamental aspects of CMake were progressively introduced. Core language features, key concepts, and important building blocks were presented. These provide a solid foundation for a deeper exploration of CMake’s functionality.

In this next part of the book, more detailed aspects of the build are the focus. Chapters cover the toolchain and cross-compilation, more advanced compiler and linker techniques and features, different types of CMake targets, how to carry out custom tasks, platform-specific features, and various build performance topics. Understanding these areas well can be the difference between a fragile, complex project, and a robust, easy-to-maintain one.

17. LANGUAGE REQUIREMENTS

Languages like C, C++, CUDA, and others are always evolving. Projects typically require a particular minimum language standard, and that too will likely change over time. Managing the compiler and linker flags to enforce this across the different toolchains is not trivial. Different compilers use different flags, and even when using the same compiler and linker, flags can be used to select different implementations of the standard library.

CMake provides two main methods for specifying language requirements. The first is to set the language standard directly, and the second is to set language requirements through compile features. Historically, the two approaches were quite different, but they have become more similar over time. While the functionality has largely been driven by the C and C++ languages, other languages and pseudo-languages such as CUDA, Objective-C/C++, and HIP are also supported.

17.1. Setting The Language Standard Directly

The simplest way for a project to control the language standards used by a build is to set them directly at the top level.

This ensures the same language standard is used throughout the project. It can be important at compile time if headers define things differently depending on what language standard is being used. Some language standard settings can also affect which standard library is added at link time. The use of C++20 modules further strengthens the need for a consistent language standard to be used throughout, since different standards flags require a different set of BMIs (built module interfaces).

As is the usual pattern with CMake, target properties control which standard will be used when building that target's sources, and when linking the final executable or shared library. For a given language, there are three target properties related to specifying the standard. In the following, `<LANG>` will commonly be either `C` or `CXX`, but `CUDA`, `OBJC`, `OBJCXX`, and `HIP` are also supported with more recent CMake versions.

`<LANG>_STANDARD`

Specifies the language standard for the target. When a target is created, the initial value of this property is taken from the `CMAKE_<LANG>_STANDARD` variable.

Language	C				
Language standard	90	99	11	17	23
Minimum CMake version	3.1		3.21		

Language	C++						
Language standard	98	11	14	17	20	23	26
Minimum CMake version	3.1	3.8	3.12	3.20	3.25		

Note that C++26 is not yet a formal standard. And while the C++ standard value 26 is recognized as valid starting with CMake 3.25, no support for what flags to use for it was implemented until CMake 3.27 for Clang, and CMake 3.30 for GNU compilers.

Language	Obj-C				
Language standard	90	99	11	17	23
Minimum CMake version	3.16		3.21		

Language	Obj-C++						
Language standard	98	11	14	17	20	23	26
Minimum CMake version	3.16		3.20	3.25			

If `OBJC_STANDARD` and `OBJCXX_STANDARD` are not defined, then `C_STANDARD` and `CXX_STANDARD` are used as fallbacks respectively. In practice, it would be unusual to set `OBJC_STANDARD` or `OBJCXX_STANDARD`. The fallback to `C_STANDARD` and `CXX_STANDARD` would typically be desirable to ensure that

C/C++ code uses language standards consistent with the Objective-C/C++ code.

Language	CUDA							
Language standard	98	03	11	14	17	20	23	26
Minimum CMake version	3.8	3.18	3.8	3.9	3.18	3.22	3.25	

Language	HIP						
Language standard	98	11	14	17	20	23	26
Minimum CMake version	3.21					3.25	

`CUDA_STANDARD` is a CUDA-specific version of what `CXX_STANDARD` would normally control. If `CUDA_STANDARD` is not defined, it effectively falls back to `CXX_STANDARD`. Some of the CUDA language standard values are recognized as valid by earlier CMake versions than shown in the above table, but again, no compiler flags for them were implemented by CMake versions earlier than those shown.

With CMake 3.30 or later, the `CMAKE_<LANG>_STANDARD_LATEST` variable provides the most recent language version supported by both CMake and the currently selected toolchain. The variable is only guaranteed to be set after the specified `<LANG>` language has been enabled. It should

typically only be used for informational purposes, not to set the required language version.

`<LANG>_STANDARD_REQUIRED`

While the `<LANG>_STANDARD` property specifies the language standard, `<LANG>_STANDARD_REQUIRED` determines whether that language standard is treated as a minimum requirement or as just a "use if available" request. When `<LANG>_STANDARD_REQUIRED` is false, if the compiler does not support the requested standard, CMake will decay the request to an earlier standard rather than halting with an error. This decaying behavior is usually unexpected, and in practice it can cause confusion. Furthermore, false is unfortunately the default. Therefore, when specifying a `<LANG>_STANDARD` property, prefer to also set its corresponding `<LANG>_STANDARD_REQUIRED` property to true to ensure the standard is enforced as a minimum requirement. When a target is created, the initial value of this property is taken from the `CMAKE_<LANG>_STANDARD_REQUIRED` variable.

`<LANG>_EXTENSIONS`

Many toolchains support their own extensions to the language standard. Compiler and linker flags are usually available to enable or disable those extensions. The `<LANG>_EXTENSIONS` target property controls whether those extensions are enabled for that target. See below for how this property is initialized.

For many compilers, the same flag is used to control both the language standard and whether extensions are enabled. This creates some complications. With CMake 3.21 or earlier, if a project sets the `<LANG>_EXTENSIONS` property without also setting the `<LANG>_STANDARD` property, `<LANG>_EXTENSIONS` may effectively be ignored. CMake 3.22 introduced policy `CMP0128` which affects this behavior. When `CMP0128` is set to `NEW`, `<LANG>_EXTENSIONS` will be honored regardless of whether `<LANG>_STANDARD` is set or not. Projects should strongly prefer the `CMP0128 NEW` behavior if at all possible.

`CMP0128` also affects how `<LANG>_EXTENSIONS` is initialized when a target is created. If the `CMAKE_<LANG>_EXTENSIONS` variable is not set, then with `CMP0128` set to `NEW`, the `<LANG>_EXTENSIONS` property will be initialized to a value consistent with the toolchain's default behavior when no flags are given. But with `CMP0128` set to `OLD` or not set, `<LANG>_EXTENSIONS` is instead initialized to false, which may result in unexpected behavior for developers who are more familiar with their toolchain.

`CMP0128` has one more potential effect when set to `NEW`. CMake will only add flags for the language standard or extensions if the compiler's default behavior doesn't already provide those settings. This sometimes confuses developers who expect to see certain flags used, but `CMP0128 NEW` does give the correct final behavior.

In practice, projects usually set the variables providing the defaults for the above target properties rather than setting the target properties directly. All targets in the project are then built with consistent, compatible settings. It is also recommended that projects set all three variables rather than just some of them. The defaults for `<LANG>_STANDARD_REQUIRED` and `<LANG>_EXTENSIONS` have proven to be relatively unintuitive for many developers. By explicitly setting them, a project makes clear the standard behavior it expects.

```
# Require C++11 and disable extensions for all targets.  
# NOTE: See further below for how to do this more robustly.  
set(CMAKE_CXX_STANDARD          11)  
set(CMAKE_CXX_STANDARD_REQUIRED ON)  
set(CMAKE_CXX_EXTENSIONS        OFF)
```

When using GCC or Clang, the above would typically add the `-std=c++11` flag. For Visual Studio compilers before VS2015 Update 3, no flags would be added, since the compiler either supports C++11 by default, or it has no support for C++11 at all. From Visual Studio 15 Update 3, the compiler supports specifying a C++ standard of C++14 or later, with C++14 being the default if not set.

In comparison, the following example requests a later C++ version and enables compiler extensions, resulting in a GCC/Clang compiler flag like `-std=gnu++14`. Visual Studio compilers again may support the requested standard by default or not, depending on the compiler version. If the compiler in

use does not support the requested C++ standard, CMake will configure the compiler to use the most recent C++ standard it supports.

```
# Use C++14 if available and allow compiler extensions
# for all targets.
# NOTE: See further below for how to do this more robustly.
set(CMAKE_CXX_STANDARD      14)
set(CMAKE_CXX_STANDARD_REQUIRED OFF)
set(CMAKE_CXX_EXTENSIONS    ON)
```

The following example shows how to set the C standard details for a specific target (only for illustration, [Section 17.2, “Setting The Language Standard By Feature Requirements”](#) presents a better way to do this):

```
# Build target Algo with C99, no compiler extensions
set_target_properties(Algo PROPERTIES
  C_STANDARD      99
  C_STANDARD_REQUIRED ON
  C_EXTENSIONS    OFF
)
```

Note that `<LANG>_STANDARD` specifies a minimum standard, not necessarily an exact requirement. CMake may select a more recent standard due to compile feature requirements (see [Section 17.2, “Setting The Language Standard By Feature Requirements”](#)). Furthermore, directly setting the `<LANG>_STANDARD` target property like this is not recommended, as it takes away the ability to increase the language standard used across the whole build with the `CMAKE_<LANG>_STANDARD`

variable. Use a compile feature requirement instead to avoid this problem.

For a standalone project that will always be built as the top level project, hard-coding variables like `CMAKE_CXX_STANDARD` and `CMAKE_CXX_EXTENSIONS` may be appropriate. But some projects may end up being absorbed into a larger parent project (see [Chapter 39, *FetchContent*](#)), and that parent project may want to enforce a higher language standard or make use of extensions that this project doesn't need. To provide the flexibility required to accommodate such use cases, the project should be more careful about how it sets these variables.

The following demonstrates how one might set the C++ language constraints in a safer way, accounting for the above considerations:

```
# Require C++20, but let a parent project ask for
# something higher
if(DEFINED CMAKE_CXX_STANDARD)
    if(CMAKE_CXX_STANDARD EQUAL 98 OR
        CMAKE_CXX_STANDARD LESS 20)
        message(FATAL_ERROR
            "This project requires at least C++20"
        )
    endif()
else()
    set(CMAKE_CXX_STANDARD 20)
endif()

# Always enforce the language constraint
set(CMAKE_CXX_STANDARD_REQUIRED ON)
```

```
# We don't need compiler extensions, but let a parent ask
# for them
if(NOT DEFINED CMAKE_CXX_EXTENSIONS)
    set(CMAKE_CXX_EXTENSIONS OFF)
endif()
```

Safer logic like the above becomes much more important once C++20 modules are involved. Problems will occur with incompatible BMIs (built module interfaces) if the same language standard is not used throughout the whole build. See [Section 17.3, “Requirements For C++20 Modules”](#) for further discussion of this topic.

17.2. Setting The Language Standard By Feature Requirements

Directly setting the language standard for a whole project is the simplest way to manage standard requirements. It has the advantage that a consistent language standard is used by all targets in the project, which may be needed to ensure its binaries are fully compatible with each other. One disadvantage of this approach is that the language standard is not applied as a usage requirement to any consumers of that project when installed. The consumer is then responsible for specifying a compatible language standard.

Compile feature requirements are one way of addressing this drawback. The `COMPILE_FEATURES` and `INTERFACE_COMPILE_FEATURES` target properties define features

when building the target and when building consumers of the target respectively. Originally, compile features were intended to handle situations where compilers might only implement some features of a language standard (a common situation in the early days of C++11). These days, such granular compile features are rarely needed, and they are instead used to specify a language standard as a whole (this requires CMake 3.8 or later).

These compile feature properties are typically populated using the `target_compile_features()` command rather than being manipulated directly. This command follows a very similar form to the various other `target_...()` commands provided by CMake:

```
target_compile_features(targetName
    <PRIVATE|PUBLIC|INTERFACE> feature1 [feature2 ...]
    [<PRIVATE|PUBLIC|INTERFACE> feature3 [feature4 ...]]
    ...
)
```

The PRIVATE, PUBLIC, and INTERFACE keywords have their usual meanings, controlling how the listed features should be applied. PRIVATE features populate the `COMPILE_FEATURES` property, which is applied to the target itself. Those features specified with the INTERFACE keyword populate the `INTERFACE_COMPILE_FEATURES` property, which is applied to any target that links to `targetName`. Features specified as PUBLIC will be added to both properties

and will therefore be applied to both the target itself and to any other target which links to it.

From CMake 3.8, a per-language meta-feature is available to indicate a particular language standard. These meta-features take the form `<lang>_std_<value>`. When listed as a required compile feature, CMake will ensure compiler flags are used which enable that language standard. The following example shows a compile feature being used to ensure that a target and anything that links against it has C++14 support enabled:

```
target_compile_features(targetName PUBLIC cxx_std_14)
```

In situations where a target has both its `<LANG>_STANDARD` property set and compile features specified (directly or transitively as a result of INTERFACE features from something it links to), CMake will enforce the stronger standard requirement. In the following example, Algo would be built with C++14, Funky with C++17, and Guff with C++14:

```
set_target_properties(Algo PROPERTIES CXX_STANDARD 11)
target_compile_features(Algo PUBLIC cxx_std_14)

set_target_properties(Funky PROPERTIES CXX_STANDARD 17)
target_compile_features(Funky PRIVATE cxx_std_11)

set_target_properties(Guff PROPERTIES CXX_STANDARD 11)
target_link_libraries(Guff PRIVATE Algo)
```

Note that this may mean a more recent language standard could be used than what the project expected, which in some

cases can result in compilation errors. For example, C++17 removed `std::auto_ptr`, so if code expects to be compiled with an older language standard and still uses `std::auto_ptr`, it could fail to compile if the toolchain strictly enforces this removal.

The CUDA, OJJC, and OJJCXX languages are a little unusual in that they are based off C or C++. The OJJC and OJJCXX languages do not as yet have their own separate set of compile features, but the compile features for the corresponding base language can be used instead. A similar situation existed for CUDA with CMake 3.16 and older, falling back to the C++ compile features. CMake 3.17 added dedicated compile feature support for CUDA.

As mentioned earlier, CMake also supports more granular values than just the `<lang>_std_<value>` compile features. Examples include things like `cxx_override` and `cxx_constexpr`, which can be used to require specific features of a language standard. If the compiler being used doesn't support the requested feature, it will fail with an error. If the requested feature is supported, CMake translates the feature into the appropriate language standard flags.

All the defined granular features are only for C++11, with a few for C++14. CMake stopped defining granular features from C++17 onward. These days, any toolchains in practical use should support all the defined granular features, so projects

may as well just use the relevant `<lang>_std_<value>` feature instead. This is far simpler, and much easier to maintain.

17.3. Requirements For C++20 Modules

While the modules language feature is part of the C++20 standard, the major toolchain vendors and members of the SG15 tooling study group are still actively discussing aspects of how to fully implement it. Build systems like CMake have to track and coordinate more things. These include scanning source files to work out whether they use or provide modules, and ensuring module information needed for a compilation is up to date. Sources may rely on files that are generated as a side effect of compiling other source files, so unlike when relying only on headers, the order of compilation matters even for the first build.

CMake 3.28 is the first release to formally support C++20 modules, at least partially. Notable limitations include no support for header units, or for `import std`. The main three toolchains are supported (GCC, Clang, and Visual Studio), but CMake generator support is much more restricted. In practice, only the Ninja generator has fairly good support for C++20 modules. The Visual Studio 17 2022 generator is partially supported, but it currently has a number of limitations which make it unsuitable for any project that will be installed or will consume another installed project. Ninja Multi-Config has some

issues with install-related scenarios as well. None of the other generators are officially supported, but this may change with future CMake releases. See the `cmake-cxxmodules` manual in the official CMake documentation for the full list of current limitations.

A key aspect of CMake's modules support is the way file scanning is handled. A project has to not only require C++20 or later as the language standard, it also has to provide the necessary information for CMake to work out which files to scan for module definitions and uses. The first part of that involves putting every source file that exports a module in a file set of type `CXX_MODULES` (see [Section 16.2.7, “File Sets”](#)). If a source file only uses but does not export a module, it should *not* be added to a `CXX_MODULES` file set.

```
add_executable(MyApp main.cpp)
target_sources(MyApp
PRIVATE
FILE_SET CXX_MODULES
FILES
    exports_some_module.cppm
    also_exports_a_module.cppm
)
target_compile_features(MyApp PRIVATE cxx_std_20)
```

In the above example, `main.cpp` uses modules defined in the other two source files. All three sources must be included in the module scanning process to ensure that exporting and importing modules are handled correctly. Since

`exports_some_module.cppm` and `also_exports_a_module.cppm` are in a `CXX_MODULES` file set, CMake knows they need to be scanned. But `main.cpp` is not in a file set, so another mechanism is needed for it to be included in the scanning process.

The simplest way to ensure that files not in a file set are scanned is to rely on policy `CMP0155`. This policy was also added in CMake 3.28. When it is set to `NEW`, scanning will automatically be enabled for any source file added to a target that requires C++20 or higher (e.g. through a `cxx_std_20` compile feature). For the above example, putting something like the following at the top of the project would ensure `CMP0155` was set to `NEW`:

```
cmake_minimum_required(VERSION 3.28)
```

Any project that uses C++20 modules needs at least CMake 3.28, so it should have this at the top of the project already. The only reason this behavior was made subject to a policy setting was to support existing projects that use C++20, but which don't use modules and which need to prevent module scanning for performance or compatibility reasons.

A project can further control scanning at the target or even the individual source file level. The `CXX_SCAN_FOR_MODULES` target property can be used to force scanning to be enabled or disabled for that target. A source file property of the same name can be used to enable or disable scanning of individual files. When set, the source file property takes priority over the target

property. Projects should not normally need to set either of these properties unless a particular target or source file causes problems for module scanning.

```
# Needs C++20, but doesn't use modules
add_executable(AnotherApp main.cpp)
target_compile_features(AnotherApp PRIVATE cxx_std_20)
set_target_properties(AnotherApp PROPERTIES
    CXX_SCAN_FOR_MODULES FALSE
)

# Imports C++20 modules...
add_executable(ModulesApp modmain.cpp special.cpp)
target_compile_features(ModulesApp PRIVATE cxx_std_20)

# ...but this file causes problems for scanning and
# doesn't use C++20 modules itself
set_source_files_properties(special.cpp PROPERTIES
    CXX_SCAN_FOR_MODULES FALSE
)
```

Modules can also be exported from and used by sources in static libraries. This is still relatively straightforward when the project is building all libraries and executables involved.

```
add_library(Algo STATIC)
target_sources(Algo
PUBLIC
    FILE_SET CXX_MODULES
    FILES
        exports_some_module.cppm
        also_exports_a_module.cppm
)
target_compile_features(Algo PUBLIC cxx_std_20)

add_executable(MyApp main.cpp)
```

```
target_compile_features(MyApp PRIVATE cxx_std_20)
target_link_libraries(MyApp PRIVATE Algo)
```

Conceptually, shared libraries are no different to static libraries, but the practical reality is very different. The visibility of CXX_MODULES file sets do not in any way imply visibility of symbols as seen by the linker. The two are orthogonal concepts with their own separate controls, and this is commonly misunderstood by developers early in their use of C++20 modules. One can readily construct a shared library with modules in a PUBLIC CXX_MODULES file set, but none of the modules end up being accessible from outside the shared library because all the module's symbols are hidden. This more complex topic is discussed in [Section 23.5.3, “Additional Complications With C++20 Modules”](#).

The installation aspects of C++20 modules also bring another constraint. The above examples all use the `cxx_std_20` compile feature to ensure the C++ standard is set to at least C++20 on each target. The `CXX_STANDARD` target property could have been set instead for these specific cases, but CMake requires using the compile feature if library targets are installed. If a compile feature of `cxx_std_20` or another higher standard isn't defined on a target that exports a PUBLIC C++20 module, and that target is installed, CMake will halt with an error in a consuming project.

Before C++20 modules, projects could usually mix targets built with different language standard versions. While technically that is not guaranteed to work, in practice it usually does. But C++20 modules change the situation due to the way BMI (built module interface) files are handled by some toolchains. A BMI is needed for any module used by the project, and CMake coordinates with the toolchain to ensure a suitable BMI is available when one is needed. BMIs are very sensitive to any compiler flag that can change the result of compiling code, and the flags that control the language standard certainly fall into that category. If two different targets are built with different language standards, such as C++20 and C++23, that would require two different BMIs for any common modules used by both targets. This can cause the build to fail due to an incompatible BMI being given to the toolchain.

17.4. Recommended Practices

Projects should avoid setting compiler and linker flags directly to control the language standard used. The required flags vary from one toolchain to another, so it is more robust, more maintainable, and more convenient to use the features that CMake provides and allow it to populate the flags appropriately. The `CMakeLists.txt` file will also more clearly express the intent, since human-readable variables and properties are used instead of often cryptic raw compiler and linker flags.

The simplest method for controlling language standard requirements is to use the `CMAKE_<LANG>_STANDARD`, `CMAKE_<LANG>_STANDARD_REQUIRED`, and `CMAKE_<LANG>_EXTENSIONS` variables. These can be used to set the language standard behavior for the entire project, ensuring consistent usage across all targets. These variables should ideally be set just after the first `project()` command in the top level `CMakeLists.txt` file. Projects should always set all three variables together to make clear how the language standard requirements should be enforced, and whether compiler extensions are permitted. Omitting `CMAKE_<LANG>_STANDARD_REQUIRED` or `CMAKE_<LANG>_EXTENSIONS` can lead to unexpected behavior, as the defaults may not be what some developers intuitively expect.

Projects should check to see if `CMAKE_<LANG>_STANDARD` and `CMAKE_<LANG>_EXTENSIONS` are already set before setting them to a particular value. Some scenarios may require enforcing stronger settings than the project's own minimum requirements, such as it being incorporated into a larger parent project that needs to use a higher language version. This becomes critical if C++20 modules are used, since they require a consistent language standard to be used throughout the build.

If using CMake 3.8 or later, compile features can be used to specify the desired language standard on a per-target basis. The `target_compile_features()` command makes this easy and

clearly specifies whether such requirements are PRIVATE, PUBLIC, or INTERFACE. The main advantage of specifying a language requirement this way is that it can be enforced transitively on other targets via PUBLIC and INTERFACE relationships. These requirements are also preserved when targets are exported and installed (see [Chapter 35, *Installing*](#)). If a target exports any C++20 modules, it must set a compile feature requiring C++20 or later.

Avoid the more granular compile features like `cxx_override` and `cxx_constexpr`. They are hard to use, difficult to maintain, and serve little practical use with most compilers in active use today. Prefer instead to use only the higher level meta-features that specify the language standard directly, such as `cxx_std_17`, `c_std_11`, and so on.

Avoid directly setting the `<LANG>_STANDARD` and `<LANG>_EXTENSIONS` properties on individual targets. Express the language standard requirement with a `<lang>_std_<value>` compile feature instead, or use appropriate logic at the top of the project to check if the standard has been set by a parent project before setting it globally for the whole build with a `CMAKE_<LANG>_STANDARD` variable. This ensures a parent project can enforce a higher language standard if it needs to. Similarly, use top level logic to conditionally set `CMAKE_<LANG>_EXTENSIONS` so it applies consistently to the whole build, but still allows a parent project to enable extensions if needed. There is no compile feature for

enabling or disabling extensions, so this can only be safely controlled with the `CMAKE_<LANG>_EXTENSIONS` variable.

If policy `CMP0128` is not set to `NEW`, the `<LANG>_EXTENSIONS` properties and their associated variables often only take effect if the corresponding `<LANG>_STANDARD` is also set. This is due to how compilers frequently combine the two into a single flag. Therefore, unless using CMake 3.22 or later with policy `CMP0128` set to `NEW`, it is difficult to escape having to specify `CMAKE_<LANG>_STANDARD`, even when compile features are used.

18. ADVANCED LINKING

[Chapter 16, *Compiler And Linker Essentials*](#) presented the usual ways that properties are used to control linking of targets. The properties and commands discussed should cover most scenarios. Nevertheless, situations arise where the project may want to use additional linking techniques and constraints not covered by those methods.

18.1. Require Targets For Linking

CMake 3.23 added support for a `LINK_LIBRARIES_ONLY_TARGETS` target property. When this is set to true, it adds constraints on the link items added to a target according to its `LINK_LIBRARIES` property, and the `INTERFACE_LINK_LIBRARIES` and `INTERFACE_LINK_LIBRARIES_DIRECT` properties of its dependencies (see [Section 18.3, “Propagating Up Direct Link Dependencies”](#) for the latter). Any item in any of those properties which *could* be a valid target name is *required* to be a target name. For the purposes of that check, an item is considered a potential target name if it has no path components and doesn’t start with `-`, `$` or ``` (after any generator expressions have been evaluated).

```
add_library(glob STATIC ...)
add_executable(App ...)
set_target_properties(App PROPERTIES
    LINK_LIBRARIES_ONLY_TARGETS TRUE
)
target_link_libraries(App PRIVATE glib) # NOTE: typo here
```

In the above example, the developer made a typo on the `target_link_libraries()` line. They intended to use the name of the `glob` target, but instead used `glib`. On some platforms, the system may provide a library named `glib` which can be found on the linker's library search path. Without the `LINK_LIBRARIES_ONLY_TARGETS` property set, the linker would find `glib` and link to it, but be unable to resolve the symbols that were expected to be provided by `glob` instead. The linker would then issue an error message about the missing symbols rather than the wrong library being linked. The developer would be confused, thinking they linked to `glob`, which should have provided the missing symbols. With `LINK_LIBRARIES_ONLY_TARGETS` set to true, CMake sees that there is no CMake target called `glib` and halts with an error at configure time. CMake's error message will immediately diagnose the real problem (the typo that caused the wrong thing to be linked).

In practice, it will probably be desirable to enable this behavior across the whole project, not just for individual targets. The `CMAKE_LINK_LIBRARIES_ONLY_TARGETS` variable is used to initialize the `LINK_LIBRARIES_ONLY_TARGETS` target property. Setting that

variable at the project's top level before any targets are created will ensure that all targets have the feature enabled.

In some cases, certain libraries provided by the toolchain may be linked with a bare name that could be a target name. The `m` library on Unix platforms is a relatively common example. A toolchain file or the project might add such a library to the linker command line of all executable and shared library targets. If `LINK_LIBRARIES_ONLY_TARGETS` is set to true, this may lead to CMake rejecting that library linking relationship. Such libraries need to be wrapped in an `INTERFACE IMPORTED` target (see [Section 19.2.5, “Interface Imported Libraries”](#)). The `IMPORTED_LIBNAME` target property also needs to be set to the name to be used on the linker command line. The following contrived example (taken from the official CMake documentation, with minor changes) demonstrates the technique:

```
add_library(Toolchain::m INTERFACE IMPORTED)
set_target_properties(Toolchain::m PROPERTIES
    IMPORTED_LIBNAME "m"
)
target_link_libraries(App PRIVATE Toolchain::m)
```

CMake doesn't check whether the value of `IMPORTED_LIBNAME` matches a target name. The value is used on the linker command line directly as provided. One can take advantage of this to mask a bare library name with a CMake target of the same name:

```
# No Toolchain:: namespace, masks bare "m" name
add_library(m INTERFACE IMPORTED)
set_target_properties(m PROPERTIES
    IMPORTED_LIBNAME "m"    # Never treated as a target name
)
target_link_libraries(App PRIVATE m)
```

Third party code that links to a bare `m` could then be used with `LINK_LIBRARIES_ONLY_TARGETS` enabled.

18.2. Customize How Libraries Are Linked

In some projects, there can be requirements around not just *what* libraries are linked, but also *how* they are linked. For example, some linkers can optimize away linked libraries and frameworks it thinks are not needed. The target may use those libraries or frameworks in a way that the linker can't detect, so the project has to somehow prevent the linker from discarding them. Another example is where a group of libraries has complex interdependencies that cannot be easily captured by CMake's cyclic dependency handling (see [Section 23.2, “Linking Static Libraries”](#)). In such cases, the project may want to direct the linker to repeatedly rescan a group of interdependent libraries to satisfy unresolved symbols.

Two new generator expressions added in CMake 3.24 provide greater control over how libraries are added to the linker command line. They directly support scenarios like those mentioned above. These new generator expressions and the

various constraints and features surrounding them can be fairly complicated. However, for the more common use cases, a fairly simple understanding will likely be sufficient. Nevertheless, it is recommended that the reader use the discussion below as a starting point, but also check the official documentation of these generator expressions. Most features are not supported for every toolchain, so consult the documentation to confirm availability for the toolchain(s) being used, and for any other limitations that may apply.

The two new generator expressions are closely related, but they serve different purposes:

```
$<LINK_GROUP:groupFeature,libs...>
$<LINK_LIBRARY:libFeature,libs...>
```

Both expressions can only be used in the LINK_LIBRARIES, INTERFACE_LINK_LIBRARIES or INTERFACE_LINK_LIBRARIES_DIRECT target properties. They can also be used in the target_link_libraries() and link_libraries() commands.

When adding the specified libs to the linker command line, the groupFeature or libFeature defines how that should be done. \$<LINK_GROUP:...> is used to express a constraint around a group of libraries as a whole, whereas \$<LINK_LIBRARY:...> expresses a constraint that applies to each listed library individually. The set of features supported by the two expressions are separate and non-overlapping.

18.2.1. Link Group Features

CMake defines only one built-in groupFeature for use with `$<LINK_GROUP:...>`, a feature called RESCAN. It ensures that the list of libraries are kept together on the linker command line. It surrounds that list of libraries with linker options that make the linker rescan the group members repeatedly to resolve symbols. With some linkers, the libraries would normally only be scanned once in a single pass. For such linkers, symbols needed by libraries earlier on the command line would have to be supplied by things later on the command line. The RESCAN feature makes the linker work harder by using multiple passes to resolve symbols within the group as much as possible. Some linkers are already multi-pass by default and don't require any additional options to be added in order to get this behavior.

```
add_library(MyThings STATIC ...)
add_executable(App ...)

target_link_libraries(App PRIVATE
    $<LINK_GROUP:RESCAN,MyThings,externalTC>
)
```

In the above example, the project defines a `MyThings` target, which is closely coupled with an externally-provided `externalTC` library. Both need symbols from each other. CMake will choose the appropriate linker flags for the toolchain to represent the group constraint when linking the `App` target. With toolchains

that use the GNU ld linker, the above example might result in a linker command line that contains the following fragment:

```
-Wl,--start-group /path/to/libMyThings.a -lexternalTC -Wl,--end-group
```

Once a library has been mentioned in a RESCAN group anywhere in the project, CMake will replace any standalone use of that library with the whole group when linking any target. A library can be a member of multiple RESCAN groups, although such cases are probably an indication that those groups may each be underspecified.

18.2.2. Link Library Features

The `$<LINK_LIBRARY:...>` generator expression has a different and larger set of built-in features. The generator expression's official documentation lists all the supported features, but a few are discussed here to demonstrate the usage.

In the following example, `Things` is the main library that consumers are expected to link to. However, the project implements some of the `Things` public API in the separate `SubPart` and `AnotherPart` static libraries. These are not just private implementation details, they are functions, etc. that consumers of `Things` might reference directly, but which `Things` itself might not reference.

```
add_library(SubPart STATIC ...)
add_library(AnotherPart STATIC ...)
```

```
add_library(Things SHARED ...)

target_link_libraries(Things PRIVATE
    SubPart
    AnotherPart
)

add_executable(App ...)
target_link_libraries(App PRIVATE Things)
```

In the example as shown, the linker would normally end up discarding all the symbols from SubPart and AnotherPart when linking Things as a shared library. The built-in WHOLE_ARCHIVE library feature can be used to prevent the linker from discarding those symbols:

```
target_link_libraries(Things PRIVATE
    $<LINK_LIBRARY:WHOLE_ARCHIVE,SubPart,AnotherPart>
)
```

CMake again chooses the appropriate flags for the linker command line to implement the constraint. With Visual Studio toolchains, the /WHOLEARCHIVE option would be used. For toolchains using the GNU ld linker, the --whole-archive flag might be used in conjunction with other flags that push and pop the state of that feature (where supported).

CMake may take advantage of the libraries being expressed in a single expression to reduce the number of flags added to the linker command line. Note though that the libraries are not

guaranteed to be listed together as a group. Use `$<LINK_GROUP:>` for cases that require the set of libraries to be kept together.

When targeting Apple platforms, a number of other built-in `$<LINK_LIBRARY:>` features are available. The FRAMEWORK feature can be used to explicitly force a library to be treated as a framework. This is more useful when linking an external framework by name rather than as a CMake target (see [Section 25.10, “Linking Frameworks”](#)). The NEEDED_FRAMEWORK and NEEDED_LIBRARY features can be used to force the linker to make a target link to a framework or library, even if the target doesn’t use any symbols from it. This may be desirable if no symbols from the framework or library are referenced directly by the target, but the framework or library has global objects whose constructors have side effects (registering handlers, etc.). Other built-in features provide support for weak imports and re-exporting symbols, but those are fairly advanced use cases.

In more complex projects, there is a greater likelihood that conflicting `$<LINK_LIBRARY:>` expressions will occur. CMake 3.24 and later support `LINK_LIBRARY_OVERRIDE` and `LINK_LIBRARY_OVERRIDE_<LIBRARY>` target properties as a potential way of addressing those situations. They allow a target to override link features attached to libraries it uses. These override properties should be considered a last resort workaround for what is already an advanced feature. They are appropriate for certain scenarios, but they should be avoided if

possible. See the official CMake documentation of the properties for examples of their usage.

18.2.3. Custom Features

The `$<LINK_LIBRARY:...>` and `$<LINK_GROUP:...>` generator expressions also support custom features, but projects won't normally need this advanced capability. The official CMake documentation explains the steps involved for those projects that do require that level of customization and control.

18.2.4. Feature Validity

It is the project's responsibility to ensure that it only uses a `$<LINK_LIBRARY:...>` or `$<LINK_GROUP:...>` feature with a set of libraries for which that feature is valid. CMake does not try to detect invalid combinations in most cases. For example, using `$<LINK_LIBRARY:WHOLE_ARCHIVE,...>` with anything other than static libraries would be inappropriate.

CMake 3.30 added some improvements that may allow combinations of features that CMake 3.29 and older do not. See the official documentation for the `CMAKE_LINK_LIBRARY_<FEATURE>_ATTRIBUTES` CMake variable for a discussion of the more advanced features that relate to this behavior.

18.2.5. Library Ordering And De-duplication

The features discussed in the preceding sections address more advanced scenarios that require certain relationships between libraries to be handled a particular way. But for most cases, accurate dependency relationships specified between targets will be enough to ensure that CMake invokes the linker with appropriate details. CMake will use this information, potentially re-ordering and de-duplicating items to be linked, but still preserving those dependency relationships. The exact linker invocation will take into account the capabilities of the linker (subject to policies `CMP0156` and `CMP0179`). For example, some linkers have the equivalent of the `RESCAN` feature always enabled for the command line as a whole, and CMake may de-duplicate linked items to avoid warnings from such linkers.

Projects do have some limited control over the ordering beyond dependencies between targets, but that additional control should generally be avoided. CMake 3.31 added the `LINK_LIBRARIES_STRATEGY` target property, which affects how libraries can be reordered. However, this property still only influences CMake's behavior, it doesn't allow a project to have absolute control. De-duplication can still effectively change the order specified by that property. Therefore, it cannot be relied on to achieve a specific order. Projects should focus instead on defining accurate relationships between targets. CMake will always honor those relationships, taking into account the target types and toolchain capabilities.

18.3. Propagating Up Direct Link Dependencies

For most projects, linking relationships between targets should be specified purely through `target_link_libraries()` calls. These clearly express relationships as something the target needs (PRIVATE), something consumers of the target need (INTERFACE), or something needed by both (PUBLIC).

In some scenarios, the nature of the relationship is more complex. Sometimes, a set of objects must be linked only by the top level executable or shared library at the head of the link dependency chain. The *link seaming* technique is an example of this. An interface is defined in a lower level library, and while that library may make use of the interface, it doesn't provide the implementation for it. Instead, the application is expected to provide the implementation, usually as object files on the linker command line (using object files ensures library ordering issues are avoided). Projects can take advantage of this technique to use different implementations in different executables. Production applications might use real implementations, whereas test executables might provide predictable values or use mocked implementations with non-essential features stubbed out.

Relationships like the above cannot be easily and robustly expressed with CMake 3.23 and earlier. The library depends on

the executable consuming it, but there may be different executables, so the library can't express the dependency. The project has to rely on adding object files directly to each executable or shared library target. It cannot attach that logic to an intermediate library that executables and shared libraries link to.

With CMake 3.24 or later, the `INTERFACE_LINK_LIBRARIES_DIRECT` target property can be used to handle these scenarios. It allows a target to specify libraries that should be treated as *direct* link dependencies of all targets up to the executable or shared library at the top of the dependency chain. Compare this with the `INTERFACE_LINK_LIBRARIES` property, which adds *indirect* dependencies to that target's immediate consumers only.

The differences between direct and indirect dependencies are subtle. One of the more important differences is in how object libraries are affected (see [Section 19.2.2, “Object Libraries”](#)). Object libraries linked *indirectly* do not add their objects to the consumer. Their objects only get added for *direct* link dependencies. This is important, because it means `INTERFACE_LINK_LIBRARIES_DIRECT` can list object libraries and those objects *will* be added to the linker command line of each target in the chain up to the executable or shared library. An object library listed in `INTERFACE_LINK_LIBRARIES` will only add object files to the linker command line of its immediate consumer. If that immediate consumer isn't an executable or

shared library, those object files won't end up being part of the eventual executable or shared library, leading to unresolved symbols.

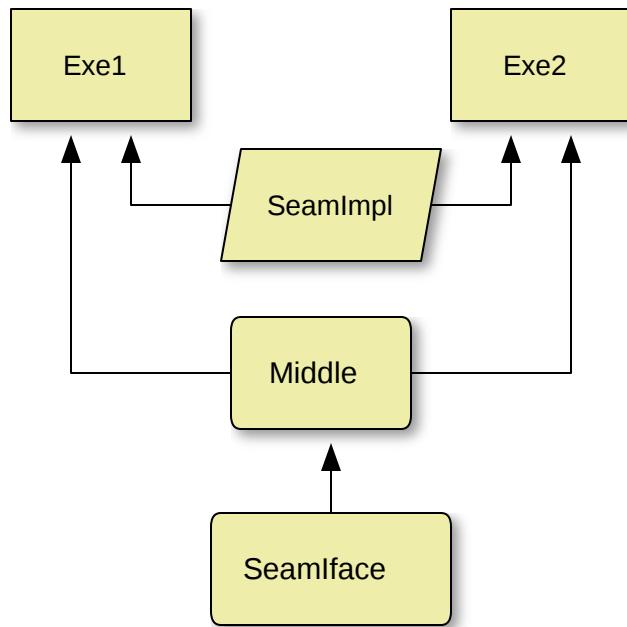
18.3.1. Link Seaming Example

Consider the following partial example:

```
add_executable(Exe1 ...)
add_executable(Exe2 ...)
add_library(Middle STATIC ...)
add_library(SeamIface STATIC ...)
add_library(SeamImpl OBJECT ...)

# INCOMPLETE: Exe1 & Exe2 still need SeamImpl to be linked
target_link_libraries(Exe1 PRIVATE Middle)
target_link_libraries(Exe2 PRIVATE Middle)
target_link_libraries(Middle PRIVATE SeamIface)
```

The final desired set of direct linking relationships can be represented like so:



In the above example, SeamIface uses symbols that it doesn't provide and doesn't pull in from its own link dependencies. It expects those symbols to be provided by the final executable or shared library it gets linked into. SeamImpl provides those implementations.

With CMake 3.23, one would have to explicitly add SeamImpl to every executable that linked directly or indirectly to SeamIface:

```

target_link_libraries(Exe1 PRIVATE SeamImpl)
target_link_libraries(Exe2 PRIVATE SeamImpl)

```

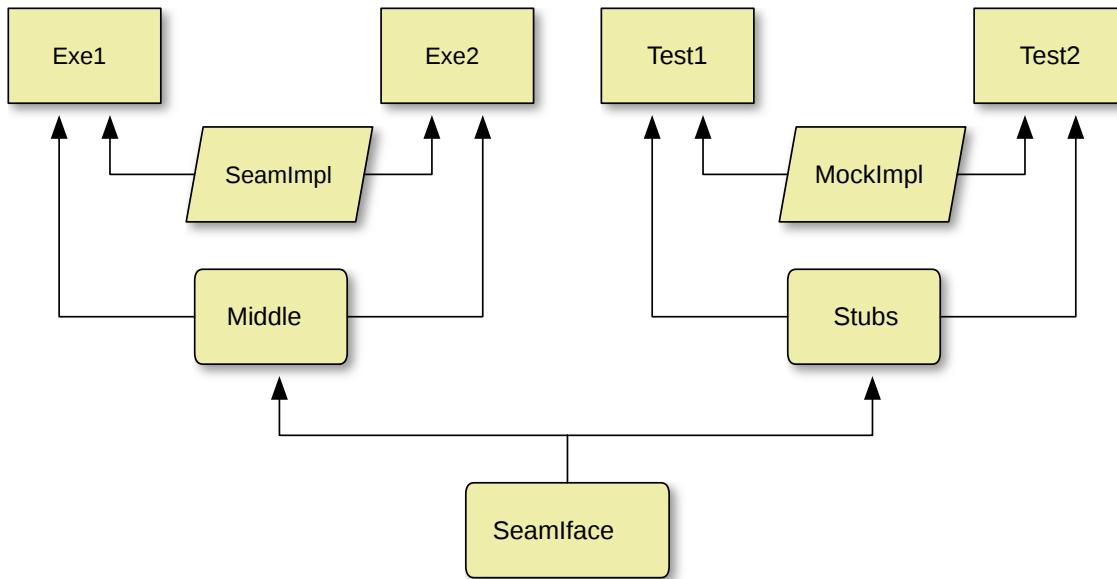
With CMake 3.24 or later, the requirement can be attached to the Middle target instead. Anything that links to Middle (directly

or indirectly) will then have SeamImpl added to its direct dependencies:

```
set_target_properties(Middle PROPERTIES  
    INTERFACE_LINK_LIBRARIES_DIRECT SeamImpl  
)
```

Attaching the implementation to Middle is more convenient if there are many executables.

Expanding the example further, it becomes clearer how this pattern allows different link seam implementations to be provided to different groups of executables:



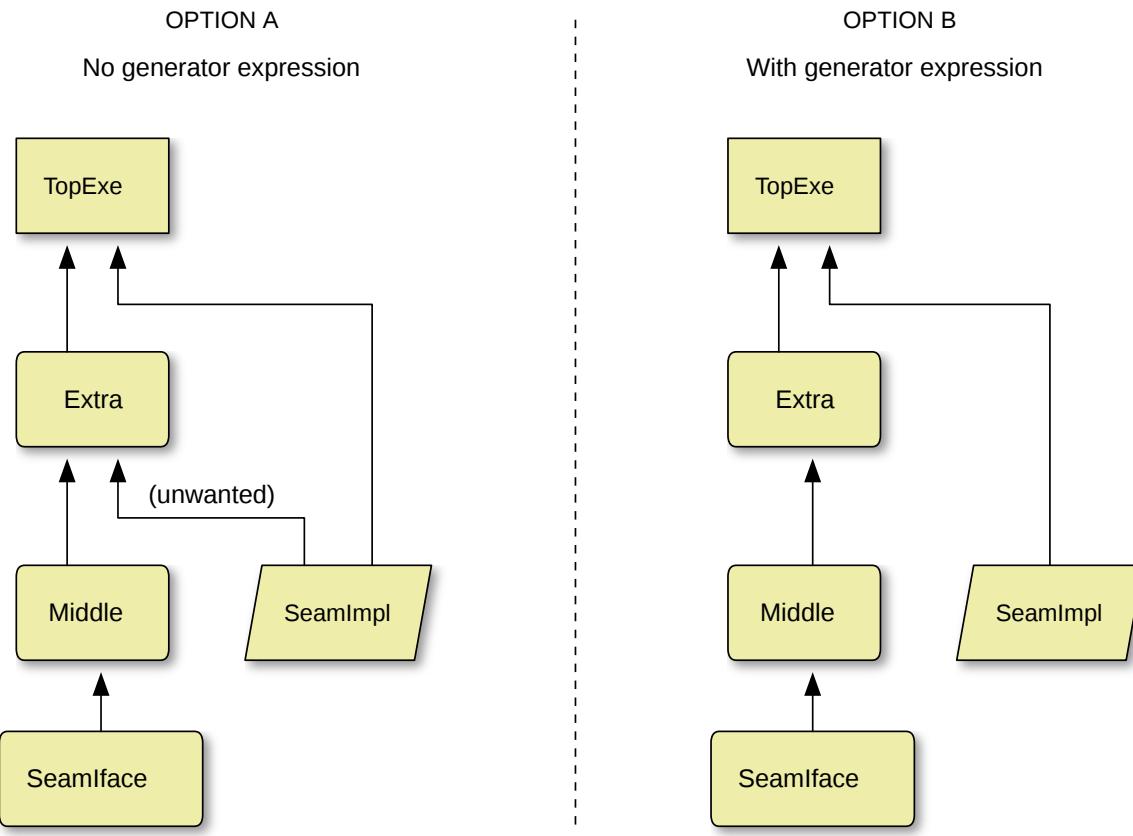
As mentioned earlier, items listed in `INTERFACE_LINK_LIBRARIES_DIRECT` will be linked to *every* target in the dependency chain up to the executable or shared library.

This can result in unwanted linking for intermediate targets. Generator expressions can be used to only add the direct link dependency to the head target at the top of the link dependency chain. This will be an executable, shared library, or module library. The earlier example can be modified to demonstrate this behavior:

```
add_executable(TopExe ...)  
add_library(Extra STATIC ...)  
add_library(Middle STATIC ...)  
add_library(SeamIface STATIC ...)  
add_library(SeamImpl OBJECT ...)  
  
target_link_libraries(TopExe PRIVATE Extra)  
target_link_libraries(Extra PRIVATE Middle)  
target_link_libraries(Middle PRIVATE SeamIface)
```

```
# OPTION A: No generator expression  
set_target_properties(Middle PROPERTIES  
    INTERFACE_LINK_LIBRARIES_DIRECT SeamImpl  
)
```

```
# OPTION B: With generator expression  
  
# Build up a generator expression that evaluates to 1 only  
# for the head target  
set(type "<TARGET_PROPERTY:TYPE>")  
set(head_targets EXECUTABLE SHARED_LIBRARY MODULE_LIBRARY)  
set(is_head "<IN_LIST:${type}, ${head_targets}>")  
  
set_target_properties(Middle PROPERTIES  
    INTERFACE_LINK_LIBRARIES_DIRECT  
    "${${is_head}:SeamImpl}"  
)
```



Extra is a static library, so it does not need the SeamImpl objects. But without using the generator expression to limit the direct linking of SeamImpl, Extra will contain its own copy of the SeamImpl objects.

18.3.2. Static Plugins

`INTERFACE_LINK_LIBRARIES_DIRECT` can be used for other scenarios too. Some projects define a library with one or more associated plugins. When the project is built as a shared library and plugin, the library loads the plugin dynamically at run time. When they are built statically, the plugin has to be linked

in to any executable that uses the library, and the library has to find the plugin using some other mechanism. Something also has to use symbols from the plugin to prevent the linker from discarding them. The project may choose to list the plugin in the library's `INTERFACE_LINK_LIBRARIES_DIRECT` property (this is the example used by CMake's own documentation for that property). More likely, an object library with a registration function that references the plugin's symbols would be listed instead. This arrangement means an executable can link to the library, and regardless of whether things were built as shared or static, the plugin will be available to the application.

The plugin scenario is likely to be more complicated than the above brief description. Implementing the plugin registration functions and the symbol search in the library can be non-trivial. They are specific to the project and the capabilities of the target platform. In certain cases, a companion `INTERFACE_LINK_LIBRARIES_DIRECT_EXCLUDE` property may be needed as well. It allows the final list of direct link dependencies to be filtered before they are added to the linker command line. Used incorrectly, it can break linker command lines by re-ordering things in a way that doesn't satisfy the dependencies between libraries. As such, it should be avoided unless it is absolutely necessary. Consult the official CMake documentation for further details on how to use the `INTERFACE_LINK_LIBRARIES_DIRECT_EXCLUDE` property and scenarios that may require it.

18.4. Recommended Practices

Where possible, link to targets rather than to raw library names or paths. Targets are more portable across platforms, and they support bringing other usage requirements rather than specifying just a basic linking relationship. Consider setting `CMAKE_LINK_LIBRARIES_ONLY_TARGETS` to true as a cache variable on the `cmake` command line or in presets to enforce this as a requirement.

The `$<LINK_GROUP:>` and `$<LINK_LIBRARY:>` generator expressions available with CMake 3.24 or later should not be used without careful consideration of the alternatives. Some of the features they offer can easily be misused as a way to cover over structural problems in the project. Avoid using `$<LINK_GROUP:RESCAN,>` if the interdependencies between the libraries can be removed through refactoring and restructuring. Rather than using `$<LINK_LIBRARY:WHOLE_ARCHIVE,>`, consider whether using object libraries or combining separate libraries into a single library would be a better solution. See [Section 23.6, “Mixing Static And Shared Libraries”](#) for further discussion of this area.

Similarly, avoid using the `INTERFACE_LINK_LIBRARIES_DIRECT` target property if the relationships between targets can be fully expressed without it. There are valid scenarios where it may be appropriate, such as when using link seaming techniques or

certain types of static plugin handling. These should be viewed as more advanced methods to solve specific problems rather than something to reach for as a first choice solution.

19. TARGET TYPES

CMake supports a wide variety of target types, not just the simple executables and libraries introduced back in [Chapter 4, *Building Simple Targets*](#). Different target types can be defined that act as a reference to other entities rather than being built themselves. They can also be used to collect together transitive properties and dependencies without actually producing their own binaries. They can even be a kind of library that is simply a collection of object files rather than a traditional static or shared library. Many things can be abstracted away as a target to hide the complexities of platform differences, locations in the filesystem, file names, and so on. This chapter covers all of these various target types and discusses their uses.

Another category of target is the utility or custom target. These can be used to execute arbitrary commands and define custom build rules, allowing projects to implement just about any sort of behavior needed. They have their own dedicated commands and unique behaviors and are covered in depth in the next chapter.

19.1. Executables

The `add_executable()` command has more than just the form introduced back in [Chapter 4, Building Simple Targets](#). Two other forms also exist which can be used to define executable targets that reference other things. The full set of supported forms are:

```
add_executable(targetName  
    [WIN32] [MACOSX_BUNDLE]  
    [EXCLUDE_FROM_ALL]  
    source1 [source2 ...]  
)  
add_executable(targetName IMPORTED [GLOBAL])  
add_executable(aliasName ALIAS targetName)
```

The `IMPORTED` form can be used to create a CMake target for an existing executable rather than one built by the project. By creating a target to represent the executable, other parts of the project can treat it just like it would any other executable target that the project built itself (with some restrictions). The most significant benefit is that it can be used in contexts where CMake automatically replaces a target name with its location on disk, such as when executing commands for tests or custom tasks (both covered in later chapters). One of the few differences compared to a regular target is that imported targets cannot be installed, a topic covered in [Chapter 35, Installing](#).

When defining an imported executable target, certain target properties need to be set before it can be useful. Most of the relevant properties for any imported target have names beginning with IMPORTED, but for executables, IMPORTED_LOCATION and IMPORTED_LOCATION_<CONFIG> are the most important. When the location of the imported executable is needed, CMake will first look at the configuration-specific property, and only if that is not set will it look at the more generic IMPORTED_LOCATION property. Often, the location doesn't need to be configuration-specific, so it is common for only IMPORTED_LOCATION to be set.

When defined without the GLOBAL keyword, an imported target will only be visible in the current directory scope and below, but adding GLOBAL makes the target visible everywhere. In contrast, regular executable targets built by the project are always global. The reasons for this and some of the associated implications of reduced target visibility are covered in [Section 19.3, “Promoting Imported Targets”](#) further below.

An ALIAS target is a read-only way to refer to another target within CMake. It can be used to read properties of the target it aliases, and it may be used in custom commands and test commands just like the aliased target (see [Section 20.1, “Custom Targets”](#) and [Section 27.1, “Defining And Executing A Simple Test”](#) respectively). An alias does not create a new build target with the alias name. There are limitations to defining and using aliases:

- Aliases cannot be installed or exported (both covered in [Chapter 35, Installing](#)).
- An alias of an alias is not supported.
- Prior to CMake 3.11, imported targets could not be aliased at all.
- From CMake 3.11, imported targets with global visibility can be aliased.
- From CMake 3.18, an alias of a non-global imported target can be created, and that alias will also be non-global. The alias cannot later be promoted to global visibility, even if the imported target it aliases is promoted (see [Section 19.3, “Promoting Imported Targets”](#)).

19.2. Libraries

The `add_library()` command also has a number of different forms. The details for libraries are more involved than for executables, which is a consequence of the variety of roles that libraries can take in a project.

19.2.1. Basic Library Types

The basic form introduced back in [Chapter 4, Building Simple Targets](#) can be used to define the common types of libraries most developers are familiar with:

```
add_library(targetName  
           [STATIC | SHARED | MODULE]
```

```
[EXCLUDE_FROM_ALL]
source1 [source2 ...]
)
```

If no STATIC, SHARED or MODULE keyword is given, the library will be either STATIC or SHARED. The choice is determined by the value of the BUILD_SHARED_LIBS variable (see [Section 23.1, “Build Basics”](#)).

19.2.2. Object Libraries

The `add_library()` command can also be used to define *object libraries*. These are a collection of object files that are not combined into a single archive or shared library:

```
add_library(targetName OBJECT
[EXCLUDE_FROM_ALL]
source1 [source2 ...]
)
```

With CMake 3.11 or earlier, object libraries cannot be linked like other library types (i.e. they cannot be used with `target_link_libraries()`). They require using a generator expression of the form `$<TARGET_OBJECTS:objLib>` as part of the list of sources for another executable or library target. With these older CMake versions, because object libraries cannot be linked, they cannot provide transitive dependencies to the targets they are added to using the above generator expression. This can make them less convenient than the other library

types, since header search paths, compiler defines, etc. have to be manually carried across to the targets they are added to.

CMake 3.12 introduced features that make object libraries behave more like other types of libraries, but with some caveats. From CMake 3.12, object libraries *can* be used with `target_link_libraries()`, either as the target being added to (i.e. the first argument to the command) or as one of the libraries being added. But because they add object files rather than actual libraries, their transitive nature is more restricted to prevent object files from being added multiple times to consuming targets. A simplistic explanation is that object files are only added to a target that links *directly* to the object library, not transitively beyond that. The object library's usage requirements *do*, however, propagate transitively exactly like an ordinary library would.



The propagation of an object library's own link library dependencies initially contained an implementation bug which was not fixed until CMake 3.14.0. Projects should set their minimum CMake version to 3.14 or later if they intend to link to object libraries.

Some developers may find object libraries more natural if coming from a background where non-CMake projects defined their targets based on sources or object files rather than a related set of static libraries. In general, however, where there

is a choice, static libraries will typically be the more convenient choice in CMake projects. Before relying on the expanded features available for object libraries in CMake 3.12 and later, consider whether an ordinary static library is more appropriate and ultimately easier to use.

19.2.3. Imported Libraries

Just like executables, libraries may also be defined as imported targets. These are heavily used by config files created during packaging and by Find module implementations (covered in [Chapter 34, Finding Things](#) and [Chapter 35, Installing](#)), but have limited use outside of those contexts. They don't define a library to be built by the project. Rather, they act as a reference to a library that is provided externally. The library might already exist on the system, it might be built by some process outside the current CMake project, it could be provided by the package that a config file is part of.

```
add_library(targetName
    (STATIC | SHARED | MODULE | OBJECT | UNKNOWN)
    IMPORTED [GLOBAL]
)
```

The library type must be given immediately after the `targetName`. If the type of library that the new target will refer to is known, it should be specified as such. This will allow CMake to treat the imported target just like a regular library target of the named type in various situations. The type can only be set

to OBJECT with CMake 3.9 or later (imported object libraries were not supported before that version). If the library type is not known, the UNKNOWN type should be given, in which case CMake will simply use the full path to the library without further interpretation in places like linker command lines. This will mean fewer checks, and in the case of Windows builds, no handling of DLL import libraries.

Except for OBJECT libraries, the location on the filesystem that the imported target represents usually needs to be specified by the IMPORTED_LOCATION or IMPORTED_LOCATION_<CONFIG> properties. In the case of Windows platforms, two properties should be set: IMPORTED_LOCATION should hold the location of the DLL and IMPORTED_IMPLIB should hold the location of the associated import library, which usually has a .lib file extension (the ..._<CONFIG> variants of these properties can also be set and will take precedence). For object libraries, instead of the above location properties, the IMPORTED_OBJECTS property must be set to a list of object files that the imported target represents.

```
# Windows-specific example of imported library
add_library(MyWindowsLib SHARED IMPORTED)

set_target_properties(MyWindowsLib PROPERTIES
    IMPORTED_LOCATION /some/path/bin/foo.dll
    IMPORTED_IMPLIB   /some/path/lib/foo.lib
)
```

```
# Assume FOO_LIB holds the location of the library but
# its type is unknown
```

```

add_library(MysteryLib UNKNOWN IMPORTED)

set_target_properties(MysteryLib PROPERTIES
    IMPORTED_LOCATION ${FOO_LIB}
)

# Imported object library, Windows example shown
add_library(MyObjLib OBJECT IMPORTED)

set_property(TARGET MyObjLib PROPERTY
    # These .obj files would be .o on most other platforms
    IMPORTED_OBJECTS /some/path/obj1.obj
        /some/path/obj2.obj
)
# Regular executable target using imported object library.
# Platform differences assumed to be handled by MyObjLib.
add_executable(MyExe ${TARGET_OBJECTS:MyObjLib})

```

CMake 3.28 improved the support for imported targets representing Apple frameworks (see [Section 25.3, “Frameworks”](#)). Project code can set `IMPORTED_LOCATION` to the `.framework` or `.xcframework` directory, and CMake will automatically find and use the `.tbd` stub within it, if present. `IMPORTED_IMPLIB` can be set to explicitly point to the `.tbd` file, but this isn’t required, nor recommended. The real library can be missing, with only the `.tbd` stub provided by the framework. This is fine, as long as the framework is only needed at build time and not to run anything. Such an arrangement is also supported for non-framework targets where `IMPORTED_IMPLIB` can point to a stub library or equivalent (supported on Windows, Linux and AIX). For example, code might be built on

one machine, but run or tested on another, on a device, or in a simulator.

Imported libraries also support a number of other target properties, most of which can typically be left alone or are automatically set by CMake. Developers who need to manually write config packages should refer to the CMake reference documentation to understand the other `IMPORTED_...` target properties which may be relevant to their situation. Most projects will rely on CMake generating such files for them though, so the need to do this should be fairly uncommon.

By default, imported libraries are defined as local targets, meaning they are only visible in the current directory scope and below. The `GLOBAL` keyword can be given to make them have global visibility instead, just like other regular targets. A library may initially be created without the `GLOBAL` keyword but later promoted to global visibility, a topic covered in detail in [Section 19.3, “Promoting Imported Targets”](#) further below.

19.2.4. Interface Libraries

Another form of the `add_library()` command allows interface libraries to be defined. These do not usually represent a physical library, instead they primarily serve to collect usage requirements and dependencies to be applied to anything that links to them. A popular example of their use is for header-only libraries where there is no physical library that needs to be

linked, but header search paths, compiler definitions, etc. need to be carried forward to anything using the headers.

```
add_library(targetName INTERFACE)
```

All the various target_...() commands can be used with their INTERFACE keywords to define the usage requirements the interface library will carry. One can also set the relevant INTERFACE_... properties directly with set_property() or set_target_properties(), but the target_...() commands are safer and easier to use.

```
add_library(MyHeaderOnlyToolkit INTERFACE)
target_include_directories(MyHeaderOnlyToolkit
    INTERFACE
        ${BUILD_INTERFACE:/some/path/include}
)
target_compile_definitions(MyHeaderOnlyToolkit
    INTERFACE
        COOL_FEATURE=1
        ${${COMPILE_FEATURES:cxx_std_11}:HAVE_CXX11}
)

add_executable(MyApp ...)
target_link_libraries(MyApp
    PRIVATE
        MyHeaderOnlyToolkit
)
```

In the above example, the MyApp target links against the MyHeaderOnlyToolkit interface library. When the MyApp sources are compiled, they will have /some/path/include as a header search path and will also have a compiler definition

`COOL_FEATURE=1` provided on the compiler command line. If the `MyApp` target is being built with C++11 support enabled, it will also have the symbol `HAVE_CXX11` defined. The headers in `MyHeaderOnlyToolkit` can then use this symbol to determine what things they declare and define rather than relying on the `__cplusplus` symbol provided by the C++ standard, the value of which is often unreliable for a range of compilers.

Ordinarily, an interface library would not have any sources, but in some cases it can make sense. Header-only libraries are one such example. The headers are likely to be of interest to developers, and they may want the headers to show up in their IDE. Since the headers are not part of any other target, they normally wouldn't appear. By adding them to the interface library as sources, IDEs usually have enough information to be able to show the headers under one or more targets.

A special sub-case of the above example is when one or more headers in a header-only library are generated as part of the build (a topic covered in [Section 20.3, “Commands That Generate Files”](#)). With CMake 3.18 or earlier, if nothing in the project actually uses the interface library, the project needs to create a separate custom target to ensure that the headers will be generated. Another limitation with CMake 3.18 and earlier is that sources cannot be added to the interface library in the `add_library()` call. A separate call to `target_sources()` has to be

used instead (see [Section 16.2.6, “Source Files”](#)). The resultant code would take the following form:

```
# Defines how to generate the header
add_custom_command(OUTPUT someHeader.h COMMAND ...)

# Required for CMake <= 3.18 to ensure header is generated
add_custom_target(GenerateSomeHeader ALL
    DEPENDS ${CMAKE_CURRENT_BINARY_DIR}/someHeader.h
)

# CMake <= 3.18 doesn't allow sources to be added to an
# INTERFACE target directly in the add_library() call
add_library(MyHeaderOnly INTERFACE)
target_sources(MyHeaderOnly
    INTERFACE
    ${CMAKE_CURRENT_BINARY_DIR}/someHeader.h
)
```

From CMake 3.19, both of the above-mentioned restrictions have been removed. Sources can be listed directly in the `add_library()` call for interface libraries, and they will be treated as private sources. This means that unlike the example above, the headers will not be added to targets that link to the interface library. Instead, they will remain associated only with the interface library itself and therefore will only show up in IDEs under that library instead of in all of its consumers. CMake will also create a build system target for the interface library if any sources are added to it. Bringing that build system target up to date like any other target will then ensure that its generated sources are created. The result is more concise, and it will usually produce a better experience in most mainstream IDEs:

```
add_custom_command(OUTPUT someHeader.h COMMAND ...)

# Requires CMake 3.19 or later
add_library(MyHeaderOnly INTERFACE
    ${CMAKE_CURRENT_BINARY_DIR}/someHeader.h
)
```

Another use of interface libraries is to provide a convenience for linking in a larger set of libraries, possibly encapsulating logic that selects which libraries should be in the set. For example:

```
# Regular library targets
add_library(Algo_Fast ...)
add_library(Algo_Accurate ...)
add_library(Algo_Beta ...)

# Convenience interface library
add_library(Algo_All INTERFACE)
target_link_libraries(Algo_All INTERFACE
    Algo_Fast
    Algo_Accurate
    ${$<$<BOOL:${ENABLE_ALGO_BETA}>:Algo_Beta}
)

# Other targets link to the interface library
# instead of each of the real libraries
add_executable(MyApp ...)
target_link_libraries(MyApp PRIVATE Algo_All)
```

The above will only include Algo_Beta in the list of libraries to link if the CMake option variable ENABLE_ALGO_BETA is true. Other targets then link to Algo_All and the conditional linking of Algo_Beta is handled by the interface library. This is an example of using an interface library to abstract away details of what is

actually going to be linked, defined, etc. so that the targets linking against them don't have to implement those details for themselves. This can be exploited to do things like abstract away completely different library structures on different platforms, switch library implementations based on some condition (variables, generator expressions, etc.), provide an old library target name where the library structure has been refactored (e.g. split up into separate libraries), and so on.

19.2.5. Interface Imported Libraries

```
add_library(targetName INTERFACE IMPORTED [GLOBAL])
```

While the use cases for INTERFACE libraries are generally well understood, the addition of the IMPORTED keyword to yield an INTERFACE IMPORTED library can sometimes be a cause of confusion. This combination usually arises when an INTERFACE library is exported or installed for use outside the project. It still serves the purpose of an INTERFACE library when consumed by another project, but the IMPORTED part is added to indicate the library came from somewhere else. The effect is to restrict the default visibility of the library to the current directory scope instead of global. With minor exceptions discussed below, adding the GLOBAL keyword to yield the keyword combination INTERFACE IMPORTED GLOBAL results in a library with little practical difference to INTERFACE alone.

An INTERFACE IMPORTED library is not required to (and indeed is prohibited from) setting an IMPORTED_LOCATION. Instead, one can set its IMPORTED_LIBNAME property, if desired. The IMPORTED_LIBNAME is intended for representing libraries provided by the toolchain or platform, but whose location isn't known. The IMPORTED_LIBNAME specifies the name to include on the linker command line. It is not permitted to specify any path, only a bare library name. [Section 18.1, “Require Targets For Linking”](#) includes an example where its use is required.

Before CMake 3.11, none of the target_...() commands could be used to set INTERFACE_... properties on any kind of IMPORTED library. These properties *could*, however, be set using set_property() or set_target_properties(). CMake 3.11 removed the restriction on using target_...() commands to set these properties, so whereas INTERFACE IMPORTED used to be very similar to plain IMPORTED libraries, with CMake 3.11 they are now much closer to plain INTERFACE libraries in terms of their set of restrictions.

The following table summarizes what the various keyword combinations support:

Keywords	Visibility	IMPORTED_LOCATION	IMPORTED_LIBNAME	Set Interface Properties	Installable
----------	------------	-------------------	------------------	--------------------------	-------------

Keywords	Visibility	IMPORTED_LOCATION	IMPORTED_LIBNAME	Set Interface Properties	Installable
INTERFACE	Global	Prohibited	Prohibited	Any method	Yes
IMPORTED	Local	Required	Prohibited	Restricted*	No
IMPORTED GLOBAL	Global	Required	Prohibited	Restricted*	No
INTERFACE IMPORTED	Local	Prohibited	Permitted	Restricted*	No
INTERFACE IMPORTED GLOBAL	Global	Prohibited	Permitted	Restricted*	No

* The various `target_...()` commands can be used to set `INTERFACE_...` properties with CMake 3.11 or later. The `set_property()` or `set_target_properties()` commands can be used with any CMake version.

One could be forgiven for thinking that the number of different interface and imported library combinations is overly complicated and confusing. For most developers, however, imported targets are generally created for them behind the scenes, and they appear to act more or less like regular targets. Of all the combinations in the above table, only plain INTERFACE targets would typically be defined by a project directly. [Chapter 35, Installing](#) covers much of the motivation and mechanics of the other combinations.

19.2.6. Library Aliases

The last form of the `add_library()` command is for defining a library alias:

```
add_library(aliasName ALIAS otherTarget)
```

A library alias is mostly analogous to an executable alias. It acts as a read-only way to refer to another library, but does not create a new build target. Library aliases cannot be installed, and they cannot be defined as an alias of another alias. Before CMake 3.11, a library alias could not be created for imported targets. However, as with other changes made for imported targets in CMake 3.11, this restriction was relaxed, and it has become possible to create aliases for globally visible imported targets. CMake 3.18 relaxed that restriction further to allow non-global aliases to be created for non-global imported targets.

There is a particularly common use of library aliases that relates to an important feature introduced in CMake 3.0. For each library that will be installed or packaged, a common pattern is to also create a matching library alias with a name of the form `projNamespace::targetName`. All such aliases within a project would typically share the same `projNamespace`. For example:

```
# Any sort of real library (SHARED, STATIC, MODULE  
# or possibly OBJECT)  
add_library(MyRealThings SHARED src1.cpp ...)  
add_library(OtherThings STATIC srcA.cpp ...)
```

```
# Aliases to the above with special names
add_library(BagOfBeans::MyRealThings ALIAS MyRealThings)
add_library(BagOfBeans::OtherThings ALIAS OtherThings)
```

Within the project itself, other targets would link to either the real targets or the namespaced targets (both have the same effect). The motivation for the aliases comes from when the project is installed and something else links to the imported targets created by the installed/packaged config files. Those config files would define imported libraries with the namespaced names rather than the bare original names (see [Section 35.3, “Installing Exports”](#)). The consuming project would then link against the namespaced names. For example:

```
# Pull in imported targets from an installed package
find_package(BagOfBeans REQUIRED) ①

# Define an executable that links to the imported
# library from the installed package
add_executable(EatLunch main.cpp ...)
target_link_libraries(EatLunch PRIVATE
    BagOfBeans::MyRealThings
)
```

① The `find_package()` command is discussed in [Chapter 34, *Finding Things*](#).

If at some point the above project wanted to incorporate the `BagOfBeans` project directly into its own build instead of finding an installed package, it could do so without changing its linking relationship because the `BagOfBeans` project provided an alias for the namespaced name:

```
# Add BagOfBeans directly to this project, making
# all of its targets directly available
add_subdirectory(BagOfBeans)

# Same definition of linking relationship still works
add_executable(EatLunch main.cpp ...)
target_link_libraries(EatLunch PRIVATE
    BagOfBeans::MyRealThings
)
```

Another important aspect of names having a double-colon (::) is that CMake will always treat them as the name of an alias or imported target. Any attempt to use such a name for a different target type will result in an error. Perhaps more usefully though, when the target name is used as part of a `target_link_library()` call, if CMake doesn't know of a target by that name, it will issue an error at generation time. Compare this to an ordinary name which CMake will treat as a library assumed to be provided by the system if it doesn't know of a target by that name. This can lead to the error only becoming apparent much later at build time.

```
add_executable(Main main.cpp)
add_library(Bar STATIC ...)
add_library(Foo::Bar ALIAS Bar)

# Typo in name being linked to, CMake will assume a
# library called "Bart" will be provided by the
# system at link time and won't issue an error.
target_link_libraries(Main PRIVATE Bart)

# Typo in name being linked to, CMake flags an error
# at generation time because a namespaced name must
```

```
# be a CMake target.  
target_link_libraries(Main PRIVATE Foo::Bart)
```

It is therefore more robust to link to namespaced names where they are available. Projects are strongly encouraged to define namespaced aliases at least for all targets that are intended to be installed/packaged. Such namespaced aliases can even be used within the project itself, not just by other projects consuming it as a pre-built package or child project. [Section 35.3, “Installing Exports”](#) also discusses how to change the name used for the `targetName` part of a namespaced name, which can allow an original target like `MyProj_Algo` to have a namespaced name like `MyProj::Algo` instead of the more verbose and repetitive `MyProj::MyProj_Algo`.

19.3. Promoting Imported Targets

When defined without the `GLOBAL` keyword, imported targets are only visible in the directory scope in which they are created or below. This behavior stems from their main intended use, which is as part of a Find module or package config file. Anything defined by a Find module or package config file is generally expected to have local visibility, so they shouldn’t generally add globally visible targets. This allows different parts of a project hierarchy to pull in the same packages and modules with different settings, yet not interfere with each other.

Nevertheless, there are situations where imported targets need to be created with global visibility, such as to ensure that the same version or instance of a particular package is used consistently throughout the whole project. Adding the GLOBAL keyword when creating the imported library achieves this, but the project may not be in control of the command that does the creation.

To provide projects with a way to address this situation, CMake 3.11 introduced the ability to promote an imported target to global visibility by setting the target's IMPORTED_GLOBAL property to true. Note that this is a one-way transition, it is not possible to demote a global target back to local visibility.

```
# Imported library created with local visibility.  
# This could be in an external file brought in  
# by an include() call rather than in the same  
# file as the lines further below.  
add_library(BuiltElsewhere STATIC IMPORTED)  
set_target_properties(BuiltElsewhere PROPERTIES  
    IMPORTED_LOCATION /path/to/libSomething.a  
)  
  
# Promote the imported target to global visibility  
set_target_properties(BuiltElsewhere PROPERTIES  
    IMPORTED_GLOBAL TRUE  
)
```

Also note that an imported target can only be promoted if it is defined in exactly the same scope as the promotion. An imported target defined in a parent or child scope cannot be promoted. The `include()` command does not introduce a new

directory scope, and neither does a `find_package()` call, so imported targets defined by files brought into the build that way *can* be promoted. In fact, this is the main use case for which the ability to promote imported targets was created.

Promoting an imported target does not promote any aliases already pointing to that target. An alias to an imported target always has the visibility that the imported target had when the alias was created. Aliases do not support promotion to global visibility.

`add_library(Original STATIC IMPORTED)`

```
# Local alias (requires CMake 3.18 or later)
add_library(LocalAlias ALIAS Original)

# Promote imported target to global visibility,
# but LocalAlias remains with local visibility
set_target_properties(Original PROPERTIES
    IMPORTED_GLOBAL TRUE
)

# Global alias (requires CMake 3.11 or later)
add_library(GlobalAlias ALIAS Original)
```

In practice, aliases to imported targets should rarely be needed. INTERFACE IMPORTED libraries can largely achieve the same thing, and they work for a wider range of CMake versions. INTERFACE IMPORTED libraries don't support reading the underlying properties of the real library target, but they do carry all the linking and transitive properties.

```
add_library(Original STATIC IMPORTED)
add_library(OtherName INTERFACE IMPORTED Original)
target_link_libraries(OtherName INTERFACE Original)
```

An added advantage of INTERFACE IMPORTED libraries is that they can be promoted to global visibility if required, whereas aliases cannot.

19.4. Recommended Practices

Version 3.0 of CMake brought with it a significant change to the recommended way projects should manage dependencies and requirements between targets. Previously, most things were managed through variables and directory-level commands. The variables had to be managed manually by the project, and the directory-level commands would apply to all targets in a directory and below without much discrimination. With CMake 3.0 and later, each target has the ability to carry all the necessary information in its own properties. This shift in focus to a target-centric model has also led to a family of pseudo target types that facilitate expressing inter-target relationships more flexibly and accurately.

Developers should become familiar with interface libraries in particular. They open up a range of techniques for capturing and expressing relationships without needing to create or refer to a physical file. They can be useful for representing the details of header-only libraries, collections of resources and many

other scenarios and should be strongly preferred over trying to achieve the same result with variables or directory-level commands alone.

Imported targets are encountered frequently once projects start using externally built packages or they refer to tools from the file system that are found through Find modules. Developers should be comfortable using imported targets, but understanding all the ins and outs of how they are defined is not usually necessary unless writing Find modules or manually creating config files for a package. Some specific cases are discussed in [Chapter 35, *Installing*](#) where developers may come up against certain limitations of imported targets, but such scenarios are not very common.

A number of older CMake modules used to provide only variables to refer to imported entities. Starting with CMake 3.0, these modules are progressively being updated to also provide imported targets, where appropriate. For those situations where a project needs to refer to an external tool or library, prefer to do so through an imported target if one is available. These typically do a better job of abstracting away things like platform differences, option-dependent tool selection, and so on. But more importantly, the usage requirements are then robustly handled by CMake. If there is a choice between using an imported library or a variable to refer to the same thing, prefer to use the imported library wherever possible.

Prefer defining static libraries over object libraries. Static libraries are simpler, have more complete and robust support from earlier CMake versions and they are well understood by most developers. Object libraries have their uses, but they are also less flexible than static libraries. In particular, object libraries cannot be linked at all prior to CMake 3.12 and not robustly before CMake 3.14. Without such linking, they don't support transitive dependencies, which forces projects to manually apply the dependencies themselves. This increases the opportunity for errors and omissions. It also reduces the encapsulation that a library target would normally provide. Even the name itself can cause some confusion among developers, since an object library is not a true library, but rather just a set of uncombined object files. But developers still sometimes expect it to behave like a real library. The changes with CMake 3.12 blur that distinction, but the remaining differences still leave room for unexpected results. This is evidenced by the number of queries relating to object libraries and their transitive behavior on the CMake mailing list and issue tracker.

Avoid using target names that are too generic. Globally visible target names must be unique, and names may clash with targets from other projects when used in a larger hierarchical arrangement. In addition, consider adding an alias namespace::... target for each target that is not private to the project (i.e. every target that may end up being installed or packaged). This allows

consuming projects to link to the namespaced target name instead of the real target name, which enables a consuming project to switch between building the child project themselves or using a pre-built installed project relatively easily. While this may initially seem like extra work for not much gain, it is emerging as an expected standard practice among the CMake community, especially for those projects that take a non-trivial amount of time to build. This pattern is discussed further in [Section 35.3, “Installing Exports”](#) and [Section 40.1, “Use Project-specific Names”](#).

Inevitably, at some point, it may become desirable to rename or refactor a library, but there may be external projects that expect the existing library targets to be available to link to. In these situations, use an interface target to provide an old name for a renamed target so that those external projects can continue to build and be updated at their convenience. When splitting up a library, define an interface library with the old target name and have it define link dependencies to the new split-out libraries. For example:

```
# Old library previously defined like this:  
add_library(DeepCompute SHARED ...)
```

Now change DeepCompute to an INTERFACE library that links to the new refactored libraries to preserve backward compatibility:

```
# Now refactored into two separate libraries  
add_library(ComputeAlgoA SHARED ...)
```

```
add_library(ComputeAlgoB SHARED ...)

# Forwarding interface library keeps old projects working
add_library(DeepCompute INTERFACE)
target_link_libraries(DeepCompute INTERFACE
    ComputeAlgoA
    ComputeAlgoB
)
```

20. CUSTOM TASKS

No build tool can implement every feature that will ever be needed by any given project. At some point, developers will need to carry out a task that falls outside the directly supported functionality. For example, a special tool may need to be run to produce source files or to post-process a target after it has been built. Files may need to be copied, verified, or a hash value computed. Build artifacts may need to be archived, or a notification service contacted. Such tasks don't always fit a predictable pattern that would allow them to be provided as a general build system capability.

CMake supports such tasks through custom commands and custom targets. These allow any command or set of commands to be executed at build time to perform whatever arbitrary tasks a project requires. CMake also supports executing tasks at configure time, enabling various techniques that rely on tasks being completed before the build stage, or even before processing later parts of the current `CMakeLists.txt` file.

20.1. Custom Targets

Library and executable targets are not the only kinds of targets that CMake supports. Projects can also define custom targets that perform arbitrary tasks, defined as a sequence of commands to be executed at build time. These custom targets are defined using the `add_custom_target()` command:

```
add_custom_target(targetName
    [ALL]
    [command1 [args1...]]
    [COMMAND command2 [args2...]]
    [DEPENDS depends1...]
    [BYPRODUCTS [files...]]
    [WORKING_DIRECTORY dir]
    [COMMENT comment]
    [VERBATIM]
    [USES_TERMINAL]          # Requires CMake 3.2 or later
    [JOB_POOL poolName]       # Requires CMake 3.15 or later
    [JOB_SERVER_AWARE bool]   # Requires CMake 3.28 or later
    [SOURCES source1 [source2...]])
)
```

A new target with the specified `targetName` will be available to the build and it will always be considered out of date. The `ALL` option makes the *all* target depend on this new custom target (the various generators name the *all* target slightly differently, but it is generally something like `all`, `ALL` or similar). If the `ALL` option is not provided, then the target is only built if it is explicitly requested or if building some other target that depends on it.

When the custom target is built, the specified command(s) will be executed in the order given, with each command able to

have any number of arguments. For improved readability, arguments can be split across multiple lines. The first command does not need to have the `COMMAND` keyword preceding it, but for clarity it is recommended to always include the `COMMAND` keyword even for the first command. This is especially true when specifying multiple commands, since it makes each command use a consistent form.

Commands can be defined to do anything that could be performed on the host platform. Typical commands involve running a script or a system-provided executable, but they can also run executable targets created as part of the build. If another executable target name is listed as the command to execute, CMake will automatically substitute the built location of that other target's executable. This works regardless of the platform or CMake generator being used, thereby freeing the project from having to work out the various platform and generator differences that lead to a range of different output directory structures, file names, etc.

If another target needs to be used as an argument to one of the commands, CMake will not automatically perform the same substitution. But it is trivial to obtain an equivalent substitution with the `$<TARGET_FILE:>` generator expression.

Projects should take advantage of the above-mentioned features to let CMake provide locations of targets rather than hard-coding paths manually. This allows the project to robustly

support all platforms and generator types with minimal effort. The following example shows how to define a custom target which uses two other targets as part of the command and argument list:

```
add_executable(Hasher hasher.cpp)
add_library(MyLib api.cpp)

add_custom_target(CreateHash
    COMMAND Hasher ${TARGET_FILE:MyLib}
)
```

When a target is used as the command to execute, CMake automatically creates a dependency on that executable target to ensure it is built before the custom target. Similarly, if a target is referred to in one of the following generator expressions anywhere in the command or its arguments, a dependency will also be automatically created on that target:

- `$<TARGET_FILE:...>`
- `$<TARGET_LINKER_FILE:...>`
- `$<TARGET SONAME FILE:...>`
- `$<TARGET_PDB FILE:...>`

For CMake 3.18 and earlier, other `$<TARGET_xxx:...>` generator expressions will also lead to a dependency being added automatically. With CMake 3.19 or later, the behavior depends on policy CMP0112. See the CMake documentation of that policy for further details. To create a dependency on a target not

mentioned in such generator expressions, use the `add_dependencies()` command to define that relationship.

If a dependency exists on a *file* rather than a target, the `DEPENDS` keyword can be used to specify that relationship. Note that `DEPENDS` should not be used for target dependencies, only file dependencies. The `DEPENDS` keyword is especially useful when the file being listed is generated by some other custom command (see [Section 20.3, “Commands That Generate Files”](#) further below), where CMake will set up the necessary dependencies to ensure the other custom commands execute before this custom target’s commands. Always use an absolute path for `DEPENDS`, since relative paths can give unexpected results due to a legacy feature that allows path matching against multiple locations.

When multiple commands are provided, each one will be executed in the order listed. But a project should not assume any particular shell behavior. Each command might run in its own separate shell, or without any shell environment at all. Custom commands should be defined as though they were being executed in isolation, and without any shell features such as redirection, variable substitution, etc. Only command order will be enforced. While some of these features may work on some platforms, they are not universally supported.

Also, since no particular shell behavior is guaranteed, escaping within the executable names or their arguments may be handled differently on different platforms. To help reduce these differences, the `VERBATIM` option can be used to ensure that the only escaping done is that by CMake itself when parsing the `CMakeLists.txt` file. The platform performs no further escaping, so the developer can have confidence in how the command is ultimately constructed for execution. If there is any chance of escaping being relevant, use of the `VERBATIM` keyword is recommended.

The directory in which the commands are executed is the current binary directory by default. This can be changed with the `WORKING_DIRECTORY` option, which can be an absolute path or a relative path, the latter being relative to the current binary directory. This means that using `${CMAKE_CURRENT_BINARY_DIR}` as part of the working directory should not be necessary, since a relative path already implies it.

The `BYPRODUCTS` option can be used to list other files that are created as part of running the command(s). If the Ninja generator is being used, this option is required if another target depends on any of the files created as a by-product of running this set of custom commands. Files listed as `BYPRODUCTS` are marked as `GENERATED` (for all generator types, not just Ninja), which ensures the build tool knows how to correctly handle dependency details related to the by-product files. For cases

where a custom target generates files as a by-product, consider whether `add_custom_command()` would be a more appropriate way to define the commands and the things it outputs (see [Section 20.3, “Commands That Generate Files”](#)).

With CMake 3.20 or later, a restricted set of generator expressions is supported for `BYPRODUCTS`. Any expression that refers to a target (e.g. `$<TARGET_FILE:...>`) may not be used.

If the commands produce no output on the console, it can sometimes be useful to specify a short message with the `COMMENT` option. The specified message is logged just before running the commands. If the commands silently fail for some reason, the comment can be a useful marker to indicate where the build failed. Note, however, that for some generators, the comment will not be shown, so this cannot be considered a reliable mechanism, but it may still be useful for those generators that do support it. A universally supported alternative is presented in [Section 20.5, “Platform Independent Commands”](#) below.

`USES_TERMINAL` is another console-related option which instructs CMake to give the command direct access to the terminal, if possible. When using the Ninja generator, this has the effect of placing the command in the console pool. This may lead to better output buffering behavior in some situations, such as helping IDE environments capture and present the build output in a more timely manner. It can also be useful if interactive

input is required for non-IDE builds. The `USES_TERMINAL` option is supported for CMake 3.2 and later.

To provide even more control over Ninja job pools, CMake 3.15 added support for the `JOB_POOL` option. Whereas `USES_TERMINAL` assigns the task to the console job pool, the `JOB_POOL` option allows the project to assign the task to any custom job pool. `USES_TERMINAL` and `JOB_POOL` cannot both be given. See [Section 26.3.2, “Ninja Generators”](#) for more on using job pools with Ninja.

`JOB_SERVER_AWARE` is a fairly specialized option introduced in CMake 3.28. When given with a value of true, CMake will define the command for the build tool in a way that allows it to communicate with a job server created by a parent process. This is only significant if the command creates a separate sub-build that can take advantage of a job server. The primary use case for this feature is to support the implementation of the `BUILD_JOB_SERVER_AWARE` and `INSTALL_JOB_SERVER_AWARE` options of the `ExternalProject_Add()` command (see [Chapter 38, *ExternalProject*](#)). Projects would not generally use `JOB_SERVER_AWARE` directly. `JOB_SERVER_AWARE` currently only has an effect if using one of the Makefile-based CMake generators, where it is used to allow it to communicate with a GNU make job server. All other CMake generators ignore the option.

The SOURCES option allows arbitrary files to be listed which will then be associated with the custom target. These files might be used by the commands or they could just be some additional files which are loosely associated with the target, such as documentation, etc. Listing a file with SOURCES has no effect on the build or the dependency relationships, it is purely for the benefit of associating those files with the target so that IDE projects can show them in an appropriate context. This feature is sometimes exploited by defining a dummy custom target and listing sources with no commands just to make them show up in IDE projects. While this works, it does have the disadvantage of creating a build target with no real meaning. Many projects deem this to be an acceptable trade-off, while some developers consider this undesirable or even an anti-pattern.

20.2. Adding Build Steps To An Existing Target

Custom commands sometimes do not require a new target to be defined. They may instead specify additional steps to be performed when building an existing target. This is where `add_custom_command()` should be used with the TARGET keyword as follows:

```
add_custom_command(TARGET targetName buildStage
    COMMAND command1 [args1...]
    [COMMAND command2 [args2...]]
    [WORKING_DIRECTORY dir]
    [BYPRODUCTS files...]
    [COMMENT comment]
    [VERBATIM]
```

```
[USES_TERMINAL]      # Requires CMake 3.2 or later  
[JOB_POOL poolName]  # Requires CMake 3.15 or later  
)
```

Most of the options are similar to those for `add_custom_target()`, but instead of defining a new target, the above form attaches the commands to an existing target. It can be an executable or library target, or even a custom target (with some restrictions). With CMake 3.29 and later, it can also be an alias target, but this is not recommended. The real target should be listed instead, since that's what the build steps would be attached to, not the alias target. The commands will be executed as part of building `targetName`, with the `buildStage` argument required to be one of the following:

PRE_BUILD

The commands should be run before any other rules for the specified target. Be aware that only the Visual Studio generators support this option. All other CMake generators will treat this as `PRE_LINK` instead. Given the limited support for this option, projects should aim for a structure which does not require a `PRE_BUILD` custom command to avoid command ordering differences between generators.

PRE_LINK

The commands will be run after sources are compiled, but before they are linked. For static library targets, the

commands will run before the library archiver tool. For custom targets, PRE_LINK is not supported.

POST_BUILD

The commands will be run after all other rules for the specified target. All target types and generators support this option, making it the preferred build stage whenever there is a choice.

POST_BUILD tasks are relatively common, but PRE_LINK and PRE_BUILD are rarely needed since they can usually be avoided by using the OUTPUT form of add_custom_command() instead (see the next section).

Multiple calls to add_custom_command() can be made to append multiple sets of custom commands to a particular target. This can be useful, for example, to have some commands run from one working directory and other commands run from somewhere else.

```
add_executable(MyExe main.cpp)

add_custom_command(TARGET MyExe
    POST_BUILD
    COMMAND script1 $<TARGET_FILE:MyExe>
)

# Additional command which will run after the above
# from a different directory
add_custom_command(TARGET MyExe
    POST_BUILD
    COMMAND writeHash $<TARGET_FILE:MyExe>
```

```
    BYPRODUCTS ${CMAKE_BINARY_DIR}/verify/MyExe.md5
    WORKING_DIRECTORY ${CMAKE_BINARY_DIR}/verify
)

```

20.3. Commands That Generate Files

Defining commands as additional build steps for a target covers many common use cases. But sometimes a project needs to create files by running a command or series of commands, and the generated files will be used in a way not supported by the `add_custom_target()` or `add_custom_command()` forms discussed above. A common example is generating a file which will be compiled as a source file in an existing library or executable target. This is where the `OUTPUT` form of `add_custom_command()` can be used. It implements the same options as the `TARGET` form, plus additional options related to dependency handling and appending to a previous `OUTPUT` command set.

```
add_custom_command(OUTPUT output1 [output2...]
    COMMAND command1 [args1...]
    [COMMAND command2 [args2...]]
    [WORKING_DIRECTORY dir]
    [BYPRODUCTS files...]
    [COMMENT comment]
    [VERBATIM]
    [USES_TERMINAL]          # Requires CMake 3.2 or later
    [JOB_POOL poolName]       # Requires CMake 3.15 or later
    [JOB_SERVER_AWARE bool]   # Requires CMake 3.28 or later
    [APPEND]
    [DEPENDS [depends1...]]
    [DEPENDS_EXPLICIT_ONLY]  # Requires CMake 3.27 or later
    [MAIN_DEPENDENCY depend]
    [IMPLICIT_DEPENDS <lang1> depend1 [<lang2> depend2...]]
```

```
[DEPFILE depfile]  
[CODEGEN] # Requires CMake 3.31 or later  
)
```

This form requires one or more output file names to be given after the `OUTPUT` keyword. The commands will be treated as a recipe for generating those files. If the output files are specified with no path or with a relative path, they are normally treated as relative to the current binary directory. In specific circumstances, they can be treated as relative to the current source directory instead (see the official CMake documentation for details). To avoid that ambiguity, projects should always use absolute paths when specifying the `OUTPUT` files. With CMake 3.20 or later, generator expressions that do not refer to a target can be used.

On its own, this form won't result in the output files being built. A target defined in the same directory scope must depend on the output files. CMake then creates dependency relationships that ensure the output files are generated before they are needed. A common error is to try to make a target defined in a different directory scope depend on the output of an `add_custom_command()`, but this is not supported. Furthermore, only one target should depend on any of the output files. Otherwise, parallel builds may run the custom command multiple times simultaneously to satisfy the dependencies of multiple targets.

The target that depends on the output of the `add_custom_command()` can be an ordinary executable, a library target, or it can even be a custom target. In fact, it is quite common for a custom target to be defined simply to provide a way for the developer to trigger the custom command. The following variation on the hashing example of the preceding section demonstrates the technique:

```
add_executable(MyExe main.cpp)

# Output file with relative path, generated in the
# build directory
add_custom_command(OUTPUT MyExe.md5
    COMMAND writeHash $<TARGET_FILE:MyExe>
)
# Absolute path needed for DEPENDS, otherwise relative
# to source directory
add_custom_target(ComputeHash
    DEPENDS ${CMAKE_CURRENT_BINARY_DIR}/MyExe.md5
)
```

When defined this way, building the `MyExe` target will not result in running the hashing step, unlike the earlier example which added the hashing command as a `POST_BUILD` step of the `MyExe` target. Instead, hashing will only be performed if the developer explicitly requests it as a build target. This allows optional steps to be defined and invoked when needed instead of always being run, which can be quite useful if the additional steps are time-consuming or won't always be relevant.

Of course, `add_custom_command()` can also be used to generate files consumed by existing targets, such as generating source files. The following example uses a shell script to create the `src.cpp` source file at build time:

```
add_custom_command(OUTPUT src.cpp
    COMMAND ${CMAKE_CURRENT_SOURCE_DIR}/write_src_cpp.sh
)
add_executable(MyExe
    main.cpp
    ${CMAKE_CURRENT_BINARY_DIR}/src.cpp
)
```

With CMake 3.31 or later, the `CODEGEN` keyword can be added to the `add_custom_command()` call. Conceptually, this is a way to communicate that the output files are source files. CMake can then provide additional features because it knows more about the files. For example, when using Ninja or one of the Makefiles generators, a global codegen target will be defined (other CMake generators silently ignore `CODEGEN`). The codegen target depends on all generated files that had the `CODEGEN` keyword included in their `add_custom_command(OUTPUT)` call. Building the codegen target ensures all `CODEGEN`-annotated generated files will exist and be up to date without having to build the rest of the project. This may be useful as a preceding step before running a static code analysis (see [Chapter 32, Static Code Analysis](#)).

```
# This sets policy CMP0171 to NEW, which is a pre-requisite
# for using the CODEGEN keyword with add_custom_command()
cmake_minimum_required(VERSION 3.31)
```

```
add_custom_command(OUTPUT src.cpp
    COMMAND ${CMAKE_CURRENT_SOURCE_DIR}/write_src_cpp.sh
    CODEGEN
)
add_executable(MyExe
    main.cpp
    ${CMAKE_CURRENT_BINARY_DIR}/src.cpp
)
```

```
cmake -G Ninja -S . --build build
cd build
cmake --build . --target codegen
run-clang-tidy -p .
```

The above sequence of commands would ensure `src.cpp` was generated, but the `MyExe` target would not be built. Neither `main.cpp` nor `src.cpp` would be compiled, but `clang-tidy` would be run on all the project's source files. For a much larger project, it may be expensive to compile, and the above would save considerable time if only the results of running `clang-tidy` were needed, such as for dedicated `clang-tidy` continuous integration job.

When not cross-compiling, the command used to generate a source file can itself be built by the project. In the following example, the Generator executable is built by the project. That is then used to generate a source file, which is in turn compiled as part of another executable, `MyExe`.

```
add_executable(Generator generator.cpp)

add_custom_command(OUTPUT src.cpp
```

```

COMMAND Generator
CODEGEN
)

add_executable(MyExe
    main.cpp
    ${CMAKE_CURRENT_BINARY_DIR}/src.cpp
)

```

CMake automatically recognizes that MyExe needs the source file generated by the custom command, which in turn requires the Generator executable. Asking for the MyExe target to be built will result in the Generator and the generated source file being built before building MyExe. But this dependency relationship has limitations. Consider the following scenario:

- The `src.cpp` file initially does not exist.
- Build the MyExe target, which results in the following sequence:
 - The Generator target is brought up to date.
 - The custom command is executed to create `src.cpp`.
 - The MyExe target is built.
- Now modify the `generator.cpp` file.
- Build the MyExe target again, which this time results in the following sequence:
 - The Generator target is brought up to date. This will cause the Generator executable to be rebuilt because its source file

was modified.

- The custom command is NOT executed, since `src.cpp` already exists.
- The `MyExe` target is NOT rebuilt because its source file remains unchanged.

One might intuitively expect that if the `Generator` target is rebuilt, then the custom command should also be re-run. The dependency CMake automatically creates does not enforce this. It creates a weaker dependency which does ensure `Generator` is brought up to date, but the custom command is only run if the output file is missing altogether. To force the custom command to be re-run if the `Generator` target is rebuilt, an explicit dependency has to be specified.

Dependencies can be manually specified with the `DEPENDS` option. Items listed with `DEPENDS` can be CMake targets or files (compare this with the `DEPENDS` option for `add_custom_target()` which can only list files). If a target is listed, it will be brought up to date any time the custom command's output files are required to be brought up to date. Similarly, if a listed file is modified, the custom command will be executed if anything requires any of the custom command's output files. Furthermore, if any listed file is itself an output file of another custom command in the same directory scope, that other custom command will be executed first. As for

`add_custom_target()`, always use an absolute path if listing a file for `DEPENDS` to avoid ambiguous legacy behavior.

```
add_executable(Generator generator.cpp)

add_custom_command(OUTPUT gen_input.json
    COMMAND ${CMAKE_CURRENT_SOURCE_DIR}/write_gen_input.sh
    DEPENDS
        # If the script changes, we want it to be re-run
        ${CMAKE_CURRENT_SOURCE_DIR}/write_gen_input.sh
)
add_custom_command(OUTPUT src.cpp
    COMMAND Generator gen_input.json
    DEPENDS
        Generator
        ${CMAKE_CURRENT_BINARY_DIR}/gen_input.json
    CODEGEN
)
add_executable(MyExe
    main.cpp
    ${CMAKE_CURRENT_BINARY_DIR}/src.cpp
)
```

In the above example, the `CODEGEN` keyword is only given for the custom command that produces the final source file, `src.cpp`. If the `codegen` target is built, the build tool will ensure anything the code generation depends on (the `Generator` target and the `gen_input.json` file) will be brought up to date.

While CMake's automatic dependencies may seem convenient, in practice the project will still typically need to list out all the required targets and files in a `DEPENDS` section, as demonstrated by the previous example. It can be easy to omit the `DEPENDS`

section by mistake, since the first build will run the custom command to create the missing output files and the build will appear to be behaving correctly. Subsequent builds will not re-run the custom command unless the output file is removed, even if any of the automatically detected dependency targets are rebuilt. This can be easy to miss, often going undetected for a long time in complex projects until a developer encounters the situation and tries to work out why something isn't being rebuilt when it was expected to be. Therefore, developers should expect that a `DEPENDS` section will typically be needed unless the custom command doesn't require anything created by the build or any of the project's source files.

Another common error is to not create a dependency on a file that is needed by the custom command, but which isn't listed as part of the command line to be executed. Such files need to appear in a `DEPENDS` section for the build to be considered robust.

The `DEPENDS_EXPLICIT_ONLY` option, supported with CMake 3.27 or later, takes this further. When present, this option tells `add_custom_command()` that the `DEPENDS` arguments fully specify everything the custom command depends on. This should normally be the case, but some projects might not define their dependencies that robustly. They may be relying on dependencies specified on the target that the outputs are added to as source files. See [Section 26.4, “Optimizing Build](#)

[Dependencies](#)” for a detailed discussion of this option and related considerations.

There are a few more dependency-related options supported by `add_custom_command()`. The `MAIN_DEPENDENCY` option is intended to identify a source file which should be considered the main dependency of the custom command. It has mostly the same effect as `DEPENDS` for the listed file, but some generators may apply additional logic such as where to place the custom command in an IDE project. An important distinction to note is that if a source file is listed as a `MAIN_DEPENDENCY`, then the custom command becomes a replacement for how that source file would normally be compiled. This can lead to some unexpected results. Consider the following example:

```
add_custom_command(OUTPUT transformed.cpp
    COMMAND transform
        ${CMAKE_CURRENT_SOURCE_DIR}/original.cpp
        transformed.cpp
    MAIN_DEPENDENCY
        ${CMAKE_CURRENT_SOURCE_DIR}/original.cpp
)
add_executable(Original    original.cpp)
add_executable(Transformed  transformed.cpp)
```

The above would lead to a linker error for the `Original` target because `original.cpp` would not be compiled to an object file, so there would be no object files at all (and therefore no `main()` function). Instead, the build tool would treat `original.cpp` as an input file used to create `transformed.cpp`. The problem can be

fixed by using `DEPENDS` instead of `MAIN_DEPENDENCY`, as this would preserve the same dependency relationship, but it would not result in the default compilation rule for the `original.cpp` source file being replaced.

The other two dependency-related options, `IMPLICIT_DEPENDS` and `DEPFILE`, are not universally supported by all project generators. `IMPLICIT_DEPENDS` directs CMake to invoke a C or C++ scanner to determine dependencies of the listed files. It is ignored for all but Makefile generators, so projects should generally avoid it. `DEPFILE` can be used to provide a `*.d` dependency file (which the project is responsible for generating), but up until CMake 3.19, only the Ninja generator supported it. From CMake 3.20, `DEPFILE` can also be used with Makefile generators, while CMake 3.21 added support for the Xcode and Visual Studio generators. While depfiles have their uses, they are more complex to work with and they shouldn't need to be manually managed for most typical projects. `IMPLICIT_DEPENDS` and `DEPFILE` cannot be used together.

CMake 3.20 also introduced another change related to `DEPFILE` which may affect projects that were using that functionality with earlier CMake versions. CMake 3.20 added policy `CMP0116` which, unlike most policies, can result in warnings even where the project is not invoking or relying on the OLD behavior. The warning draws attention to the changed handling of relative paths when `DEPFILE` is used with a call to `add_custom_command()`.

anywhere other than in the top level source directory. CMake cannot reliably check the contents of a depfile, since it can be and usually is updated at build time. Therefore, it conservatively issues a warning unless the project has been updated to ensure that policy CMP0116 is set to NEW. Projects that were using DEPFILE with CMake 3.19 or earlier should be checked to ensure that absolute paths are used in accordance with the CMP0116 policy requirements. They can then be updated to set the policy to avoid the warning. This can be done globally by adjusting the version range passed to the `cmake_minimum_required()` call, as shown in the earlier CODEGEN example, or locally around the call in question. The following example demonstrates how to adjust the policy setting locally without affecting the minimum CMake version requirement (see [Chapter 13, Policies](#) for further details):

```
# Give ourselves a local policy set we can safely modify
cmake_policy(PUSH)

# Use the NEW policy setting only if it is available
if(POLICY CMP0116)
    cmake_policy(SET CMP0116 NEW)
endif()

# We guarantee that depfile.d will only use absolute paths
add_custom_command(OUTPUT ...
    DEPFILE /some/absolute/path/to/depfile.d
    ...
)

# Restore the original policy settings
cmake_policy(POP)
```

The OUTPUT and TARGET forms also have slightly different behavior when it comes to appending more dependencies or commands to the same output file or target. For the OUTPUT form, the APPEND keyword must be specified and the first OUTPUT file listed must be the same for the first and subsequent calls to `add_custom_command()`. Only COMMAND and DEPENDS can be used for the second and subsequent calls for the same output file. The other options, such as MAIN_DEPENDENCY, WORKING_DIRECTORY, and COMMENT, are either not allowed or are ignored when the APPEND keyword is present. In contrast, for the TARGET form, no APPEND keyword is necessary for second and subsequent calls to `add_custom_command()` for the same target, but no dependency-related keywords can be given. The COMMENT and WORKING_DIRECTORY options can be specified for each call, and they will take effect for the commands being added in that call.

Adding generated sources to a target can also affect how consumers of that target are built. With CMake 3.27 and earlier, CMake doesn't know whether the consumer might need the generated files too. For example, if one of the generated files is a header, both the target and any other targets that consume it might contain sources that include the header. To be conservative, CMake will ensure the build tool builds the custom commands of the target with the generated sources before it starts compiling any files from the consumer. This ensures the header will exist before anything tries to use it. But if the generated header is intended to only be included by the

target's own sources, making a consumer wait for the target's custom commands before compiling the consumer's sources is unnecessarily inefficient.

CMake 3.28 changed the behavior when the Ninja generator is used, and the target with the generated file has one or more file sets (see [Section 16.2.7, “File Sets”](#)). Compilation of a consumer's sources will only wait for completion of custom commands that generate files in a target's PUBLIC or INTERFACE file sets. Put another way, generated files are assumed to be PRIVATE unless a file set indicates otherwise. Because this can change the behavior of existing projects in a way that may break the build if they were relying on the old behavior, the new behavior only applies if policy CMP0154 is set to NEW. Where possible, projects should prefer to put all generated files in file sets, which will make explicit whether each file is intended for consumers or not.

In addition to the policies mentioned above, CMP0118 and CMP0163 also affect some aspects of how generated files are handled. If projects follow the preceding advice in this section, they should avoid most of the scenarios where these two policies may be relevant.

20.4. Configure Time Tasks

Both `add_custom_target()` and `add_custom_command()` define commands to be executed during the build stage. This is

typically when custom commands should be run, but there are some situations where a custom task needs to be performed during the configure stage instead. Some examples of when this is needed include:

- Executing external commands to obtain information to be used during configuration. The command output is often captured directly into CMake variables for further processing.
- Writing or touching files which need to be updated any time CMake is re-run.
- Generation of `CMakeLists.txt` or other files which need to be included or processed as part of the current configure step.

CMake provides the `execute_process()` command for running such tasks during the configure stage:

```
execute_process(  
    COMMAND command1 [args1...]  
    [COMMAND command2 [args2...]]  
    [WORKING_DIRECTORY directory]  
    [RESULT_VARIABLE resultVar]  
    [OUTPUT_VARIABLE outputVar]  
    [ERROR_VARIABLE errorVar]  
    [OUTPUT_STRIP_TRAILING_WHITESPACE]  
    [ERROR_STRIP_TRAILING_WHITESPACE]  
    [INPUT_FILE inFile]  
    [OUTPUT_FILE outFile]  
    [ERROR_FILE errorFile]  
    [OUTPUT QUIET]  
    [ERROR QUIET]  
    [TIMEOUT seconds]  
    # CMake 3.8 or later required:  
    [ENCODING encoding]
```

```
# CMake 3.10 or later required:  
[RESULTS_VARIABLE resultsVar]  
# CMake 3.15 or later required:  
[COMMAND_ECHO STDOUT | STDERR | NONE]  
# CMake 3.18 or later required:  
[ECHO_OUTPUT_VARIABLE]  
[ECHO_ERROR_VARIABLE]  
# CMake 3.19 or later required:  
[COMMAND_ERROR_IS_FATAL ANY | LAST]  
)
```

Similar to `add_custom_command()` and `add_custom_target()`, one or more `COMMAND` sections specify the tasks to be executed and the `WORKING_DIRECTORY` option can be used to control where those commands are run. The commands are passed to the operating system for execution as is with no intermediate shell environment. Therefore, features like input/output redirection and environment variables are not supported. The commands run immediately.

If multiple commands are given, they are executed in order, but instead of being fully independent, the standard output from one command is piped to the input of the next. In the absence of any other options, the output of the *last* command is sent to the output of the CMake process, but the standard error of *every* command is sent to the standard error stream of the CMake process.

The standard output and error streams can be captured and stored in variables instead of being sent to the default pipes. The output of the last command can be captured by specifying

the name of a variable to store it in with the `OUTPUT_VARIABLE` option. Similarly, the standard error streams of all commands can be stored in the variable named by the `ERROR_VARIABLE` option. Passing the same variable name to both of these options will result in the standard output and standard error being merged, just as they would be if outputting to a terminal. With CMake 3.18 or later, the `ECHO_OUTPUT_VARIABLE` and `ECHO_ERROR_VARIABLE` options can be added to echo the output and error streams while also capturing them to variables. This can be useful for long-running commands where seeing progress in the output helps to confirm that the command has not hung.

If the `OUTPUT_STRIP_TRAILING_WHITESPACE` option is present, any trailing whitespace will be omitted from the content stored in the output variable. The `ERROR_STRIP_TRAILING_WHITESPACE` option does a similar thing for the content stored in the error variable. If using the output or error variables' contents for any sort of string comparison, a common problem is failing to account for trailing whitespace, so its removal is often desirable.

Instead of capturing the output and error streams in variables, they can be sent to files. The `OUTPUT_FILE` and `ERROR_FILE` options can be used to specify the names of files to send the streams to. Just like the variable-focused options, specifying the same file name for both results in a merged stream. In addition, a file can

be specified for the input stream to the first command with the INPUT_FILE option. Note, however, that the OUTPUT_STRIP_TRAILING_WHITESPACE and ERROR_STRIP_TRAILING_WHITESPACE options have no effect on content sent to files. There is also no ability to echo the output or error streams when capturing to files.

The same stream cannot be captured in a variable and sent to a file at the same time. It is possible, however, to send different streams to different places, such as the output stream to a variable and the error stream to a file or vice versa. It is also possible to silently discard the content of a stream altogether with the OUTPUT QUIET and ERROR QUIET options. These options can be useful if just success or failure of a command is of interest.

When capturing output on Windows, the encoding of the output stream may be important. For example, if the output contains paths from the file system, those paths may contain Unicode characters. The default encoding might not represent those correctly, resulting in corrupted data in the output. With CMake 3.8 or later, the ENCODING option can be used to specify the encoding to use. The default behavior performs no decoding, but it may be more appropriate to force decoding the output as UTF-8 with the options ENCODING UTF8 (with CMake 3.11 or later, the more RFC-compliant ENCODING UTF-8 is also accepted, but the end result is the same).

Success or failure of the commands can be captured using the RESULT_VARIABLE option. The result of running the commands will be stored in the named variable as either an integer return code of the last command or a string containing some kind of error message. The if() command conveniently treats both non-empty error strings and integer values other than 0 as boolean true (unless a project is unlucky enough to have an error string that satisfies one of the special cases, see [Section 7.1.1, “Basic Expressions”](#)). Therefore, checking for the success of a call to execute_process() is generally relatively simple:

```
execute_process(  
    COMMAND runSomeScript  
    RESULT_VARIABLE result  
)  
  
if(result)  
    message(FATAL_ERROR "runSomeScript failed: ${result}")  
endif()
```

From CMake 3.10, if the result of each individual command is required rather than just the last one, the RESULTS_VARIABLE option can be used instead. This option stores the result of each command in the variable named by resultsVar as a list.

With CMake 3.19 or later, the COMMAND_ERROR_IS_FATAL option can be used as a more concise way of halting with an error if the command fails. It avoids the need to receive the result in a variable and perform an explicit check, since the check is performed by the execute_process() command directly. The

option must be followed by either ANY or LAST. When more than one COMMAND is given, specifying ANY will cause the execute_process() command to fail with a fatal error if any of the commands fail. If LAST is given instead, then execute_process() only fails if the last COMMAND fails. If only one COMMAND is given, then ANY and LAST are equivalent.

```
# Automatically halt with an error if either command fails
execute_process(
    COMMAND runSomeScript
    COMMAND runSomethingElse
    COMMAND_ERROR_IS_FATAL ANY
)
```

CMake 4.0 added support for a CMAKE_EXECUTE_PROCESS_COMMAND_ERROR_IS_FATAL variable. This can be used to specify a default value for COMMAND_ERROR_IS_FATAL when no RESULT_VARIABLE or RESULTS_VARIABLE keyword is present. While it may be useful in specific scenarios, the variable can easily cause unintended behavior changes in nested scopes if not used carefully. Projects are probably better off avoiding the variable and using the COMMAND_ERROR_IS_FATAL keyword in each call where needed.

The TIMEOUT option can be used to handle commands which may run longer than expected or which might never complete. This ensures the configure step doesn't block indefinitely and allows an unexpectedly long configure step to be treated as an error. Note, however, that the TIMEOUT option on its own won't cause

CMake to halt and report an error. It is still necessary to either check the result using `RESULT_VARIABLE` and an `if()` test, or provide the `COMMAND_ERROR_IS_FATAL` option.

Note that in the initial CMake 3.19.0 release, if a command timed out, it was not caught and treated as a fatal error by the `COMMAND_ERROR_IS_FATAL` option. That was fixed in CMake 3.19.2, so consider this to be the minimum CMake version if using this option. If using the `RESULT_VARIABLE` method, the result variable will hold an error string indicating the command was terminated due to timeout if it runs for too long, so printing it in the error message is useful.

CMake 3.15 added support for the `COMMAND_ECHO` option, which must be followed by one of `STDOUT`, `STDERR` or `NONE`. This controls where to echo each `COMMAND` (the command line itself, not the command's output), or in the case of `NONE`, prevents commands from being echoed. If the `COMMAND_ECHO` option is not present, the default behavior is determined by the `CMAKE_EXECUTE_PROCESS_COMMAND_ECHO` variable, which supports the same three values. If that variable isn't defined either, or the CMake version is 3.14 or earlier, commands are not echoed.

When CMake executes the commands, the child process largely inherits the same environment as the main process, but CMake 3.23 and earlier has one important exception. The first time CMake is run on a project, the `CC` and `CXX` environment variables

of the child process are explicitly set to the C and C++ compilers being used by the main build (if the main project has enabled the C and C++ languages). For subsequent CMake runs, the `CC` and `CXX` environment variables are *not* substituted in this way. This can lead to unexpected results if the commands perform actions that rely on the `CC` and `CXX` environment variables having the same values every time `execute_process()` is called. This behavior was undocumented before CMake 3.24, but it has been present since early versions of CMake. The behavior was added to facilitate child processes being able to configure and run sub-builds with the same compilers as the main project. In some cases, however, the child process might not want the compiler to be preserved, such as when the main build is cross-compiling, but the child process should use the default host compilers. CMake 3.24 introduced policy `CMP0132` which avoids the above behavior when it is set to `NEW`. When using CMake 3.23 or earlier, projects can set an undocumented variable `CMAKE_GENERATOR_NO_COMPILER_ENV` to a boolean true value and the effect will be the same as setting `CMP0132` to `NEW`.

20.5. Platform Independent Commands

The `add_custom_command()`, `add_custom_target()`, and `execute_process()` commands projects a great deal of freedom. Any task not already directly supported by CMake can be implemented using commands provided by the host operating system instead. These custom commands are inherently

platform-specific though. This works against one of the main reasons many projects use CMake in the first place, to abstract away platform differences as much as possible.

A large proportion of custom tasks are related to file system manipulation. Creating, deleting, renaming or moving files and directories form the bulk of these tasks, but the commands to do so vary between operating systems. As a result, projects often end up using `if-else` conditions to define the different platforms' versions of the same command, or worse, they only bother to implement the commands for some platforms. Many developers are not aware that CMake provides a command mode which abstracts away many of these platform-specific tasks:

```
cmake -E cmd [args...]
```

The full set of supported commands can be listed using `cmake -E help`, but some of the more commonly used ones include `copy`, `copy_if_different`, `echo`, `env`, `make_directory`, `md5sum`, `rm` and `tar`.

Consider the example of a custom task to remove a particular directory and all its contents:

```
set(discardDir "${CMAKE_CURRENT_BINARY_DIR}/private"

# Naive platform specific implementation (not robust)
if(WIN32)
    add_custom_target(MyCleanup
        COMMAND rmdir /S /Q "${discardDir}"
```

```

        )
elseif(UNIX)
    add_custom_target(MyCleanup
        COMMAND rm -rf "${discardDir}"
    )
else()
    message(FATAL_ERROR "Unsupported platform")
endif()

# Platform independent equivalent
add_custom_target(MyCleanup
    COMMAND "${CMAKE_COMMAND}" -E rm -R "${discardDir}"
)

```

The platform-specific implementation shows how projects often try to implement this scenario, but the if-else conditions are testing the *target* platform rather than the *host* platform. In a cross compiling scenario, this may result in the wrong command being used. The platform-independent version has no such weakness. It always selects the right command for the *host* platform.

The example also shows how to invoke the `cmake` command correctly. The `CMAKE_COMMAND` variable is populated by CMake and it contains the full path to the `cmake` executable being used in the main build. Using `CMAKE_COMMAND` in this way ensures that the same version of CMake is also used for the custom command. The `cmake` executable does not have to be on the current PATH and if multiple versions of CMake are installed, the correct version is always used, regardless of which one might otherwise have been selected based on the user's PATH. It also

ensures the build uses the same CMake version during the build stage as was used in the configure stage, even if the user's PATH environment variable changes.

Earlier in this chapter, it was noted that the COMMENT option for add_custom_target() and add_custom_command() isn't always reliable. Instead of using COMMENT, projects can use the -E echo command to intersperse comments anywhere in a sequence of custom commands:

```
set(discardDir "${CMAKE_CURRENT_BINARY_DIR}/private")

add_custom_target(MyCleanup
    COMMAND ${CMAKE_COMMAND} -E
        echo "Removing ${discardDir}"
    COMMAND ${CMAKE_COMMAND} -E
        rm -R "${discardDir}"
    COMMAND ${CMAKE_COMMAND} -E
        echo "Recreating ${discardDir}"
    COMMAND ${CMAKE_COMMAND} -E
        make_directory "${discardDir}"
)
```

CMake's command mode is a very useful way of carrying out a range of common tasks in a platform-independent way. Sometimes, however, more complex logic is required and such custom tasks are often implemented using platform specific shell scripts. An alternative is to use CMake itself as a scripting engine, providing a platform-independent language in which to express arbitrary logic. The -P option to the cmake command puts CMake into script processing mode:

```
cmake [options] -P filename
```

The `filename` argument is the name of the CMake script file to execute. The usual `CMakeLists.txt` syntax is supported, but there is no `configure` or `generate` step and the `CMakeCache.txt` file is not updated. The script file is essentially processed as just a set of commands rather than as a project, so any commands which relate to build targets or project-level features are not supported. Nonetheless, script mode allows complex logic to be implemented and it comes with the advantage of not requiring any additional shell interpreter to be installed.

While script mode doesn't support command line options like ordinary shells or command interpreters, it does support passing in variables with `-D` options, just like ordinary `cmake` invocations. Since no `CMakeCache.txt` file is updated in script mode, `-D` options can be used freely without affecting the main build's cache. Such options must be placed before `-P`.

```
cmake -DOPTION_A=1 -DOPTION_B=foo -P myCustomScript.cmake
```

With CMake 3.29 and later, CMake scripts can also end a script immediately and set an exit code with the `cmake_language(EXIT)` subcommand. This can be used to indicate more detailed information to the caller than just success or failure. Different non-zero exit codes may be used to indicate different error

conditions. With earlier CMake versions, a script can only use message(FATAL_ERROR) to indicate non-success to its caller.

```
if(someConditionFailed)
    message(NOTICE "Failed some condition")
    cmake_language(EXIT 25)
endif()
```

For maximum portability, only specify exit codes in the range 0 to 125. Some shells may interpret values higher than that specially, and numbers above 255 might not be supported at all.

Note that cmake_language(EXIT) cannot be used by projects. It is only supported in script mode. Attempting to call it from projects will result in an immediate fatal error.

20.6. Combining The Different Approaches

The example below demonstrates many of the features discussed in this chapter. It shows how custom tasks can be specified in different ways. An important aspect of the example is how it accomplishes non-trivial things without having to resort to platform specific commands or functionality.

By putting the archiving logic in the separate archiver.cmake file, it can also be used either within a project as shown, or it can be invoked on its own through CMake's script mode. This can be useful from a development and testing perspective, or to

provide a platform-independent way of archiving a directory for general use outside any project.

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.19)
project(Example)

# This executable generates files in a directory passed
# as a command line argument
add_executable(GenerateFiles generateFiles.cpp)

# Custom target to run the above executable and archive
# its results
set(outDir "foo")
add_custom_target(Archiver
    COMMAND ${CMAKE_COMMAND} -E echo "Archiving files"
    COMMAND ${CMAKE_COMMAND} -E rm -R "${outDir}"
    COMMAND ${CMAKE_COMMAND} -E make_directory "${outDir}"
    COMMAND GenerateFiles "${outDir}"
    COMMAND ${CMAKE_COMMAND} "-DTAR_DIR=${outDir}"
        -P "${CMAKE_CURRENT_SOURCE_DIR}/archiver.cmake"
)
```

archiver.cmake

```
cmake_minimum_required(VERSION 3.19)

if(NOT TAR_DIR)
    message(FATAL_ERROR "TAR_DIR must be set")
endif()

set(archive archive.tar)

# Create an archive of the directory
execute_process(
    COMMAND ${CMAKE_COMMAND} -E
        tar cf ${archive} "${TAR_DIR}"
    COMMAND_ERROR_IS_FATAL LAST
)
```

```

# Compute MD5 checksum of the archive
execute_process(
    COMMAND ${CMAKE_COMMAND} -E md5sum ${archive}
    OUTPUT_VARIABLE md5output
    COMMAND_ERROR_IS_FATAL LAST
)

# Extract just the checksum from the output
string(REGEX MATCH "^[^ ]*" md5sum "${md5output}")
message("Archive MD5 checksum: ${md5sum}")

```

20.7. Recommended Practices

When custom tasks need to be executed, it is preferable that they be done during the build stage rather than the configure stage. A fast configure stage is important because it can be invoked automatically when some files are modified (e.g. any CMakeLists.txt file in the project, any file included by a CMakeLists.txt file, or any file listed as a source of a configure_file() command as discussed in the next chapter). For this reason, prefer to use add_custom_target() or add_custom_command() instead of execute_process() if there is a choice. If the task needs to run immediately or as part of a cmake -P script mode invocation, then execute_process() is appropriate.

It is relatively common to see platform-specific commands used with add_custom_command(), add_custom_target(), and execute_process(). Quite often, such commands can instead be expressed in a platform-independent way using CMake's

command mode (-E). Where possible, prefer to use these platform-independent commands.

CMake can also be used as a platform-independent scripting language, processing a file as a sequence of CMake commands when invoked with the -P option. The use of CMake scripts instead of a platform-specific shell or a separately installed script engine can reduce the complexity of the project, and reduce the additional dependencies it requires to build. Specifically, consider whether CMake's script mode would be a better choice than using a Unix shell script, a Windows batch file, or even a script for a language like Python, Perl, etc. which may not be available by default on all platforms. The next chapter shows how to manipulate files directly with CMake instead of having to resort to such tools and methods.

When implementing custom tasks, try to avoid features that lack support in all situations:

- If a comment associated with a custom command is important enough that it should always be shown, prefer to use command mode -E echo rather than the COMMENT keyword with `add_custom_command()` and `add_custom_target()`. Not all generators show COMMENT output, but they all show output from a command that uses -E echo. Use COMMENT if the comment is only providing a more concise description of the task than the command itself. COMMENT integrates better with

generators that overwrite a single line on the console with progress rather than putting each comment on its own line.

- Try to avoid using PRE_BUILD with the TARGET form of add_custom_command().
- Consider whether using IMPLICIT_DEPENDS or DEPFILE options with add_custom_command() is worth the generator-specific behavior.
- Avoid listing a source file as a MAIN_DEPENDENCY in add_custom_command() unless the intention is to replace the default build rule for that source file.

Pay special attention to dependencies for the inputs and outputs of custom tasks. If listing a file in DEPENDS for either add_custom_target() or add_custom_command(), always use an absolute path to avoid non-robust legacy path matching behavior. Also ensure that *all* files created by add_custom_command() are listed as OUTPUT files, or as BYPRODUCTS for intermediate files. If any of those files are headers, make sure they are part of a file set in the target owning those headers. CMake 3.28 and later may assume generated headers are not used outside of that target unless the header is in a PUBLIC or INTERFACE file set, and this will directly affect how CMake constructs dependencies between targets.

When listing build targets as the command or arguments in a call to add_custom_command() or add_custom_target(), prefer to

explicitly list them as DEPENDS items rather than relying on CMake's automatic target dependency handling. The weaker automatic dependencies may not enforce all the relationships that developers may intuitively expect.

When calling `execute_process()`, the success of the command should be checked by capturing the result using `RESULT_VARIABLE` and testing it with the `if()` command, or by using the `COMMAND_ERROR_IS_FATAL` option. This includes when a `TIMEOUT` option is being used, since `TIMEOUT` on its own will not generate an error, it will only ensure the command doesn't run longer than the nominated timeout period.

In certain types of projects, the difference between executing custom commands with optimized targets versus non-optimized targets may have a noticeable effect on build times. A common example of this is where custom commands are used to run code generators that are themselves built as part of the project. If code generation is a non-trivial process, it may be desirable to have the code generators build with the Release configuration, even when building the rest of the project as Debug. The Ninja Multi-Config generator introduced with CMake 3.17 is the only generator which directly supports this workflow. Given the fairly new status of this generator, consider carefully before relying heavily on this capability. The interested reader should consult the CMake documentation for

further details on this and other related advanced features of the Ninja Multi-Config generator.

21. WORKING WITH FILES

Many projects need to manipulate files and directories as part of the build. While such manipulations range from trivial through to quite complex, the more common tasks include:

- Constructing paths or extracting components of a path.
- Obtaining a list of files from a directory.
- Copying files.
- Generating a file from string contents.
- Generating a file from another file's contents.
- Reading in the contents of a file.
- Computing a checksum or hash of a file.

CMake provides a variety of features related to working with files and directories. In some cases, there can be multiple ways of achieving the same thing, so it is useful to be aware of the different choices and understand how to use them effectively. A number of these features are frequently misused, some due to such misuse being prevalent in online tutorials and examples, leading to the belief that it is the right way to do things. Some of the more problematic anti-patterns are discussed in this chapter.

Much of CMake's file-related functionality is provided by the `file()` command, with a few other commands offering alternatives better suited to certain situations or providing related helper capabilities. CMake's command mode, which was introduced in the previous chapter, also provides a variety of file-related features which overlap with much of what `file()` provides, but it covers a complimentary set of scenarios to `file()` rather than being an alternative in most cases.

21.1. Manipulating Paths

One of the most basic parts of file handling is manipulating file names and paths. Projects often need to extract file names, file suffixes, etc. from full paths, or convert between absolute and relative paths. With CMake 3.19 and earlier, this functionality is spread across two commands, `get_filename_component()` and `file()`. The two have some overlap and there are inconsistencies. CMake 3.20 introduced a new command, `cmake_path()` which supersedes most of the path-handling capabilities of those two commands. It provides a more consistent, more predictable interface.

21.1.1. `cmake_path()`

The official documentation for `cmake_path()` is fairly comprehensive. It covers the concepts used, presents the various sub-commands in logical, task-based groups and provides numerous examples. The reader is encouraged to study the material presented therein for a deeper understanding of the command. Only some key concepts and sub-commands for more common tasks are described here.

The `cmake_path()` command never accesses the underlying file system. It only operates on paths syntactically, so it knows nothing about symbolic links or the existence of a path. It uses a clearly defined path structure where forward slashes are always used as directory separators, regardless of the host or target platform. A drive letter or mapped drive name (e.g. C: or //myserver) is supported only if the host platform supports it.

The following example path and table demonstrate the terminology used:

```
C:/one/two/start.middle.end
```

Path component	Example
ROOT_NAME	C:
ROOT_DIRECTORY	/
ROOT_PATH	C:/
FILENAME	start.middle.end
EXTENSION	.middle.end
STEM	start
RELATIVE_PART	one/two/start.middle.end
PARENT_PATH	C:/one/two

The GET sub-command can be used to retrieve any of the above path components (replace <COMP> with one of the items from the first column

in the above table):

```
cmake_path(GET pathVar <COMP> [LAST_ONLY] outVar)
```

`LAST_ONLY` can only be given if `<COMP>` is either `EXTENSION` or `STEM`. By default, an `EXTENSION` starts at the left-most dot (.) character of the `FILENAME`, but `LAST_ONLY` changes this to use the right-most dot character instead. The `STEM` is the `FILENAME` without the `EXTENSION`, with the `LAST_ONLY` keyword changing the meaning of `EXTENSION` in this case as well.

```
set(path "a.b.c")

cmake_path(GET path EXTENSION result)           # .b.c
cmake_path(GET path EXTENSION LAST_ONLY result) # .c

cmake_path(GET path STEM result)                 # a
cmake_path(GET path STEM LAST_ONLY result)       # a.b
```

As demonstrated in the above example, note that `pathVar` is the name of a variable holding a path, it is not a string:

```
# WRONG: Cannot use a string for the path
cmake_path(GET "/some/path/example" FILENAME result)

# Correct, but can be improved (see below)
set(path "/some/path/example")
cmake_path(GET path FILENAME result)
```

While using `set()` to create a path variable is permitted, `cmake_path()` has a dedicated `SET` sub-command which is more robust and has additional features:

```
cmake_path(SET pathVar [NORMALIZE] input)
```

The main advantage of using `cmake_path(SET)` over `set()` is that the former automatically converts a native path to a cmake-style path, as expected by other `cmake_path()` sub-commands. Another advantage is the ability to normalize the path. The CMake documentation describes the formal rules for what the `NORMALIZE` keyword implies, but essentially it means to simplify a path by resolving things like `.` and `..`, collapsing multiple consecutive path separators `(/)` down to a single separator and a few other special cases. Note that because `cmake_path()` never accesses the file system, it does not resolve symbolic links as part of normalization.

```
cmake_path(SET path NORMALIZE "/some//path/xxx/..example")
```

```
# The path variable now holds the value: /some/path/example
```

One can also query a path to see if it has a particular path component:

```
cmake_path(<OP> pathVar outVar)
```

Valid values for `<OP>` include all the same `<COMP>` values for `GET`, except prefixed with `HAS_` (e.g. `HAS_EXTENSION`, `HAS_RELATIVE_PART`). In addition, `IS_ABSOLUTE` and `IS_RELATIVE` are also supported values for `<OP>`, but they have some less obvious behavioral aspects to be aware of. `IS_ABSOLUTE` technically means that the path unambiguously refers to a location without needing to refer to some relative point. The consequences of this are mostly relevant for Windows hosts and paths, since a path has to start at the root `/` and also have a drive letter to be

considered absolute. On non-Windows host platforms, paths having a drive letter are considered malformed. The same path can therefore yield different results on different host platforms. This is especially dangerous if cross-compiling on a Windows host and testing paths intended for a non-Windows target platform.

The following table shows the result of `cmake_path(IS_ABSOLUTE pathVar result)` for different cases:

pathVar	Windows host	Other host platforms
C:/somewhere	Absolute	Undefined
C:somewhere	Relative	Undefined
/somewhere	Relative	Absolute

On all platforms, the result of `IS_RELATIVE` is always the opposite of `IS_ABSOLUTE`, so it exhibits the same platform-dependent differences.

There are sub-commands for converting to absolute or relative paths:

```
cmake_path(RELATIVE_PATH pathVar
    [BASE_DIRECTORY baseDir]
    [OUTPUT_VARIABLE outVar]
)
cmake_path(ABSOLUTE_PATH pathVar [NORMALIZE]
    [BASE_DIRECTORY baseDir]
    [OUTPUT_VARIABLE outVar]
)
```

Relative paths are considered relative to the specified `baseDir`, if given, or `CMAKE_CURRENT_SOURCE_DIR` otherwise. If no `outVar` is given, the `pathVar` is modified in-place. The `NORMALIZE` keyword has the usual effect of normalizing the resultant path. One can also explicitly normalize a path with another sub-command:

```
cmake_path(NORMAL_PATH pathVar [OUTPUT_VARIABLE outVar])
```

Across all of CMake's file handling, most of the time a project can use forward slashes for directory separators on all platforms and CMake will do the right thing, converting to native paths as necessary on the project's behalf. Occasionally, however, a project may need to explicitly convert between CMake and native paths. One such example is when working with custom commands and needing to pass a path to a script which requires native paths. For these situations, the `NATIVE_PATH` sub-command can be used:

```
cmake_path(NATIVE_PATH pathVar [NORMALIZE] outVar)
```

There are other `cmake_path()` sub-commands, but the ones presented above cover the most common use cases.

21.1.2. Older Commands

For projects that must support CMake 3.19 or earlier, the `cmake_path()` command cannot be used. The same capabilities are more or less available with the much older `get_filename_component()` and `file()` commands though, albeit in less consistent syntactic forms. These two

commands also potentially access the file system as part of resolving paths, unlike `cmake_path()` which doesn't.

With CMake 3.19 and earlier, the primary method for performing path-related operations is the `get_filename_component()` command. It has three different forms. The first form allows for the extraction of the different parts of a path or file name, similar to the functionality provided by `cmake_path(GET)`:

```
get_filename_component(outVar input component [CACHE])
```

The result of the call is stored in the variable named by `outVar`. The component to extract from `input` is specified by `component`, which must be one of the following:

DIRECTORY

Extract the path part of `input` without the file name. Prior to CMake 2.8.12, this option used to be `PATH`, which is still accepted as a synonym for `DIRECTORY` to preserve compatibility with older versions.

NAME

Extract the full file name, including any extension. This essentially just discards the directory part of `input`.

NAME_WE

Extract the base file name only. This is like `NAME` except only the part of the file name up to but not including the first `"."` is extracted.

NAME_WLE

Similar to NAME_WE except the name up to the last "." is extracted. This option is only available with CMake 3.14 or later.

EXT

This is the complement to NAME_WE. It extracts just the extension part of the file name from the first "." onward. This can be thought of as the longest extension in the file name.

LAST_EXT

Similar to EXT except the shortest extension is returned (i.e. the part of the file name from the last "." onward). This option is only available with CMake 3.14 or later.

The CACHE keyword is optional. If present, the result is stored as a cache variable rather than a regular variable. Typically, it is not desirable to store the result in the cache, so the CACHE keyword is not often required.

```
set(input /some/path/foo.bar.txt)

# /some/path
get_filename_component(path1 ${input} DIRECTORY)
get_filename_component(path2 ${input} PATH)

# foo.bar.txt
get_filename_component(fullName ${input} NAME)

# foo
get_filename_component(baseNameShort ${input} NAME_WE)

# foo.bar
get_filename_component(baseNameLong ${input} NAME_WLE)
```

```
# .bar.txt
get_filename_component(extensionLong ${input} EXT)

# .txt
get_filename_component(extensionShort ${input} LAST_EXT)
```

The second form of `get_filename_component()` is used to obtain an absolute path:

```
get_filename_component(outVar input component
    [BASE_DIR baseDir] [CACHE]
)
```

In this form, `input` can be a relative path or it can be an absolute path. If `BASE_DIR` is given, relative paths are interpreted as being relative to `baseDir` instead of the current source directory (i.e. `CMAKE_CURRENT_SOURCE_DIR`). `BASE_DIR` will be ignored if `input` is already an absolute path. Unlike `cmake_path()`, this command can access the file system and resolve symbolic links. The `component` argument controls how symbolic links are handled for the path stored in `outVar`:

ABSOLUTE

Compute the absolute path of `input` without resolving symbolic links.

REALPATH

Compute the absolute path of `input` with symbolic links resolved.

The `file()` command provides the inverse operation, converting an absolute path to relative:

```
file(RELATIVE_PATH outVar relativeToDir input)
```

CMake 3.19 also added a `file()` sub-command which is essentially equivalent to the `REALPATH` operation of `get_filename_component()`:

```
file(REAL_PATH input outVar
    [BASE_DIRECTORY baseDir]
    [EXPAND_TILDE]      # Requires CMake 3.21 or later
)
```

With CMake 3.21 or later, when the `EXPAND_TILDE` keyword is given and `input` starts with a tilde (~), the tilde will be replaced by the path to the user's home directory. This mimics the behavior of most Unix shells.

Unfortunately, the `file(REAL_PATH)` sub-command introduced a number of inconsistencies:

- The order of the `input` and `outVar` arguments is different to the complementary `RELATIVE_PATH` operation.
- The `file()` command uses `REAL_PATH` (note the underscore), whereas `get_filename_component()` uses `REALPATH`.
- The optional base directory keyword is named `BASE_DIRECTORY` for `file(REAL_PATH)`, whereas it is named `BASE_DIR` for the `get_filename_component()` command.

The above inconsistencies can make the use of these commands somewhat more error-prone, so extra care is needed.

The following example demonstrates the usage of these `file()` sub-commands:

```
set(basePath    /base)
set(fooBarPath /base/foo/bar)
set(otherPath   /other/place)

file(RELATIVE_PATH fooBar ${basePath} ${fooBarPath})
file(RELATIVE_PATH other  ${basePath} ${otherPath})

file(REAL_PATH ${other} otherReal
     BASE_DIRECTORY ${basePath})
)
```

At the end of the above code block, the variables have the following values:

```
fooBar      = foo/bar
other       = ../other/place
otherReal  = /other/place
```

The third form of the `get_filename_component()` command is a convenience for extracting parts of a full command line (there is no equivalent `cmake_path()` command for this):

```
get_filename_component(progVar input PROGRAM
                      [PROGRAM_ARGS argVar] [CACHE]
)
```

With this form, `input` is assumed to be a command line which may contain arguments. CMake will extract the full path to the executable which

would be invoked by the specified command line, resolving the executable's location using the PATH environment variable if necessary and store the result in `progVar`. If `PROGRAM_ARGS` is given, the set of command line arguments are also stored as a list in the variable named by `argVar`. The `CACHE` keyword has the same meaning as the other forms of `get_filename_component()`.

The `file()` command offers two more forms which help transform paths between platform native and CMake formats:

```
file(TO_NATIVE_PATH input outVar)
file(TO_CMAKE_PATH  input outVar)
```

The `TO_NATIVE_PATH` form converts `input` into a native path for the host platform. This amounts to ensuring the correct directory separator is used (backslash on Windows, forward slash everywhere else). The `TO_CMAKE_PATH` form converts all directory separators in `input` to forward slashes. This is the representation used by CMake for paths on all platforms. The `input` can also be a list of paths specified in a form compatible with the platform's `PATH` environment variable. All colon separators are replaced with semicolons, thereby converting a `PATH`-like `input` into a CMake list of paths.

```
# Unix example
set(customPath /usr/local/bin:/usr/bin:/bin)

file(TO_CMAKE_PATH ${customPath} outVar)
# outVar = /usr/local/bin;/usr/bin;/bin
```

21.2. Copying Files

The need to copy a file during the configure stage or during the build itself is relatively common. Because copying a file is generally a familiar task to most users, it is natural for new CMake developers to implement file copying in terms of the same methods they already know. Unfortunately, this often results in the use of platform-specific shell commands with `add_custom_target()` and `add_custom_command()`, sometimes also with dependency problems that require developers to run CMake multiple times, or to manually build targets in a particular sequence.

In almost all cases, CMake offers better alternatives to such platform-specific approaches. In this section, a number of techniques for copying files are presented. Some are aimed at meeting a particular need, while others are intended to be more generic and can be used in a variety of situations. All methods presented work exactly the same way on all platforms.

One of the most useful commands for copying files at configure time is, unfortunately, one of the less intuitively named. The `configure_file()` command allows a single file to be copied from one location to another, optionally performing CMake variable substitution along the way. The copy is performed immediately, so it is a configure-time operation. A slightly reduced form of the command is as follows:

```
configure_file(source destination  
[COPYONLY | @ONLY] [ESCAPE_QUOTES]  
# See below for availability  
[NO_SOURCE_PERMISSIONS | USE_SOURCE_PERMISSIONS |
```

```
FILE_PERMISSIONS permissions... ]
```

```
)
```

The `source` must be an existing file and can be an absolute or relative path, with the latter being relative to the current source directory (i.e. `CMAKE_CURRENT_SOURCE_DIR`). The `destination` can be an existing directory or the file name to copy to. Using a directory name is risky, since if there is no directory by the specified name, a file of that name will be created instead. The `destination` can include a path, which can be absolute or relative. If the `destination` is not an absolute path, it is interpreted as being relative to the current binary directory (i.e. `CMAKE_CURRENT_BINARY_DIR`). If any part of the destination path does not exist, CMake will attempt to create the missing directories as part of the call. Note that it is not unusual to see projects include `CMAKE_CURRENT_SOURCE_DIR` or `CMAKE_CURRENT_BINARY_DIR` as part of the path with the `source` and `destination` respectively, but this just adds unnecessary clutter and should be avoided.

By default, the destination file will have the same permissions as the source file. With CMake 3.19 or later, the `NO_SOURCE_PERMISSIONS` option can be given and the destination file will be readable by everyone, writable by the user only and not executable. With CMake 3.20 or later, `USE_SOURCE_PERMISSIONS` or `FILE_PERMISSIONS` can be used. The former is already the default behavior, but it can be specified to clearly indicate the intent. `FILE_PERMISSIONS` gives full control over the permissions assigned to the destination. These three permission-related keywords are also supported by the `file(COPY)` and

`file(GENERATE)` commands. Examples of how permissions can be specified are included in the discussion of those commands further below.

If the `source` file is modified, the build will consider the `destination` to be out of date and will re-run `cmake` automatically. If the configure and generation time is non-trivial and the `source` file is being modified frequently, this can be a source of frustration for developers. For this reason, `configure_file()` is best used only for files that don't need to be changed all that often.

When performing the copy, `configure_file()` has the ability to substitute CMake variables. Without the `COPYONLY` or `@ONLY` options, anything in the `source` file that looks like a use of a CMake variable (i.e. has the form `${someVar}`) will be replaced by the value of that variable. If no variable exists with that name, an empty string is substituted. Strings of the form `@someVar@` are also substituted in the same way. The following shows a number of substitution examples:

CMakeLists.txt

```
set(FOO "String with spaces")
configure_file(various.txt.in various.txt)
```

various.txt.in

```
CMake version: ${CMAKE_VERSION}
Substitution works inside quotes too: "${FOO}"
No substitution without the $ and {}: FOO
Empty ${} specifier gets removed
Escaping has no effect: \${FOO}
@-syntax also supported: @FOO@
```

various.txt

```
CMake version: 3.7.0
Substitution works inside quotes too: "String with spaces"
No substitution without the $ and {}: FOO
Empty specifier gets removed
Escaping has no effect: \String with spaces
@-syntax also supported: String with spaces
```

The `ESCAPE_QUOTES` keyword can be used to cause any substituted quotes to be preceded with a backslash.

CMakeLists.txt

```
set(BAR "Some \"quoted\" value")
configure_file(quoting.txt.in quoting.txt)
configure_file(quoting.txt.in quoting_escaped.txt
    ESCAPE_QUOTES
)
```

quoting.txt.in

```
A: @BAR@
B: "@BAR@"
```

quoting.txt

```
A: Some "quoted" value
B: "Some "quoted" value"
```

quoting_escaped.txt

```
A: Some \"quoted\" value
B: "Some \"quoted\" value"
```

As the above example shows, the `ESCAPE_QUOTES` option causes escaping of all quotes regardless of their context. Therefore, a degree of

care must be taken when the file being copied is sensitive to spaces and quoting in any substitutions which may be performed.

Some file types need to have the `${someVar}` form preserved without substitution. A classic example of this is copying a Unix shell script where `${someVar}` is a common way to refer to a shell variable. In such cases, substitution can be limited to only the `@someVar@` form with the `@ONLY` keyword:

CMakeLists.txt

```
set(USER_FILE whoami.txt)
configure_file(whoami.sh.in whoami.sh @ONLY)
```

whoami.sh.in

```
#!/bin/sh
echo ${USER} > "@USER_FILE@"
```

whoami.sh

```
#!/bin/sh
echo ${USER} > "whoami.txt"
```

Substitution can also be disabled entirely with the `COPYONLY` keyword. If it is known that substitution is not needed, specifying `COPYONLY` is good practice, since it prevents unnecessary processing and any unexpected substitutions.

When using `configure_file()` and substituting file names or paths, a common mistake is to mishandle spaces and quoting. The source file may need to surround a substituted variable with quotes if it needs to be treated as a single path or file name. This is why the source file in the above

example used "@USER_FILE@" rather than @USER_FILE@ as the filename to write the output to.

Substitution of CMake variables in \${someVar} or @someVar@ form can also be performed on strings, not just files. The `string(CONFIGURE)` command provides equivalent functionality and options. It can be useful when the content to be copied requires more complex steps than a simple substitution:

```
string(CONFIGURE input outVar [@ONLY] [ESCAPE_QUOTES])
```

The `configure_file()` command uses files for input and output. The `string(CONFIGURE)` sub-command uses strings for input and output. CMake 3.18 added a third method that supports using a string for input and a file for output:

```
file(CONFIGURE
      OUTPUT outFile
      CONTENT inputString
      [@ONLY] [ESCAPE_QUOTES]
      # ... Other rarely used options
    )
```

The `OUTPUT` and `CONTENT` specify the output file and input string respectively. If the `outFile` is a relative path, it is assumed to be relative to the current binary directory. The remaining options have exactly the same meaning as they do for the `configure_file()` command.

Where no substitution is needed, another alternative is to use one of the relevant `file()` sub-commands. The most flexible and mature, available

with all CMake versions, are the closely related `COPY` and `INSTALL` forms, both of which support the same set of options:

```
file(<COPY|INSTALL> fileOrDir1 [fileOrDir2...]
      DESTINATION dir
      [NO_SOURCE_PERMISSIONS | USE_SOURCE_PERMISSIONS |
       [FILE_PERMISSIONS permissions...]
       [DIRECTORY_PERMISSIONS permissions...]]
      [FOLLOW_SYMLINK_CHAIN]    # Requires CMake 3.15 or later
      [FILES_MATCHING]
      [ [PATTERN pattern | REGEX regex] [EXCLUDE]
        [PERMISSIONS permissions...] ] [...]
)
```

Multiple files or even entire directory hierarchies can be copied to a chosen directory, even preserving symlinks if present. Any source files or directories specified without an absolute path are treated as being relative to the current source directory. Similarly, if the destination directory is not absolute, it will be interpreted as being relative to the current binary directory. The destination directory structure is created as necessary.

If a source is a directory name, it will be copied into the destination. To copy the directory's contents into the destination instead, append a forward slash (/) to the source directory like so:

```
# --> destDir/srcDir
file(COPY base/srcDir DESTINATION destDir)

# --> destDir
file(COPY base/srcDir/ DESTINATION destDir)
```

By default, the `COPY` form will result in all files and directories keeping the same permissions as the source from which they are copied, whereas the

`INSTALL` form will not preserve the original permissions. The `NO_SOURCE_PERMISSIONS` and `USE_SOURCE_PERMISSIONS` options can be used to override these defaults, or the permissions can be explicitly specified with the `FILE_PERMISSIONS` and `DIRECTORY_PERMISSIONS` options. The permission values are based on those supported by Unix systems:

`OWNER_READ OWNER_WRITE OWNER_EXECUTE`

`GROUP_READ GROUP_WRITE GROUP_EXECUTE`

`WORLD_READ WORLD_WRITE WORLD_EXECUTE`

`SETUID` `SETGID`

If a particular permission is not understood on a given platform, it is simply ignored. Multiple permissions can be (and usually are) listed together. For example, a Unix shell script might be copied to the current binary directory as follows:

```
file(COPY whoami.sh
      DESTINATION .
      FILE_PERMISSIONS
      OWNER_READ OWNER_WRITE OWNER_EXECUTE
      GROUP_READ GROUP_EXECUTE
      WORLD_READ WORLD_EXECUTE
)
```

The `COPY` and `INSTALL` signatures both also preserve the timestamps of the files and directories being copied. Furthermore, if the source is already present at the destination with the same timestamp, the copy for that file is

deemed as already having been done and will be skipped. The only other difference between `COPY` and `INSTALL` apart from the default permissions is that the `INSTALL` form prints status messages for each copied item, whereas `COPY` does not. This difference is because the `INSTALL` form is typically used as part of CMake scripts run in script mode for installing files, where common behavior is to print the name of each file installed.

With CMake 3.15 or later, the `FOLLOW_SYMLINK_CHAIN` keyword is supported. When this option is present, symlinks in the list of files to copy/install will be copied recursively, with symlinks being preserved. The recursion stops with the final non-symlink file being copied as normal. When copying or installing symlinks like this, all paths are stripped off, so this functionality really only suits situations where symlinks point to things in the same directory.

Consider a fairly standard set of library symlinks on Linux, such as the following:

```
libMyStuff.so.2.4.3  
libMyStuff.so.2 --> libMyStuff.so.2.4.3  
libMyStuff.so    --> libMyStuff.so.2
```

If `libMyStuff.so` was given to the `file(COPY)` or `file(INSTALL)` command and the `FOLLOW_SYMLINK_CHAIN` option was present, all three of the above would be copied/installed and the relative symlinks would all be preserved exactly as shown. Note that the symlinks are only followed in one direction, there is no logic for finding things that link *to* a file listed. So for the above example, if only

`libMyStuff.so.2` was listed in the `file()` command, the `libMyStuff.so` symlink would not be discovered and therefore it wouldn't be copied/installed.

Both `COPY` and `INSTALL` support applying certain logic to files that match or do not match a particular wildcard pattern or regular expression. This can be used to limit which files are copied and to override the permissions just for the matched files. Multiple patterns and regular expressions can be given in the one `file()` command. The use is best demonstrated by example.

The following copies all header (`.h`) and script (`.sh`) files from `someDir`, except headers whose file name ends with `_private.h`. Headers are given the same permissions as the file they are copied from, whereas scripts are given owner read, write and execute permissions. The directory structure is preserved.

```
file(COPY someDir
      DESTINATION .
      FILES_MATCHING
        REGEX *_private\\.h EXCLUDE
        PATTERN *.h
        PATTERN *.sh PERMISSIONS
          OWNER_READ OWNER_WRITE OWNER_EXECUTE
    )
```

If the whole source should be copied but permissions need to be overridden for just a subset of matched files, the `FILES_MATCHING` keyword can be omitted and the patterns and regular expressions are used purely to apply permission overrides.

```
file(COPY someDir
    DESTINATION .
    # Make Unix shell scripts executable by everyone
    PATTERN *.sh PERMISSIONS
        OWNER_READ OWNER_WRITE OWNER_EXECUTE
        GROUP_READ GROUP_EXECUTE
        WORLD_READ WORLD_EXECUTE
    # Ensure only owner can read/write private key files
    REGEX _dsa\$|_rsa\$ PERMISSIONS
        OWNER_READ OWNER_WRITE
)
)
```

For very simple file copying operations, CMake 3.21 or later provides an alternative sub-command that some developers may find easier to use:

```
file(COPY_FILE source destination
    [RESULT result]
    [ONLY_IF_DIFFERENT]
)
```

If `ONLY_IF_DIFFERENT` is given, then the timestamp of the destination will not be updated if it already has the same contents as the `source` file. It will typically be advisable to include this option to avoid triggering unnecessary rebuilds of anything that depends on the destination.

If the `RESULT` keyword is given, the outcome of the command is stored in the named variable. This allows processing to continue and recover from an error. The value stored in `outVar` will be 0 upon success or an error message otherwise. Without the `RESULT` keyword, processing will halt if any error is encountered.

CMake offers further methods for copying files and directories. Whereas `configure_file()` and `file()` are used mainly at configure time or in a CMake script at install time, CMake’s command mode is often used for copying files and directories at build time. Command mode is the preferred way to copy content as part of `add_custom_target()` and `add_custom_command()` rules, since it provides platform independence (see [Section 20.5, “Platform Independent Commands”](#)). There are four commands related to copying, the first of which is used to copy individual files:

```
cmake -E copy file1 [file2...] destination
```

With CMake 3.26 or later, the following alternative form can also be used:

```
cmake -E copy -t destination files...
```

Both forms are equivalent, but the second form avoids triggering an error if the list of files to be copied is empty. If only one source file is provided, then `destination` is treated as the name of the file to copy to, unless it names an existing directory. When the destination is an existing directory, the source file will be copied into it. This behavior is consistent with that of most operating systems’ native copy commands, but it also means that the behavior is dependent on the state of the file system before the copy operation. Therefore, it is more robust to explicitly specify the target file name when copying a single file unless it is guaranteed that the destination is a directory that will already exist.

As a convenience, if `destination` includes a path (relative or absolute), CMake will try to create the destination path as needed when copying only a single source file. This means that when copying individual files, the `copy` command does not require an earlier step to ensure the destination directory exists. If more than one source file is listed, `destination` must refer to an existing directory. Once again, CMake's command mode can be used to ensure this using `make_directory` which creates the named directory if it does not already exist, including any parent directories as needed. The following shows how to safely put these command mode commands together:

```
add_custom_target(CopyOne
    COMMAND ${CMAKE_COMMAND} -E
        copy a.txt output/textfiles/a.txt
)
add_custom_target(CopyTwo
    COMMAND ${CMAKE_COMMAND} -E
        make_directory output/textfiles
    COMMAND ${CMAKE_COMMAND} -E
        copy a.txt b.txt output/textfiles
)
```

The `copy` command will always copy the source to the destination, even if the destination is already identical to the source. This results in the target timestamps always being updated, which can sometimes be undesirable. If the timestamps should not be updated if the files already match, then the `copy_if_different` command may be more appropriate:

```
cmake -E copy_if_different file1 [file2...] destination
```

This functions exactly like the `copy` command except if a source file already exists at the destination and is the same as the source, no copy is performed and the timestamp of the target is left alone.

It is also possible to copy entire directories rather than individual files:

```
cmake -E copy_directory dir1 [dir2...] destination
```

Unlike the file-related `copy` commands, the destination directory is created if required, including any intermediate path. Note also that `copy_directory` copies the *contents* of the source directories into the destination, not the source directories themselves. For example, suppose a directory `myDir` contains a file `someFile.txt` and the following command was issued:

```
cmake -E copy_directory myDir targetDir
```

The result would be that `targetDir` would contain the file `someFile.txt`, not `myDir/someFile.txt`.

With CMake 3.26 or later, the following signature is also supported:

```
cmake -E copy_directory_if_different dir1 [dir2...] destination
```

Again, this works the same as its `cmake -E copy_directory` counterpart, except that only new or modified files will be copied. Time stamps will only be updated on destination files or directories that are modified.

Generally speaking, `configure_file()` and `file()` are best suited to copying files at configure time, whereas CMake's command mode is the preferred way to copy at build time. While it is possible to use command mode in conjunction with `execute_process()` to copy files at configure time, there is little reason to do so. The `configure_file()` and `file()` commands are both more direct, and they have the added benefit that they stop on any error automatically.

21.3. Reading And Writing Files Directly

CMake offers more than just the ability to copy files. It also provides a number of commands for reading and writing file contents. The `file()` command provides the bulk of the functionality, with the simplest being the forms that write directly to a file:

```
file(WRITE fileName content)
file(APPEND fileName content)
```

Both of these commands will write the specified `content` to the named file. The only difference between the two is that if `fileName` already exists, `APPEND` will append to the existing contents, whereas `WRITE` will discard the existing contents before writing. The `content` is just like any other function argument and can be the contents of a variable or a string.

```
set(msg "Hello world")
file(WRITE hello.txt ${msg})
file(APPEND hello.txt " from CMake")
```

The above would result in the file `hello.txt` containing the single line `Hello world` from CMake. Note that newlines are not automatically added, so the text from the APPEND line continues directly after the WRITE line's text without a break. To have a newline written, it must be included in the content passed to the `file()` command. One way is to use a quoted value spread across multiple lines:

```
file(WRITE multi.txt "First line  
Second line  
")
```

If using CMake 3.0 or later, the bracket syntax introduced back in [Section 6.1, “Variable Basics”](#) can sometimes be more convenient, since it prevents any variable substitution of the content.

```
file(WRITE multi.txt [[  
First line  
Second line  
]])  
  
file(WRITE userCheck.sh [= [  
#!/bin/bash  
[[ -n "${USER}" ]] && echo "Have USER"  
]=])
```

In the above, the contents to be written to `multi.txt` consist only of simple text with no special characters, so the simplest bracket syntax where = characters can be omitted is sufficient, leaving just a pair of square brackets to mark the start and end of the content. Note how the behavior to ignore the first newline immediately after the opening bracket makes the command more readable.

The contents for `userCheck.sh` are much more interesting and highlight the features of bracket syntax. Without bracket syntax, CMake would see the `${USER}` part and treat it as a CMake variable substitution, but because bracket syntax performs no such substitution, it is left as is. For the same reason, the various quote characters in the content are also not interpreted as anything other than part of the content. They do not need to be escaped to prevent them being interpreted as the start or end of an argument. Furthermore, note how the embedded contents contain a pair of square brackets. This is the sort of situation the variable number of = signs in the start and end markers is meant to handle, allowing the markers to be chosen so that they do not match anything in the content they surround. When writing out multiple lines to a file and when no substitution should be performed, bracket syntax is often the most convenient way to specify the content to be written.

Sometimes a project may need to write a file whose contents depend on the build type. A naive approach would be to assume the `CMAKE_BUILD_TYPE` variable could be used as a substitution, but this does not work for multi-configuration generators like Xcode, Visual Studio or Ninja Multi-Config. Instead, the `file(GENERATE...)` command can be used:

```
file(GENERATE
    OUTPUT outFile
    INPUT inFile | CONTENT content
    [CONDITION expression]
    # Requires CMake 3.19 or later:
    [TARGET target]
    # Requires CMake 3.20 or later:
    [NO_SOURCE_PERMISSIONS | USE_SOURCE_PERMISSIONS |
```

```
[FILE_PERMISSIONS permissions...]  
)
```

This works somewhat like `file(WRITE...)` except that it writes out one file for each build type supported for the current CMake generator. Either of the `INPUT` or `CONTENT` options must be present, but not both. They define the content to be written to the specified output file.

`outFile`, `inFile` and `content` all support generator expressions, which is how the file names and contents are customized for each build type. A build type can be skipped by using the `CONDITION` option. The expression must evaluate to either 0 or 1 after any generator expressions have been expanded. The output file is not generated if it evaluates to 0.

If a generator expression in any of the arguments needs a target for it to be evaluated, but the target is not part of the expression (e.g. `$<TARGET_PROPERTY:propName>`), the `TARGET` option must be provided so it can be resolved. The `TARGET` option is only supported with CMake 3.19 or later.

With CMake 3.20 or later, the permissions for the `outFile` can be specified in the same way as for `configure_file()` or `file(COPY)`. The `NO_SOURCE_PERMISSIONS` and `USE_SOURCE_PERMISSIONS` keywords are only valid if using the `INPUT` option, but `FILE_PERMISSIONS` can be used with either `INPUT` or `CONTENT`.

The following examples show how to make use of generator expressions to customize the contents and file names depending on the build type.

```
# Generate unique files for all but Release
file(GENERATE
    OUTPUT
        ${CMAKE_CURRENT_BINARY_DIR}/outFile-$<CONFIG>.txt
    INPUT
        ${CMAKE_CURRENT_SOURCE_DIR}/input.txt.in
    CONDITION
        $<NOT:$<CONFIG:Release>>
)
```

```
# Embedded content, bracket syntax does not
# prevent the use of generator expressions
file(GENERATE
    OUTPUT
        ${CMAKE_CURRENT_BINARY_DIR}/details-$<CONFIG>.txt
    CONTENT [[
        Built as "$<CONFIG>" for platform "$<PLATFORM_ID>".
        Defines: $<TARGET_PROPERTY:COMPILE_DEFINITIONS>
    ]]
    TARGET SomeTarget
)
```

In the first case above, any generator expressions in the `input.txt.in` file will be evaluated when writing the output file. This is somewhat analogous to the way `configure_file()` substitutes CMake variables, except this time the substitution is for generator expressions. The second case demonstrates how bracket syntax can be a particularly convenient way of defining file contents inline, even when generator expressions and quoting are involved.

Usually, the output file would be different for each build type. But in some situations, it may be desirable for the output file to always be the same, such as where the file contents do not depend on the build type but rather on some other generator expressions. To support such use cases, CMake allows the output file to be the same for different build types, but only if the generated file contents are also identical for those build types. CMake disallows multiple `file(GENERATE...)` commands trying to generate the same output file.

Like for `file(COPY...)`, the `file(GENERATE...)` command will only modify the output file if the contents actually change. Therefore, the output file's timestamp will also only be updated if the contents differ. This is useful when the generated file is used as an input in a build target, such as a generated header file, since it can prevent unnecessary rebuilds.

There are some important differences in the way `file(GENERATE...)` behaves compared to most other CMake commands. Because it evaluates generator expressions, it cannot write out the files immediately. Instead, the files are written as part of the generation phase, which occurs after all of the `CMakeLists.txt` files have been processed. This means that the generated files won't exist when the `file(GENERATE...)` command returns, so the files cannot be used as inputs to something else during the configure phase. In particular, since the generated files won't exist until the end of the configure phase, they cannot be copied or read with `configure_file()`, `file(COPY...)`, etc. They can, however, still be used as inputs for the *build* phase, such as generated sources or headers.

Another point to note is that before CMake 3.10, `file(GENERATE...)` handled relative paths differently compared to usual CMake conventions. The behavior of relative paths was left unspecified and usually ended up being relative to the working directory of when `cmake` was invoked. This was unreliable and inconsistent, so in CMake 3.10 the behavior was changed to make `INPUT` act as relative to the current source directory and `OUTPUT` relative to the current binary directory, just like most other CMake commands that handle paths. Projects should consider relative paths unsafe to use with `file(GENERATE...)` unless the minimum CMake version is set to 3.10 or later.

The `file()` command can not only copy or create files, it can also be used to read in a file's contents:

```
file(READ fileName outVar  
    [OFFSET offset] [LIMIT byteCount] [HEX]  
)
```

Without any of the optional keywords, this command reads all the contents of `fileName` and stores them as a single string in `outVar`. The `OFFSET` option can be used to read only from the `offset` specified, counted in bytes from the beginning of the file. The maximum number of bytes to read can also be limited with the `LIMIT` option. If the `HEX` option is given, the contents will be converted to a hexadecimal representation, which can be useful for files containing binary data rather than text.

If it is more desirable to break up the file contents line-by-line, the `STRINGS` sub-command may be more convenient. Instead of storing the

entire file's contents as a single string, it stores them as a list, with each line being one list item.

```
file(STRINGS fileName outVar
      [LENGTH_MAXIMUM maxBytesPerLine]
      [LENGTH_MINIMUM minBytesPerLine]
      [LIMIT_INPUT maxReadBytes]
      [LIMIT_OUTPUT maxStoredBytes]
      [LIMIT_COUNT maxStoredLines]
      [REGEX regex]
      # ... other less commonly used options not shown
)
```

The LENGTH_MAXIMUM and LENGTH_MINIMUM options can be used to exclude strings longer or shorter than a certain number of bytes respectively. The total number of bytes read can be limited using LIMIT_INPUT, while the total number of bytes stored can be limited using LIMIT_OUTPUT. Perhaps more likely to be useful, however, is the LIMIT_COUNT option which limits the total number of *lines* stored rather than the number of bytes.

The REGEX option is a useful way to extract only specific lines from a file. For example, the following obtains a list with all lines in `myStory.txt` that contain either `PKG_VERSION` or `MODULE_VERSION`.

```
file(STRINGS myStory.txt versionLines
      REGEX "(PKG|MODULE)_VERSION"
)
```

It can also be combined with LIMIT_COUNT to obtain just the first match. The following example shows how to combine `file()` and `string()` to

extract a portion of the first line matching a regular expression.

```
set(regex "^ *FOO_VERSION *= *([^\n]+) *$")
file(STRINGS config.txt fooVersion
    REGEX "${regex}"
)
string(REGEX REPLACE "${regex}" "\\1"
    fooVersion "${fooVersion}"
)
```

If `config.txt` contained a line like this:

```
FOO_VERSION = 2.3.5
```

Then the value stored in `fooVersion` would be `2.3.5`.

21.4. File System Manipulation

In addition to reading and writing files, CMake also supports other common file system operations.

```
file(MAKE_DIRECTORY dirs...)
file(REMOVE files...)
file(REMOVE_RECURSE filesOrDirs...)
file(RENAME source destination
    # CMake 3.21 or later required for these options
    [RESULT outVar]
    [NO_REPLACE]
)
```

The `MAKE_DIRECTORY` sub-command will ensure the listed directories exist. Intermediate paths are created as necessary and no error is reported if a directory already exists.

The REMOVE sub-command can be used to delete files. If any of the listed files do not exist, the `file()` command does not report an error. Attempting to delete a directory with the REMOVE sub-command will have no effect. To delete directories and all of their contents, use the REMOVE_RECURSE sub-command instead.

The RENAME sub-command renames a file or directory. The `source` and `destination` must be the same type, i.e. both files or both directories. It is not permitted to specify a file as the `source` and an existing directory for the `destination`. To move a file into a directory, the file name must be specified as part of the `destination`. Furthermore, any path part of the `destination` must already exist — the RENAME form will not create intermediate directories.

Ordinarily, `file(RENAME)` will halt if any error is encountered. With CMake 3.21 or later, if the RESULT keyword is given, the outcome of the command is stored in the named variable instead. This allows processing to continue and recover from an error. The value stored in `outVar` will be 0 upon success or an error message otherwise. Note that if `destination` already exists, it is not considered an error unless NO_REPLACE is given (CMake 3.21 or later required). Without NO_REPLACE, the `destination` will be silently replaced by the `source`.

```
# Requires CMake 3.21 or later
file(RENAME someFile toSomethingElse
    RESULT result
    NO_REPLACE
)
if(result)
```

```
message(WARNING "File rename failed, taking action")
# ... handle failure to rename the file
endif()
```

CMake's command mode also supports a very similar set of capabilities which can be used at build time rather than configure time:

```
cmake -E make_directory dirs...
cmake -E remove [-f] files... # deprecated from CMake 3.17
cmake -E remove_directory dir # deprecated from CMake 3.17
cmake -E rm [-rRf] filesOrDirs...
cmake -E rename source destination
```

These commands largely behave in a comparable way to their `file()`-based counterparts, with only slight variations. The `remove_directory` command can strictly only be used with a single directory, whereas `file(REMOVE_RECURSE...)` can remove multiple items and both files and directories can be listed. The `remove` command accepts an optional `-f` flag which is intended to change the behavior when an attempt is made to remove a file that does not exist. The documented behavior of this flag is that without `-f`, a non-zero exit code is returned, whereas with `-f`, a zero exit code will be returned. This is intended to mimic aspects of the behavior of the Unix `rm -f` command. Unfortunately, due to a long-standing bug in the implementation, this isn't the actual behavior and the exit code of `cmake -E remove` should be considered unreliable, with or without the `-f` flag. The `rm` command was added in CMake 3.17 as a replacement for both the `remove` and `remove_directory` commands. It fixes the exit code bug and is more closely aligned with the Unix `rm` command.

CMake 3.14 added two new `file()` sub-commands which enable the project to query and manipulate file system links:

```
file(READ_SYMLINK linkName outVar)
file(CREATE_LINK pointedTo linkName
    [RESULT outVar]
    [COPY_ON_ERROR]
    [SYMBOLIC])
)
```

The `READ_SYMLINK` sub-command gives the path of what `linkName` points to. Note that symlinks often use relative paths and the value stored in `outVar` will just be the raw relative path for such cases.

The `CREATE_LINK` command allows the project to create hard or symbolic links. Hard links are created by default, but the `SYMBOLIC` option can be given to create a symbolic link instead. In most situations, `SYMBOLIC` would be recommended since it supports more scenarios (e.g. linking across different file systems). The `RESULT` keyword can be used to name a variable in which to store the result of the operation. The value stored will be 0 upon success or an error message otherwise. Without the `RESULT` option, a failure will cause CMake to halt with a fatal error. The `COPY_ON_ERROR` option provides a fallback for when an attempt to create a link fails, downgrading the operation to copy `pointedTo` to `linkName`. It exists primarily to allow the command to be used where creation of links is not supported, such as a hard link to a path on a different drive or device.

All CMake versions allow basic creation of symbolic links using CMake's command mode too (hard links cannot be created via this method):

```
cmake -E create_symlink pointedTo linkName
```

CMake 3.14 also added the ability to query the size of a file:

```
file(SIZE fileName outVar)
```

The specified `fileName` must exist and importantly it must also be readable.

CMake 3.19 added `file()` sub-commands for setting file and directory permissions:

```
file(CHMOD | CHMOD_RECURSE
      files... directories...
      [PERMISSIONS permissions...]
      [FILE_PERMISSIONS permissions...]
      [DIRECTORY_PERMISSIONS permissions...]
)
```

The `CHMOD` and `CHMOD_RECURSE` sub-commands are identical in their behavior except that the latter will also descend recursively into subdirectories. The supported values for `permissions` are the same as those supported by the `file(COPY)` sub-command. `FILE_PERMISSIONS` or `DIRECTORY_PERMISSIONS` will apply only to their respective type of entity and they will override `PERMISSIONS` for that entity type. One can specify just one of the two more specific types to operate on just that type of entity. The following shows how to take

advantage of this to set permissions just for directories and leave file permissions unmodified:

```
file(CHMOD_RECURSE ${someFilesAndDirs}
    DIRECTORY_PERMISSIONS
        OWNER_READ OWNER_WRITE OWNER_EXECUTE
        GROUP_READ GROUP_EXECUTE
        WORLD_READ WORLD_EXECUTE
)
```

21.5. File Globbing

CMake also supports listing the contents of one or more directories with either a recursive or non-recursive form of globbing:

```
file(GLOB outVar
    [LIST_DIRECTORIES true|false]
    [RELATIVE path]
    [CONFIGURE_DEPENDS]    # Requires CMake 3.12 or later
    expressions...
)
```

```
file(GLOB_RECURSE outVar
    [LIST_DIRECTORIES true|false]
    [RELATIVE path]
    [FOLLOW_SYMLINKS]
    [CONFIGURE_DEPENDS]    # Requires CMake 3.12 or later
    expressions...
)
```

These commands find all files whose names match any of the provided **expressions**, which can be thought of as simplified regular expressions. It may be easier to think of them as ordinary wildcards with the addition of

character subset selection. For `GLOB_RECURSE`, they can also include path components.

Some examples should help clarify basic use:

`*.txt` All files whose name ends with `.txt`.

`foo?.txt` Files like `foo2.txt`, `fooB.txt`, etc.

`bar[0-9].txt` Matches all files of the form `barX.txt` where X is a single digit.

`/images/*.png` For `GLOB_RECURSE`, this will match only those files with a `.png` extension and that are in a subdirectory called `images`. This can be a useful way of finding files in a well-structured directory hierarchy.

For `GLOB`, both files and directories matching the expression are stored in `outVar`. For `GLOB_RECURSE`, on the other hand, directory names are not included by default but this can be controlled with the `LIST_DIRECTORIES` option. Furthermore, for `GLOB_RECURSE`, symlinks to directories are normally reported as entries in `outVar` rather than descending into them, but the `FOLLOW_SYMLINKS` option directs CMake to descend into the directory instead of listing it.

The set of file names returned will be full absolute paths by default, regardless of the expressions used. The `RELATIVE` option can be used to change this behavior such that the reported paths are relative to a specific directory.

```
set(base /usr/share)
file(GLOB_RECURSE images)
```

```
    RELATIVE ${base}
    ${base}/*/* .png
)
```

The above will find all images below `/usr/share` and include the path to those images, except with the `/usr/share` part stripped off. Note the `/*/*` in the expression to allow any directory below the base point to be matched.

Developers should be aware that the `file(GLOB...)` commands are not as fast as, say, the Unix `find` shell command. Therefore, run time can be non-trivial if using it to search parts of the file system that contain many files.

The `file(GLOB)` and `file(GLOB_RECURSE)` commands are some of the most misused parts of CMake. They should not be used to collect a set of sources, headers or any other type of file that is an input to the build. One reason this should be avoided is that if files are added or removed, CMake is not automatically re-run, so the build is unaware of the change. This becomes particularly problematic if developers are using a version control system and are switching between branches, etc. where the set of files might change, but not in a way which causes CMake to re-run. The `CONFIGURE_DEPENDS` option added in CMake 3.12 tries to address this deficiency, but it comes with performance penalties and is not guaranteed to be supported by all project generators. The use of this option should be avoided.

Unfortunately, it is very common to see tutorials and examples use `file(GLOB)` and `file(GLOB_RECURSE)` to collect the set of sources to pass to commands like `add_executable()` and `add_library()`. This is explicitly discouraged by the CMake documentation. Such a practice also ignores the possibility that some files might only be intended for specific platforms. For projects with many files spread across multiple directories, there are better ways to collect the set of source files which do not suffer from such deficiencies. [Section 43.5.1, “Building Up A Target Across Directories”](#) presents alternative strategies which avoid these problems and encourage a more modular, self-contained directory structure.

21.6. Downloading And Uploading

The `file()` command has a number of other forms which carry out different tasks. A surprisingly powerful pair of sub-commands enable projects to download files from and upload files to an arbitrary URL.

```
file(DOWNLOAD url fileName [options...])
file(UPLOAD   fileName url [options...])
```

The **DOWNLOAD** form downloads a file from the specified `url` and saves it to `fileName`. If a relative `fileName` is given, it is interpreted as being relative to the current binary directory. CMake 3.19 and later allow the `fileName` to be omitted, in which case the file is downloaded but discarded. This can be used to check that a URL exists without having to save the file anywhere (not recommended for files that are expected to be large).

The **UPLOAD** form performs the complementary operation, uploading the named file to the specified `url`. For uploads, a relative path is interpreted as being relative to the current source directory.

The following options can be used, most of which are common to both **DOWNLOAD** and **UPLOAD**:

LOG outVar

Save logged output from the operation to the named variable. This can be useful to help diagnose problems when a download or upload fails.

SHOW_PROGRESS

When present, this option causes progress information to be logged as status messages. This can produce a fairly noisy CMake configure stage, so it is probably best to use this option only to temporarily help test a failing connection.

TIMEOUT seconds

Abort the operation if more than `seconds` have elapsed.

INACTIVITY_TIMEOUT *seconds*

This is a more specific kind of timeout. Some network connections may be of poor quality or may simply be very slow. It might be desirable to allow an operation to continue as long as it is making some sort of progress, but if it stalls for more than some acceptable limit, the operation should fail. The `INACTIVITY_TIMEOUT` option provides this capability, whereas `TIMEOUT` only allows the total time to be limited.

TLS_VERIFY *value*

This option accepts a boolean value indicating whether to perform server certificate verification when downloading from or uploading to a `https://` url. If this option is not provided, CMake looks for a variable named `CMAKE_TLS_VERIFY` instead. If neither the option nor the variable are defined, CMake 3.30 and later will then check for a `CMAKE_TLS_VERIFY` environment variable. If none of these have been set, the default behavior is to *not* verify the server certificate with CMake 3.30 and earlier, and to enable verification with CMake 3.31 and later. Note that `UPLOAD` support for this option was only added in CMake 3.18.

TLS_VERSION *minVersion*

When downloading from or uploading to a `https://` url, this option specifies the minimum TLS version for the connection. It is supported with CMake 3.30 and later. If not set, the `CMAKE_TLS_VERSION` CMake variable is checked, falling back to the

`CMAKE_TLS_VERSION` environment variable otherwise. If none of these are set, no explicit constraint is placed on the minimum TLS version if using CMake 3.30. With CMake 3.31 and later, the default minimum TLS version is 1.2.

TLS_CAINFO fileName

A custom Certificate Authority file can be specified with this option. It only affects `https://` urls. If this option is not provided, CMake looks for a variable named `CMAKE_TLS_CAINFO` instead. Note that UPLOAD support for this option was only added in CMake 3.18.

EXPECTED_HASH ALGO=value

This option is only supported for DOWNLOAD. It specifies the checksum of the file being downloaded so that CMake can verify the contents. `ALGO` can be any one of the hashing algorithms CMake supports, the most commonly used being MD5 and SHA1. Some older projects may use `EXPECTED_MD5` as an alternative to `EXPECTED_HASH MD5=...`, but new projects should prefer the `EXPECTED_HASH` form.

With CMake 3.7 or later, the following options are also available for both DOWNLOAD and UPLOAD:

USERPWD username:password

Provides authentication details for the operation. Be aware that hard-coding passwords is a security issue and should generally be avoided. If providing passwords with this option, the content should come from

outside the project, such as from an appropriately protected file read from the user's local machine at configure time.

HTTPHEADER header

Includes a HTTP header for the operation and can be repeated multiple times as needed to provide more than one header value. The following partial example demonstrates one of the motivating cases for this option:

```
file(DOWNLOAD
    "https://bkt.s3.amazonaws.com/myfile.tar.gz"
    myfile.tar.gz
EXPECTED_HASH
    SHA1=${myfileHash}
HTTPHEADER
    "Host: bkt.s3.amazonaws.com"
HTTPHEADER
    "Date: ${timestamp}"
HTTPHEADER
    "Content-Type: application/x-compressed-tar"
HTTPHEADER
    "Authorization: AWS ${s3key}:${signature}"
)
```

CMake 3.24 added the ability to download only part of a file:

RANGE_START offset

RANGE_END offset

The offsets are the number of bytes from the start of the file in both cases. Omitting RANGE_START will start downloading from the

beginning of the file. Omitting RANGE_END will download to the end of the file.

The `file()`-based download and upload commands tend to find use more as part of install steps, packaging or test reporting, but they can also occasionally find use for other purposes. Examples include things like downloading bootstrap files at configure time or bringing a file into the build which cannot or should not be stored as part of the project sources (e.g. sensitive files that should only be accessible for certain developers, very large files, etc.). Later chapters provide specific scenarios where these commands are used with great effect.

21.7. Recommended Practices

A range of CMake functionality related to file handling has been presented in this chapter. The various methods can be used very effectively to carry out a range of tasks in a platform-independent way, but they can also be misused. Establishing good patterns and applying them consistently throughout a project will help ensure new developers are exposed to better practices.

Consider using the `cmake_path()` command for path handling if the project's minimum CMake version is 3.20 or later. It generally uses a more consistent syntax than analogous capabilities of the much older `get_filename_component()` and `file()` commands. On the other hand, `cmake_path()` does not access the underlying file system, so it cannot be used if resolving symbolic links is required.

Note that the `if(IS_ABSOLUTE)` and `cmake_path(IS_ABSOLUTE)` commands interpret the path based on the *host* platform, but there are subtle differences between the two. They can yield different results for the same path in some cases. `cmake_path(IS_ABSOLUTE)` follows the implementation of the C++ `std::filesystem::path::is_absolute()` function, whereas `if(IS_ABSOLUTE)` uses its own logic with handling for some special cases. Take extra care if cross-compiling from a Windows host to a non-Windows target platform, or vice versa. If either command is used inappropriately, some paths may yield undefined behavior or give an opposite result to the value one may intuitively expect.

The `configure_file()` command is one that new developers often overlook, yet it is a key method of providing a file whose contents can be tailored according to variables determined at configure time, or even just to do a simple file copy. A common naming convention is for the file name part of the source and destination to be the same, except the source has an extra `.in` appended. Some IDE environments understand this convention and will provide appropriate syntax highlighting on the source file based on the file's extension without the `.in` suffix. The presence of the `.in` suffix not only serves as a clear reminder that the file needs to be transformed before use, it also prevents it from being accidentally picked up instead of the destination if CMake or the compiler look for files in multiple directories. This is especially relevant when the destination is a C/C++ header and the current source and binary directories are both on the header search path.

Choosing the most appropriate command for copying files is not always clear. The following may serve as a useful guide when choosing between `configure_file()`, `file(COPY)` and `file(INSTALL)`:

- If file contents need to be modified to include CMake variable substitutions, `configure_file()` is the most concise way to achieve it.
- If a file just needs to be copied but its name will change, the syntax of `configure_file()` is slightly shorter than `file(COPY...)`, but either would be suitable.
- If copying more than one file or a whole directory structure, use `file(COPY)` or `file(INSTALL)`.
- If control over file or directory permissions is required as part of the copy, `file(COPY)` or `file(INSTALL)` must be used if the project's minimum CMake version is 3.19 or earlier.
- `file(INSTALL)` should only be used as part of install scripts. Prefer `file(COPY)` for other situations.

Prior to CMake 3.10, the `file(GENERATE...)` command had different handling of relative paths compared to most other commands provided by CMake. Rather than relying on developers being aware of this different behavior, projects should instead prefer to always specify the `INPUT` and `OUTPUT` files with an absolute path to avoid errors or files being generated in unexpected locations.

When downloading or uploading files with the `file(DOWNLOAD...)` or `file(UPLOAD...)` commands, security and efficiency aspects should be carefully considered. Strive to avoid embedding any sort of authentication details (usernames, passwords, private keys, etc.) in any file stored in a version control system for the project's sources. Such details should come from outside the project, such as through environment variables (still somewhat insecure), files found on the user's file system with appropriate permissions limiting access, or a keychain of some kind. Make use of the `EXPECTED_HASH` option when downloading to re-use previously downloaded content from an earlier run and avoid a potentially time-consuming remote operation. If the downloaded file's hash cannot be known in advance, then the `TLS_VERIFY` option is highly recommended to ensure the integrity of the content. Also consider specifying a `TIMEOUT`, `INACTIVITY_TIMEOUT`, or both to prevent a configure run from blocking indefinitely if network connectivity is poor or unreliable.

22. SPECIFYING VERSION DETAILS

Versioning is one of those things that frequently doesn't get the attention it deserves. The importance of what a version number communicates to users is often underestimated, resulting in users with unmet expectations or confusion about changes between releases. There are also the inevitable tensions between marketing and how a versioning strategy affects the technical implementation of builds, packaging and so on. Thinking about and establishing these things early places the project in a better position when it comes time to deliver the first public release. This chapter explores ways to implement an effective versioning strategy, taking advantage of CMake features to provide a robust, efficient process.

22.1. Project Version

A project version often needs to be defined near the beginning of the top level `CMakeLists.txt` file so that various parts of the build can refer to it. Source code may want to embed the project version so that it can be displayed to the user or recorded in a log file, packaging steps may need it to define release version details and so on. One could simply set a variable

near the start of the `CMakeLists.txt` file to record a version number in whatever form is needed like so:

```
cmake_minimum_required(VERSION 3.0)
project(FooBar)
set(FooBar_VERSION 2.4.7)
```

If individual components need to be extracted, a slightly more involved set of variables may need to be defined. One example may look something like this:

```
cmake_minimum_required(VERSION 3.0)
project(FooBar)
set(FooBar_VERSION_MAJOR 2)
set(FooBar_VERSION_MINOR 4)
set(FooBar_VERSION_PATCH 7)
set(FooBar_VERSION
    ${FooBar_VERSION_MAJOR}.${FooBar_VERSION_MINOR}.${FooBar_VERSION_
PATCH})
)
```

Different projects may use different conventions for the naming of variables. The structure of version numbers can also vary from project to project, with the resultant lack of consistency making it that much more difficult to bring together many projects as part of a larger collection or superbuild (discussed in [Section 43.1, “Superbuild Structure”](#)).

CMake 3.0 introduced new functionality which makes specifying version details easier and brings some consistency to project version numbering. The `VERSION` keyword was added to the `project()` command, mandating a version number of the form *major.minor.patch.tweak* as the

expected format. From that information, a set of variables are automatically populated to make the full version string as well as each version component individually available to the rest of the project. Where a version string is provided with some parts omitted (the *tweak* part is often left out, for example), the corresponding variables are left empty.

The following table shows the automatically populated version variables when the `VERSION` keyword is used with the `project()` command:

PROJECT_VERSION	projectName_VERSION
PROJECT_VERSION_MAJOR	projectName_VERSION_MAJOR
PROJECT_VERSION_MINOR	projectName_VERSION_MINOR
PROJECT_VERSION_PATCH	projectName_VERSION_PATCH
PROJECT_VERSION_TWEAK	projectName_VERSION_TWEAK

The two sets of variables serve slightly different purposes. The project-specific `projectName_...` variables can be used to obtain the version details anywhere from the current directory scope or below. A call like `project(FooBar VERSION 2.7.3)` results in variables named `FooBar_VERSION`, `FooBar_VERSION_MAJOR` and so on. Since no two calls to `project()` can use the same `projectName`, these project-specific variables won't be overwritten by other calls to the `project()` command. The `PROJECT_...` variables, on the other hand, are updated every time `project()` is called, so they can be used to provide the

version details of the most recent call to `project()` in the current scope or above. From CMake 3.12, an analogous set of variables also provides the version details set by the `project()` call in the top level `CMakeLists.txt` file. These variables are:

`CMAKE_PROJECT_VERSION`

`CMAKE_PROJECT_VERSION_MAJOR`

`CMAKE_PROJECT_VERSION_MINOR`

`CMAKE_PROJECT_VERSION_PATCH`

`CMAKE_PROJECT_VERSION_TWEAK`

This same pattern is also followed to provide variables for the project name, description and homepage url, the latter two being added in CMake versions 3.9 and 3.12 respectively. As a general guide, the `PROJECT_...` variables can be useful for generic code (especially modules) as a way to define sensible defaults for things like packaging or documentation details. The `CMAKE_PROJECT_...` variables are sometimes used for defaults too, but they can be a bit less reliable since their use typically assumes a particular top level project. The `projectName_...` variables are the most robust, since they are always unambiguous in which project's details they will provide.

When working with projects that support CMake versions earlier than 3.0, it is sometimes the case that they will define their own version-related variables which clash with those automatically defined by CMake 3.0 and

later. This can lead to `CMP0048` policy warnings which highlight the conflict. The following shows an example of code which leads to such a warning:

```
cmake_minimum_required(VERSION 2.8.12)

set(FooBar_VERSION 2.4.7)
project(FooBar)
```

In the above, the `FooBar_VERSION` variable is explicitly set, but this variable name conflicts with the variable that the `project()` command would automatically define. The resultant policy warning is intended as an encouragement for the project to either use a different variable name or to update to a minimum CMake version of 3.0 and set the version details in the `project()` command instead.

22.2. Source Code Access To Version Details

Once the version details are defined in the `CMakeLists.txt` file, a very common need is to make them available to source code compiled by the project. A number of different approaches can be used, each with their own strengths and weaknesses. One of the most common techniques used by those new to CMake is to add a compiler define at the top level of the project:

```
cmake_minimum_required(VERSION 3.0)
project(FooBar VERSION 2.4.7)
add_definitions(-DFOOBAR_VERSION=\"${FooBar_VERSION}\")
```

This makes the version available as a raw string able to be used like so:

```
void printVersion()
{
    std::cout << FOOBAR_VERSION << std::endl;
}
```

While this approach is fairly simple, adding the definition to the compilation of every single file in the project comes with some drawbacks. Apart from cluttering up the command line of every file to be compiled, it means that any time the version number changes, the whole project gets rebuilt. This may seem like a minor point, but developers who regularly switch between different branches in a source control system will almost certainly get very annoyed by all the unnecessary recompilations. A slightly better approach uses source properties to define the FOOBAR_VERSION symbol only for those files where it is needed. For example:

```
cmake_minimum_required(VERSION 3.0)
project(FooBar VERSION 2.4.7)

add_executable(FooBar main.cpp src1.cpp src2.cpp ...)

get_source_file_property(defs src1.cpp COMPILE_DEFINITIONS)
list(APPEND defs "FOOBAR_VERSION=\${FooBar_VERSION}")
set_source_files_properties(src1.cpp PROPERTIES
    COMPILE_DEFINITIONS "\${defs}")
)
```

This avoids adding the compiler definition to every file, instead only adding it to those files that need it. As mentioned in [Section 10.5, “Source Properties”](#), however, there can be negative impacts on the build dependencies when setting individual source properties, and these once

again result in more files being rebuilt than should be necessary. Therefore, this approach may seem like an improvement, but often it won't be.

Rather than passing the version details on the command line, another common approach is to use `configure_file()` to write a header file that supplies the version details. For example:

foobar_version.h.in

```
#include <string>

inline std::string getFooBarVersion()
{
    return "@Foobar_VERSION@";
}

inline unsigned getFooBarVersionMajor()
{
    return @Foobar_VERSION_MAJOR@;
}

inline unsigned getFooBarVersionMinor()
{
    return @Foobar_VERSION_MINOR@ +0;
}

inline unsigned getFooBarVersionPatch()
{
    return @Foobar_VERSION_PATCH@ +0;
}

inline unsigned getFooBarVersionTweak()
{
    return @Foobar_VERSION_TWEAK@ +0;
}
```

main.cpp

```

#include "foobar_version.h"
#include <iostream>

int main(int argc, char* argv[])
{
    std::cout
        << "VERSION = " << getFooBarVersion() << "\n"
        << "MAJOR   = " << getFooBarVersionMajor() << "\n"
        << "MINOR   = " << getFooBarVersionMinor() << "\n"
        << "PATCH   = " << getFooBarVersionPatch() << "\n"
        << "TWEAK   = " << getFooBarVersionTweak()
        << std::endl;
    return 0;
}

```

CMakeLists.txt

```

cmake_minimum_required(VERSION 3.0)
project(FooBar VERSION 2.4.7)

configure_file(foobar_version.h.in foobar_version.h @ONLY)
add_executable(FooBar main.cpp)
target_include_directories(FooBar PRIVATE
    ${CMAKE_CURRENT_BINARY_DIR}
)

```

The `+0` in `foobar_version.h.in` is necessary for the *minor*, *patch* and *tweak* parts to allow their corresponding variables to be empty in the case of those version components being omitted.

Providing version details through a header like this is an improvement over the previous techniques. The version details are not included on the command line of any source file's compilation and only those files that `#include` the `foobar_version.h` header will be recompiled when the version details change. Providing all the different version components

rather than just the version string also has no impact on command lines. Nevertheless, if the version number is needed in many different source files, this can still result in more recompilation than is really necessary. This approach can be further refined by moving the implementations out of the header into their own .cpp file, and compiling that as its own library.

foobar_version.h

```
#include <string>

std::string getFooBarVersion();
unsigned   getFooBarVersionMajor();
unsigned   getFooBarVersionMinor();
unsigned   getFooBarVersionPatch();
unsigned   getFooBarVersionTweak();
```

foobar_version.cpp.in

```
#include "foobar_version.h"

std::string getFooBarVersion()
{
    return "@Foobar_VERSION@";
}

unsigned getFooBarVersionMajor()
{
    return @Foobar_VERSION_MAJOR@;
}

unsigned getFooBarVersionMinor()
{
    return @Foobar_VERSION_MINOR@ +0;
}

unsigned getFooBarVersionPatch()
{
    return @Foobar_VERSION_PATCH@ +0;
}
```

```
unsigned getFooBarVersionTweak()
{
    return @FooBar_VERSION_TWEAK@ +0;
}
```

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.0)
project(FooBar VERSION 2.4.7)

configure_file(foobar_version.cpp.in foobar_version.cpp
    @ONLY
)
add_library(FooBarVersion STATIC
    ${CMAKE_CURRENT_BINARY_DIR}/foobar_version.cpp
)
target_include_directories(FooBarVersion
    PUBLIC $<BUILD_INTERFACE:${CMAKE_CURRENT_SOURCE_DIR}>
)

add_executable(FooBar main.cpp)
target_link_libraries(FooBar PRIVATE FooBarVersion)

add_library(FooToolkit mylib.cpp)
target_link_libraries(FooToolkit PRIVATE FooBarVersion)
```

This arrangement has none of the previous approaches' drawbacks. When the version details change, only one source file needs to be recompiled (the generated `foobar_version.cpp` file), and the `FooBar` and `FooToolkit` targets only need to be relinked. The `foobar_version.h` header never changes, so any file that depends on it does not become out of date when the version details change. No options are added to the compilation command line of any source file either, so no other recompilations are triggered as a result of changing version details.

In situations where the project provides a library and header as part of a release package, the above arrangement is also robust. The header does not contain the version details, the library does. Therefore, code using the library can call the version functions and be confident that the details they receive are those the library was built with. This can be helpful in complicated end user environments where multiple versions of a project might be installed and not necessarily structured how the project intended.

One variant of this approach is to make `FooBarVersion` an object library rather than a static library. The result is more or less the same, but there isn't much to be gained, and it may feel less natural to developers. Making it a shared library loses some of the robustness advantages and again introduces a little more complexity for little benefit. In general, a static library is the better choice.

If the version functions are exposed as part of the API for a broader shared library, the additional concerns discussed in [Section 23.5, “Symbol Visibility”](#) and [Section 23.6, “Mixing Static And Shared Libraries”](#) should be noted. In such cases, it may be more appropriate to add the `foobar_version.cpp` file to that shared library directly rather than creating a separate static library for it.

22.3. Source Control Commits

It is not unusual for projects to want to record details related to their source control system. This might include the revision or commit hash of the sources at the time of the build, the name of the current branch or most recent tag and so on. The approach outlined above with version details

provided through a dedicated .cpp file lends itself well to adding more functions to return such details. For example, the current git hash can be provided relatively easily:

foobar_version.cpp.in

```
std::string getFooBarGitHash()
{
    return "@Foobar_GIT_HASH@";
}
// Other functions as before...
```

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.0)
project(FooBar VERSION 2.4.7)

# The find_package() command is covered later in the
# Finding Things chapter. Here, it provides the
# GIT_EXECUTABLE variable after searching for the git
# binary in some standard/well-known locations for the
# current platform.
find_package(Git REQUIRED)
execute_process(
    COMMAND ${GIT_EXECUTABLE} rev-parse HEAD
    RESULT_VARIABLE result
    OUTPUT_VARIABLE FooBar_GIT_HASH
    OUTPUT_STRIP_TRAILING_WHITESPACE
)
if(result)
    message(FATAL_ERROR
        "Failed to get git hash: ${result}"
    )
endif()

configure_file(foobar_version.cpp.in foobar_version.cpp
    @ONLY
)
# Targets, etc....
```

A slightly more interesting example is measuring how many commits have occurred since a particular file changed. Consider embedding the project's version in a separate file rather than in the `CMakeLists.txt` file, where the only thing in this separate file is the project version number. A reasonable assumption can then be made that the file only changes when the version number changes. As a result, measuring the number of commits since that file changed on the current branch is generally a good measure of the number of commits since the last version update.

The following example moves the project version out to a separate file named `projectVersionDetails.cmake` and provides the number of commits through a new function in the generated `foobar_version.cpp` file. It demonstrates a pattern suitable for any project where the version is set by the top level `project()` call, but in a way that won't interfere with a parent project if it is incorporated into a larger project hierarchy (a topic discussed in [Chapter 39, *FetchContent*](#)).

foobar_version.cpp.in

```
unsigned getFooBarCommitsSinceVersionChange()
{
    return @FooBar_COMMITS_SINCE_VERSION_CHANGE@;
}
// Other functions as before...
```

projectVersionDetails.cmake

```
# This file should contain nothing but the following line
# setting the project version. The variable name must not
# clash with the FooBar_VERSION* variables automatically
# defined by the project() command.
set(FooBar_VER 2.4.7)
```

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.0)
include(projectVersionDetails.cmake)
project(FooBar VERSION ${FooBar_VER})

find_package(Git REQUIRED)
execute_process(
    COMMAND ${GIT_EXECUTABLE} rev-list
        -1 HEAD projectVersionDetails.cmake
    RESULT_VARIABLE result
    OUTPUT_VARIABLE lastChangeHash
    OUTPUT_STRIP_TRAILING_WHITESPACE
)
if(result)
    message(FATAL_ERROR
        "Failed to get hash of last change: ${result}"
    )
endif()

execute_process(
    COMMAND ${GIT_EXECUTABLE} rev-list
        ${lastChangeHash}..HEAD
    RESULT_VARIABLE result
    OUTPUT_VARIABLE hashList
    OUTPUT_STRIP_TRAILING_WHITESPACE
)
if(result)
    message(FATAL_ERROR
        "Failed to get list of git hashes: ${result}"
    )
endif()
string(REGEX REPLACE "[\n\r]+;" ";" hashList "${hashList}")
list(LENGTH hashList FooBar_COMMITS_SINCE_VERSION_CHANGE)

configure_file(foobar_version.cpp.in foobar_version.cpp
    @ONLY
)
# Targets, etc....
```

The above approach works out the git hash of the last change to the version details file, then uses `git rev-list` to obtain the list of commit hashes for the whole repository since that commit. The commits are initially found as a string with one hash per line, which is then converted into a CMake list by replacing newline characters with the list separator (`;`). The `list()` command then simply counts how many items are in the list to give the number of commits. A simpler approach would use `git rev-list --count` to obtain the number directly, but older versions of git do not support the `--count` option, so the above method is preferable if older git versions need to be supported.

Other variations are also possible. Some projects use `git describe` to provide various details including branch names, most recent tag, etc., but note that tag and branch details can change without changing commits. If a branch or tag is moved or renamed, the build might not be repeatable. If version details only rely on file commit hashes, no such weakness is created. This also gives the project freedom in creating, renaming or deleting tags as needed after builds have confirmed the commits have no errors (think of release tags being applied to commits after continuous integration builds, testing, etc. confirm there are no problems).

Source control systems like Subversion present other challenges. On the one hand, Subversion maintains a global revision number for the whole repository, so there is no need to first obtain commit hashes and then count them. But Subversion also has the complication that it allows mixing different revisions of different files. As a result, approaches like the one outlined above for git can be defeated by a developer checking out different

revisions of files but leaving the project version file alone. This is not a scenario one would expect for an automated continuous integration system, but it may be more likely for a developer working locally on their own machine, depending on the way they like to work.

Another consideration of techniques like those above is what forces the generated version .cpp file to be updated. CMake ensures the configure step is re-run if the project version file changes, since it is brought into the main `CMakeLists.txt` file via an `include()` command. If, however, commits are made to other files, CMake will not be aware of them. It may be possible to implement hooks into the version control system (e.g. git's post-commit hook) to force CMake to re-run, but this is more likely to annoy developers than to help them. Ultimately, a compromise between convenience and robustness will typically be made. That said, the accuracy of the source control details will likely only be critical for releases, and it should be easy enough to ensure that the release process explicitly invokes CMake.

22.4. Recommended Practices

Projects are not required to follow any particular versioning system, but by following the *major.minor.patch.tweak* format, certain functionality comes for free with CMake. New developers will also have an easier time understanding the versioning used by the project. As will be seen in later chapters (notably [Chapter 36, Packaging](#)), the version format is more important when making packaged releases, but since many projects report

their own version number at run time, the version format affects the build too.

The meaning of each of the numbers making up the version format is up to the project, but there are conventions that end users often expect. For example, a change in the *major* value usually means a significant release, often involving changes that are not backward compatible or that represent a change in direction for the project. If a *minor* value changes, users tend to see this as an incremental release, most likely adding new features without breaking existing behavior. When only the *patch* value changes, users may not see it as a particularly important change and expect it to be relatively minor, such as fixing some bugs but not introducing new functionality. The *tweak* value is often omitted and doesn't tend to have a common interpretation beyond being even less significant than *patch*. Note that these are just general observations, projects can and do give the version numbers completely different meanings. For ultimate simplicity, a project might use just a single number and nothing else, effectively specifying every release as a new *major* version. While this would be easy to implement, it would also provide less guidance to end users and require good quality release notes to manage user expectations between each version.

The `VERSION` keyword of the `project()` command is one example of how CMake provides extra convenience when the *major.minor.patch.tweak* format is used. The project provides a single version string and the `project()` command automatically defines a set of variables making the various parts of the version number available. Some CMake modules may also use these variables as defaults for certain meta data, so it is generally

advisable to set the project version with the `project()` command using the `VERSION` keyword. This keyword was added in CMake 3.0, but if supporting older CMake versions, this functionality still needs to be considered. Projects should not define variables whose names clash with the automatically defined ones, or else later CMake versions will issue a warning. To prevent such warnings, avoid explicitly setting variables with names of the form `xxx_VERSION` or `xxx_VERSION_yyy`.

When defining the version number, consider doing so in its own dedicated file which CMake then pulls in via an `include()` command. This allows the project to take advantage of changes in version number aligning with changes in that file as seen by the project's source control system. To minimize unnecessary recompilation on version changes, generate a `.c` or `.cpp` file which contains functions that return version details rather than embedding those details in a generated header or as compiler definitions to be passed on the command line. Also ensure that names given to such functions incorporate something specific to the project or place them in a project-specific namespace. This allows the same pattern to be replicated across many projects which may later be combined into a single build without causing name clashes.

Establish versioning strategies and implementation patterns early in a project's life. This helps developers gain a clear understanding about how and when version details get updated and it encourages thinking about the release process well before the pressures of the first delivery. It also allows less efficient approaches to be weeded out early so that build efficiency is

maximized in advance of releases where version numbers change and where build turnaround times may become more important.

23. LIBRARIES

Compared to writing ordinary applications, creating and maintaining libraries is typically more involved, especially shared libraries. All the usual concerns about code correctness and maintainability still apply, but shared libraries in particular also bring with them additional considerations relating to API consistency, preserving binary compatibility between releases, symbol visibility, and more. Furthermore, each platform typically has its own set of unique features and requirements, making cross-platform library development a challenging task.

For the most part, however, a core set of capabilities are supported by all major platforms, it's just that the way to define or use them varies. CMake provides a number of features which abstract away these differences so that developers can focus on the capabilities and leave the implementation details up to the build system.

23.1. Build Basics

The fundamental command for defining a library was covered in previous chapters and has the following form:

```
add_library(targetName [STATIC | SHARED | MODULE | OBJECT]
            [EXCLUDE_FROM_ALL]
            [sources...])
```

A shared library will be produced if either the SHARED or MODULE keyword is provided. Alternatively, if no STATIC, SHARED, MODULE, or OBJECT keyword is given, a shared library will be produced if the BUILD_SHARED_LIBS variable has a value of true at the time `add_library()` is called.

The main difference between SHARED and MODULE is that SHARED libraries are intended for other targets to link against, whereas MODULE libraries are not. MODULE libraries are typically used for things like plugins or other optional libraries that can be loaded at runtime. The loading of such libraries is often dependent on an application configuration setting or detection of some system feature. Other executables and libraries do not normally link against a MODULE library.

On most Unix-based platforms, the file name of a STATIC or SHARED library will have `lib` prepended by default, whereas MODULE might not. Apple platforms also support frameworks and loadable bundles, which allow additional files to be bundled with the library in a well-defined directory structure. This is covered in detail in [Section 25.3, “Frameworks”](#).

On Windows platforms, library names do not have any `lib` prefix prepended, regardless of the type of library. Static library

targets produce a single `.lib` archive, whereas shared library targets result in two separate files, one for the runtime (the `.dll` or dynamic link library) and the other for linking against at build time (the `.lib` import library). Developers sometimes confuse import and static libraries due to the same file suffix being used for both, but CMake generally handles them correctly without any special intervention.

When using GNU tools on Windows (e.g. with the MinGW or MSYS project generators), CMake has the ability to convert GNU import libraries (`.dll.a`) to the same format that Visual Studio produces (`.lib`). This can be useful if distributing a shared library built with GNU tools to enable it to be linked to binaries built with Visual Studio. Note that Visual Studio must be installed for this conversion to be possible. The conversion is enabled by setting the `GNUToMS` target property to `true` for a shared library. This target property is initialized by the value of the `CMAKE_GNUToMS` variable at the time `add_library()` is called.

23.2. Linking Static Libraries

As first mentioned back in [Section 16.2.1, “Linking Libraries”](#), CMake handles some special cases specific to linking static libraries. If a library A is listed as a `PRIVATE` dependency for a static library target B, then A will effectively be treated as a `PUBLIC` dependency as far as linking is concerned (and *only* for

linking). This is because the private A library will still need to be added to the linker command line of anything linking to B in order for symbols from A to be found at link time. If B was a shared library, the private library A that it depends on would not need to be listed on the linker command line. CMake handles all this transparently, so the developer typically doesn't need to concern themselves with the details beyond specifying the PUBLIC, PRIVATE, and INTERFACE dependencies with `target_link_libraries()`.

For the curious, when exporting the A and B targets (discussed in [Section 35.3, “Installing Exports”](#)), CMake will use the `$<LINK_ONLY:>` generator expression to implement the "only for linking" logic. Projects won't typically need to use `$<LINK_ONLY:>` directly themselves, but its use can be seen in the export files that CMake generates.

In typical projects, static libraries will not contain cyclic dependencies where two or more libraries depend on each other. Nevertheless, some scenarios give rise to such situations, and CMake will recognize and handle the cyclic dependency as long as the relevant linking relationships have been specified (i.e. by `target_link_libraries()`). A slightly modified version of the example from the CMake documentation highlights the behavior:

```
add_library(A STATIC a.cpp)
add_library(B STATIC b.cpp)
```

```
target_link_libraries(A PUBLIC B)
target_link_libraries(B PUBLIC A)

add_executable(Main main.cpp)
target_link_libraries(Main A)
```

In the above, the link command for `Main` will contain `A B A B`. This repetition is provided automatically by CMake without developer intervention, but in certain pathological cases, more than one repetition may be required. While CMake provides the `LINK_INTERFACE_MULTIPLICITY` target property for this purpose, such situations usually point to a need for the project to be restructured. `OBJECT` libraries may also be a useful tool for addressing such deep interdependencies, since they effectively act like a collection of sources rather than actual libraries. The ordering of object files on the linker command line is usually not important, whereas library ordering typically is.

It is also worth noting that CMake may change the order of libraries based on the dependency information between targets, so projects should ensure they specify those details accurately. CMake may also de-duplicate the set of libraries if the linker is known to not need repetitions.

23.3. Shared Library Versioning

A CMake project which does not expect its libraries to be used outside the project itself doesn't typically need version information for any shared libraries it creates. The whole project tends to be updated together when deployed, so there are few issues about ensuring binary compatibility between releases, etc. But if the project provides libraries and other software could link against them, library versioning becomes very important. Library version details add greater robustness, allowing other software to specify the interface they expect to link against and have available to them at run time.

Most platforms offer functionality for specifying the version number of a shared library, but the way it is done varies considerably. Platforms generally have the ability to encode version details into the shared library binary, and this information is sometimes used to determine whether a binary can be used by another executable or shared library that links to it. Some platforms also have conventions for setting up files and symbolic links with different levels of the version number in their names. On Linux, for example, a common set of file and symbolic links for a shared library might look like this:

```
libMyStuff.so.2.4.3  
libMyStuff.so.2 --> libMyStuff.so.2.4.3  
libMyStuff.so    --> libMyStuff.so.2
```

CMake takes care of most of the platform differences with regard to version handling for shared libraries. When linking a

target to a shared library, it will follow platform conventions when deciding which of the file or symlink names to link against. When building a shared library, CMake automates the creation of the full set of files and symlinks if version details are provided.

A shared library's version details are defined by the `VERSION` and `SOVERSION` target properties. The interpretation of these properties is different across the platforms CMake supports, but by following *semantic versioning* principles, these differences can be handled fairly seamlessly. Semantic versioning assumes a version number is specified in the form *major.minor.patch*, where each version component is an integer. The `VERSION` property would be set to the full *major.minor.patch*, whereas `SOVERSION` would be set to just the *major* part. As a project evolves and makes releases, semantic versioning implies that the version details should be modified as follows:

- When an incompatible API change is made, increment the *major* part of the version and reset the *minor* and *patch* parts to 0. This means the `SOVERSION` property will change every time there is an API breakage and *only* if there is an API breakage.
- When functionality is added in a backwards compatible manner, increment the *minor* part and reset the *patch* to 0. The *major* part remains unchanged.

- When a backwards compatible bug fix is made, increment the *patch* value and leave the *major* and *minor* parts unchanged.

If the version details of a shared library are modified according to these principles, API incompatibility issues at run time will be minimized on all platforms. Consider the following example, which produces the set of symbolic links shown earlier for Linux:

```
add_library(MyStuff SHARED source1.cpp ...)  
set_target_properties(MyStuff PROPERTIES  
    VERSION 2.4.3  
    SOVERSION 2  
)
```

On Apple platforms, the `otool -L` command can be used to print the version details encoded into the resultant shared library. The output for the shared library produced by the above example would report the version details as having a *compatibility version* of 2.0.0 and *current version* 2.4.3. Anything that linked against the `MyStuff` library would have the name `libMyStuff.2.dylib` encoded into it as the name of the library to look for at run time. Linux platforms show a similar structure in their symbolic links for shared libraries, and normal practice is to use just the *major* part for the library's soname.

CMake 3.17 added the `MACHO_COMPATIBILITY_VERSION` and `MACHO_CURRENT_VERSION` target properties to support

advanced use cases for Apple platforms (typically related to matching libtool conventions). These additional properties allow file and symlink naming to be decoupled from the internal names embedded in the Mach-O binaries. Projects should rarely need this more complex functionality and are advised to avoid using these properties unless specific scenarios require them.

On Windows, CMake behavior is to extract a *major.minor* version from the `VERSION` property and encode that into the DLL as the DLL image version. Windows does not have the concept of a soname, and with CMake 3.26 or earlier, the `SOVERSION` property is not used. With CMake 3.27 or later, the `DLL_NAME_WITH_SOVERSION` target property can be set to true to add the `SOVERSION` as part of the DLL library base name on Windows platforms. Loosely speaking, this makes Windows DLLs have similar `SOVERSION` behavior to other platforms. The `CMAKE_DLL_NAME_WITH_SOVERSION` variable can be used to set the default behavior for targets without that property set.

```
add_library(MyStuff SHARED source1.cpp ...)
set_target_properties(MyStuff PROPERTIES
    VERSION      2.4.3
    SOVERSION    2
    DLL_NAME_WITH_SOVERSION TRUE  # Requires CMake 3.27+
)
```

On Windows, the above example would produce a shared library with the file name `MyStuff-2.dll`. This property does

not affect the file name of the associated import library, which would still be `MyStuff.lib`.

It should be noted that semantic versioning is not strictly required by any platform. Rather, it provides a well-defined specification which brings some certainty around dependency management between shared libraries and the things that use them. It happens to closely reflect how library versions are usually interpreted on most Unix-based platforms, and CMake aims to make the most of the `VERSION` and `SOVERSION` target properties to provide shared libraries which follow native platform conventions.

Projects should be aware that if only one of the `VERSION` and `SOVERSION` target properties are set, on most platforms the missing one is treated as though it had the same value as the one that was provided. This is unlikely to result in good version handling unless just a single number is used for the version number (i.e. no minor or patch parts). Such version numbering may be appropriate in certain cases, but projects should generally endeavor to follow the principles discussed above for more flexible and more robust runtime behavior.

23.4. Interface Compatibility

The `VERSION` and `SOVERSION` target properties allow API versioning to be specified at the binary level in a platform-independent manner. CMake also provides other properties

which can be used to define requirements for compatibility between CMake targets when they are linked to one another. These can be used to describe and enforce details that version numbering alone cannot capture.

Consider a realistic example where a networking library only provides support for the `https://` protocol and other similar secure capabilities if an appropriate SSL toolkit is available. Other parts of the program may need to adjust their own functionality based on whether SSL is supported, while the program as a whole should be consistent about whether SSL features can be used. This can be enforced with an *interface compatibility* property.

A few different types of interface compatibility properties can be defined, but the simplest is a boolean property. The basic idea is that libraries specify the name of a property they will use to advertise a particular boolean state. Then they define that property with the relevant value. When multiple libraries that are being linked together define the same property name for an interface compatibility, CMake will check that they specify the same value and issue an error if they are different. A basic example looks something like this:

```
add_library(Networking net.cpp)
set_target_properties(Networking PROPERTIES
    COMPATIBLE_INTERFACE_BOOL SSL_SUPPORT
    INTERFACE_SSL_SUPPORT YES
)
```

```

add_library(Util util.cpp)
set_target_properties(Util PROPERTIES
    COMPATIBLE_INTERFACE_BOOL SSL_SUPPORT
    INTERFACE_SSL_SUPPORT YES
)

add_executable(MyApp myapp.cpp)
target_link_libraries(MyApp PRIVATE Networking Util)
target_compile_definitions(MyApp PRIVATE
    $<$<BOOL:$<TARGET_PROPERTY:SSL_SUPPORT>>:HAVE_SSL>
)

```

Both library targets advertise that they define an interface compatibility for the property name `SSL_SUPPORT`. The `COMPATIBLE_INTERFACE_BOOL` property is expected to hold a list of names, each of which requires an associated property of the same name with `INTERFACE_` prepended to be defined on that target. When the libraries are used together as a link dependency for `MyApp`, CMake checks that both libraries define `INTERFACE_SSL_SUPPORT` with the same value. In addition, CMake will also automatically populate the `SSL_SUPPORT` property of the `MyApp` target with the same value too, which can then be used as part of a generator expression and made available to the source code of `MyApp` as a compile definition as shown. This allows the `MyApp` code to tailor itself to whether SSL support has been compiled into the libraries it uses. Continuing with the example, rather than `MyApp` simply detecting whether SSL support is available, it can specify a requirement by explicitly defining its `SSL_SUPPORT` property to hold the value that the libraries must be compatible with. In

that case, rather than automatically populating the SSL_SUPPORT property of MyApp, CMake will compare the values and ensure the libraries are consistent with the specified requirement.

```
# Require libraries to have SSL support
set_target_properties(MyApp PROPERTIES SSL_SUPPORT YES)
```

The above examples are somewhat contrived, the same constraints could have been enforced in other ways. The real advantages of interface compatibility specifications start to emerge as a project becomes more complicated and its targets are spread across many directories or come from externally built projects. Interface compatibilities are assigned as properties of the targets, so they only need to be defined in one place and are then made available anywhere the target can be used without further effort. Consuming targets don't have to know the details of how the interface compatibility is determined, only the final decision stored in the target's INTERFACE_... properties.

CMake also supports interface compatibilities expressed as a string. These work essentially the same way as the boolean case except that the named properties are required to have exactly the same values and can hold any arbitrary contents. The earlier example can be modified to require that libraries use the same SSL implementation, not just agree on whether they support SSL or not:

```

add_library(Networking net.cpp)
set_target_properties(Networking PROPERTIES
    COMPATIBLE_INTERFACE_STRING SSL_IMPL
    INTERFACE_SSL_IMPL OpenSSL
)

add_library(Util util.cpp)
set_target_properties(Util PROPERTIES
    COMPATIBLE_INTERFACE_STRING SSL_IMPL
    INTERFACE_SSL_IMPL OpenSSL
)

add_executable(MyApp myapp.cpp)
target_link_libraries(MyApp PRIVATE Networking Util)
target_compile_definitions(MyApp PRIVATE
    SSL_IMPL=$<TARGET_PROPERTY:SSL_IMPL>
)

```

In the above, the `SSL_IMPL` property is used as a string interface compatibility with the libraries specifying that they use OpenSSL as their SSL implementation. Just as for the boolean case, the `MyApp` target could have defined its `SSL_IMPL` property to specify a requirement rather than letting CMake populate it with the value from the libraries.

The other kind of interface compatibility CMake supports is a numeric value. Numeric interface compatibilities are used to determine the *minimum* or *maximum* value defined for a property among a set of libraries rather than to require the properties to have the *same* value. This can be exploited to allow a target to detect things like a minimum protocol version it could support,

or to work out the largest temporary buffer size needed among the libraries it links to.

```
add_library(BigFast strategy1.cpp)
set_target_properties(BigFast PROPERTIES
    COMPATIBLE_INTERFACE_NUMBER_MIN PROTOCOL_VER
    COMPATIBLE_INTERFACE_NUMBER_MAX TMP_BUFFERS
    INTERFACE_PROTOCOL_VER 3
    INTERFACE_TMP_BUFFERS 200
)

add_library(SmallSlow strategy2.cpp)
set_target_properties(SmallSlow PROPERTIES
    COMPATIBLE_INTERFACE_NUMBER_MIN PROTOCOL_VER
    COMPATIBLE_INTERFACE_NUMBER_MAX TMP_BUFFERS
    INTERFACE_PROTOCOL_VER 2
    INTERFACE_TMP_BUFFERS 15
)

add_executable(MyApp myapp.cpp)
target_link_libraries(MyApp PRIVATE BigFast SmallSlow)
target_compile_definitions(MyApp PRIVATE
    MIN_API=$<TARGET_PROPERTY:PROTOCOL_VER>
    TMP_BUFFERS=$<TARGET_PROPERTY:TMP_BUFFERS>
)
```

In the above, PROTOCOL_VER is defined as a *minimum* numeric interface compatibility, so the PROTOCOL_VER property of MyApp will be set to the smallest value specified for the INTERFACE_PROTOCOL_VER property of the libraries it links to, which in this case is 2. Similarly, TMP_BUFFERS is defined as a *maximum* numeric interface compatibility and the MyApp TMP_BUFFERS property receives the largest value among the

INTERFACE_TMP_BUFFERS property of its linked libraries, which is 200.

At this point, it would be natural to think about using the same property for both a minimum and maximum numeric interface compatibility to allow both the smallest and largest value to be detected in the parent. This is not possible because CMake does not (and cannot) allow the same property to be used with more than one kind of interface compatibility. If a property was used for multiple types of interface compatibilities, it would be impossible for CMake to know which type should be used to compute the value to be stored in the parent's result property. For example, if PROTOCOL_VER were both a minimum and maximum interface compatibility in the above example, CMake could not determine the value to store in the PROTOCOL_VER property of MyApp - should it store the minimum or maximum value? Instead, separate properties must be used to achieve this:

```
add_library(BigFast strategy1.cpp)
set_target_properties(BigFast PROPERTIES
    COMPATIBLE_INTERFACE_NUMBER_MIN PROTOCOL_VER_MIN
    COMPATIBLE_INTERFACE_NUMBER_MAX PROTOCOL_VER_MAX
    INTERFACE_PROTOCOL_VER_MIN 3
    INTERFACE_PROTOCOL_VER_MAX 3
)

add_library(SmallSlow strategy2.cpp)
set_target_properties(SmallSlow PROPERTIES
    COMPATIBLE_INTERFACE_NUMBER_MIN PROTOCOL_VER_MIN
    COMPATIBLE_INTERFACE_NUMBER_MAX PROTOCOL_VER_MAX
```

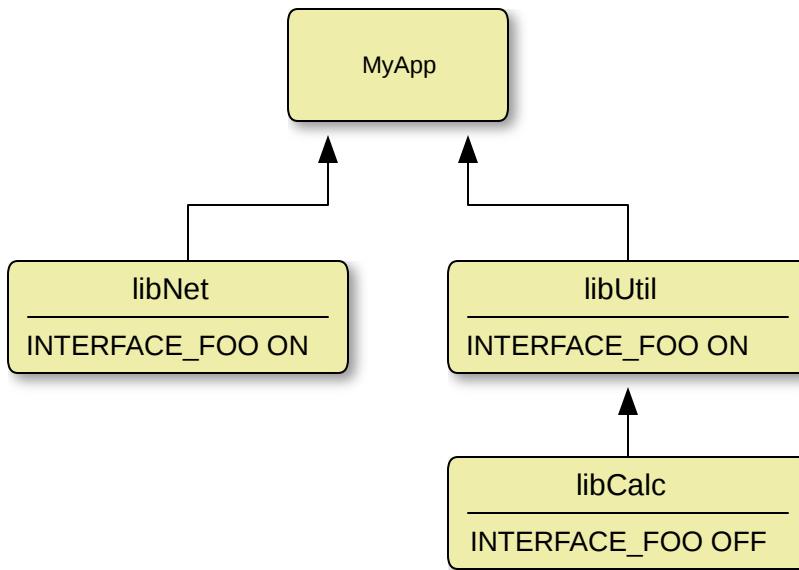
```
INTERFACE_PROTOCOL_VER_MIN 2
INTERFACE_PROTOCOL_VER_MAX 2
)

add_executable(MyApp myapp.cpp)
target_link_libraries(MyApp PRIVATE BigFast SmallSlow)
target_compile_definitions(MyApp PRIVATE
    PROTOCOL_VER_MIN=$<TARGET_PROPERTY:PROTOCOL_VER_MIN>
    PROTOCOL_VER_MAX=$<TARGET_PROPERTY:PROTOCOL_VER_MAX>
)
```

The result of the above example is that MyApp knows the range of protocol versions it needs to support based on the protocols used by the libraries it links to.

If one target defines an interface compatibility of any particular type, other targets are not required to define it too. Any target which does not define a matching interface compatibility is simply ignored for that particular property. This ensures libraries only need to define interface compatibilities that are relevant to them.

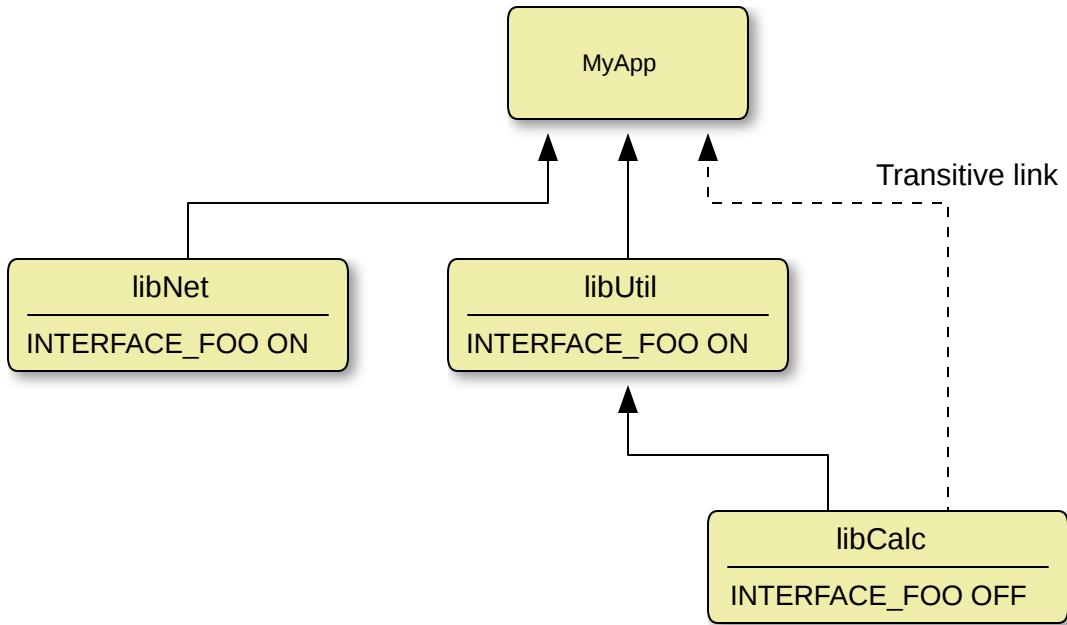
When there are multiple levels of library link dependencies, there are some subtle complexities to how interface compatibilities are handled. Consider the structure shown in the following diagram, which contains a number of library and executable targets and their direct link dependencies.



If all link dependencies are considered PRIVATE, then only libNet and libUtil are direct link dependencies of MyApp, so only those two libraries are required to have consistent values for their INTERFACE_FOO property. The value of that property in the libCalc library is not considered, since it is not a direct dependency of MyApp. Furthermore, the only direct link dependency of libUtil is libCalc, so the INTERFACE_FOO property of libCalc has no other library it is required to be consistent with. Even though both libUtil and libCalc define an interface compatibility for the same property name, because they are not both *direct* link dependencies of a common target, they are not required to have compatible values.

Now consider the situation where libCalc is a PUBLIC link dependency of libUtil. In that case, the final linking

relationships will actually look like this:



When libCalc is a PUBLIC link dependency of libUtil, anything that links to libUtil will also link to libCalc. Thus, libCalc becomes a direct link dependency of MyApp and therefore it *does* participate in interface compatibility checking with libNet and libUtil. This means great care must be taken when defining interface compatibilities to ensure that they accurately express the correct things, since their reach can extend out to targets beyond what may initially seem obvious when PUBLIC link relationships are involved.

23.5. Symbol Visibility

Simplistically, a library can be thought of as a container of compiled source code, providing various functions and global data which other code can call or use. For static libraries, the container is really just a collection of object files, and the tool putting it together is sometimes referred to as an archiver or librarian. Shared libraries, on the other hand, are produced by the linker, which processes the object code, archives, etc. and decides what to include in the final shared library binary. Some functions and global data may be hidden, meaning they have been marked as okay for the linker to use to resolve internal code dependencies, but code outside the shared library cannot call or use them. Other symbols are exported, so code both inside and outside the shared library can access them. This is referred to as a symbol's *visibility*.

Compilers have different ways of specifying symbol visibility, and they also have different default behaviors. Some make all symbols visible by default, whereas others hide symbols by default. Compilers also differ in the syntax used to mark individual functions, classes, and data as visible or not, which adds to the complexity of writing portable shared libraries. To avoid some of that complexity, some developers opt to make all symbols visible and avoid having to explicitly mark any symbols for export. While this may initially seem like a win, it comes with a range of downsides:

- It is equivalent to saying every function, class, type, global variable, etc. is freely available for anything to use. This is rarely desirable, but may be acceptable if the project is content to rely on its documentation to define the symbols which should be considered public.
- By making all symbols visible, consuming code cannot be prevented from using things they shouldn't. Other code linking to the library may come to rely on some internal symbol, making it harder for the shared library to change its implementation or internal structure without breaking consuming projects.
- When all symbols are to be treated as visible, the linker cannot know whether each symbol will be used by anything, so it has to include them all in the final shared library. When only a subset of the symbols are exported, the linker has the opportunity to identify code which can never be used by the visible symbols and discard it. This can often result in a much smaller binary, which then has the potential to load faster at run time.
- Languages like C++ which support templates have the potential to define a huge number of symbols. If all symbols are visible by default, this can result in the symbol table of a shared library growing quite large. In extreme cases, this can have a measurable impact on run time startup performance.
- Functions used in the internal implementation of the library may use names which expose details about what the library

does or how it does it. This might be a security concern in some contexts, or it may reveal commercial IP that shouldn't be visible to those receiving the library.

The above points highlight that symbol visibility is as much about enforcing the public-private nature of a library's API as it is about the low-level mechanics of shared library performance and package size. There are clear advantages to only exporting those symbols which should be considered public, but the compiler- and platform-specific nature of how to achieve that often presents a substantial hurdle for multi-platform projects. CMake considerably simplifies this process by abstracting away those differences behind a few properties, variables, and a helper module.

23.5.1. Specifying Default Visibility

By default, Visual Studio compilers assume all symbols are hidden unless explicitly exported. Other compilers, such as GCC and Clang are the opposite, making all symbols visible by default and only hiding symbols if explicitly told to. If a project wishes to have the same default symbol visibility across all its compilers and platforms, one of these two approaches must be selected. But hopefully the disadvantages highlighted in the preceding section provide a compelling argument for choosing that symbols be hidden by default.

The first step to enforcing hidden default visibility is to define the `<LANG>_VISIBILITY_PRESET` set of properties on a shared library target. For the two most common languages where this functionality is used, the property names are `C_VISIBILITY_PRESET` and `CXX_VISIBILITY_PRESET` for C and C++ respectively. The value given to this property should be `hidden`, which changes the default visibility to hide all symbols. Other supported values include `default`, `protected` and `internal`, but these are less likely to be useful for cross-platform projects. They either specify what is already the default behavior, or are variants of `hidden` with more specialized meanings in some contexts.

The second step is to specify that inlined functions should also be hidden by default. For C++ code that makes heavy use of templates, this can substantially reduce the size of the final shared library binary. This behavior is controlled by the target property `VISIBILITY_INLINES_HIDDEN` and applies to all languages. It should hold the boolean value `TRUE` to hide inline symbols by default.

Both `<LANG>_VISIBILITY_PRESET` and `VISIBILITY_INLINES_HIDDEN` can be specified on each shared library target, or a default can be set by the appropriate CMake variables. When a target is created, its `<LANG>_VISIBILITY_PRESET` property is initialized by the value of the CMake variable

`CMAKE_<LANG>_VISIBILITY_PRESET`, and its `VISIBILITY_INLINES_HIDDEN` property is initialized by the `CMAKE_VISIBILITY_INLINES_HIDDEN` variable. This is typically more convenient than setting the properties for each target individually.

For those projects wishing to make all symbols visible by default across all platforms, this only requires changing the default behavior of Visual Studio compilers. From version 3.4, CMake provides the `WINDOWS_EXPORT_ALL_SYMBOLS` target property which provides this behavior, but with caveats. Defining this property to a true value will cause CMake to write a `.def` file containing all symbols from all object files used to create the shared library and pass that `.def` file to the linker. This fairly brute force method prevents the source code from selectively hiding any symbols, so it should only be used where *all* symbols should be made visible. This target property is initialized by the `CMAKE_WINDOWS_EXPORT_ALL_SYMBOLS` CMake variable when a shared library target is created.

23.5.2. Specifying Individual Symbol Visibilities

Most common compilers support specifying the visibility of individual symbols, but the way they do so varies. In general, Visual Studio uses one method, and most other compilers follow the method used by GCC. The two share a similar structure, but they use different keywords. This means source code for

languages like C, C++, and their derivatives can use a common preprocessor define for visibility control, and projects can instruct CMake to provide the appropriate definition.

There are three primary cases where symbol visibility can be specified: classes, functions, and variables. In the following example which contains declarations for each of these three cases, note the position of `MYTOOLS_EXPORT`:

```
// Export non-private members of a class
class MYTOOLS_EXPORT SomeClass {...};

// Make a free function visible
MYTOOLS_EXPORT void someFunction();

// Make a global variable visible
MYTOOLS_EXPORT extern int myGlobalVar;
```

When building the shared library containing the implementations of the above, `MYTOOLS_EXPORT` needs to evaluate to keywords that *export* the symbol for use by other libraries and executables. On the other hand, if the same declarations are read by code belonging to a target outside the shared library, `MYTOOLS_EXPORT` must evaluate to keywords that *import* the symbol. With Visual Studio compilers, these keywords take the form `__declspec(...)`, whereas GCC and compatible compilers use `__attribute__(...)`.

Coming up with the right contents for `MYTOOLS_EXPORT` for all compilers and for both the exporting and importing cases can

be somewhat messy. Add into the mix that developers might choose to build a library as either shared or static and the complexity grows. Thankfully, CMake provides the `GenerateExportHeader` module which handles all of these details in a very convenient fashion. This module provides the following function:

```
generate_export_header(target
    [BASE_NAME baseName]
    [EXPORT_FILE_NAME exportFileName]
    [EXPORT_MACRO_NAME exportMacroName]
    [DEPRECATED_MACRO_NAME deprecatedMacroName]
    [NO_EXPORT_MACRO_NAME noExportMacroName]
    [STATIC_DEFINE staticDefine]
    [NO_DEPRECATED_MACRO_NAME noDeprecatedMacroName]
    [DEFINE_NO_DEPRECATED]
    [PREFIX_NAME prefix]
    [CUSTOM_CONTENT_FROM_VARIABLE var]
)
```

Typically, none of the optional arguments are needed and only the shared library target name is provided. CMake writes out a header file in the current binary directory, using the target name in lowercase with `_export.h` appended as the header file name. The header provides a define for symbol `export` with a similarly structured name, this time using the uppercase target name with `_EXPORT` appended. The following demonstrates this typical usage:

CMakeLists.txt

```
# Hide things by default
set(CMAKE_CXX_VISIBILITY_PRESET      hidden)
```

```

set(CMAKE_VISIBILITY_INLINES_HIDDEN YES)

# NOTE: myTools.cpp must #include myTools.h
add_library(MyTools myTools.cpp)
target_sources(MyTools
    PUBLIC
        FILE_SET HEADERS
        FILES myTools.h
)

include(GenerateExportHeader)
generate_export_header(MyTools)
target_sources(MyTools
    PUBLIC
        FILE_SET HEADERS
        BASE_DIRS ${CMAKE_CURRENT_BINARY_DIR}
        FILES ${CMAKE_CURRENT_BINARY_DIR}/mytools_export.h
)

```

myTools.h

```

#include "mytools_export.h"

class MYTOOLS_EXPORT SomeClass
{
    // ...
};

MYTOOLS_EXPORT void someFunction();
MYTOOLS_EXPORT extern int myGlobalVar;

```

Adding `mytools_export.h` to the `HEADERS` file set has a number of advantages. The current binary directory is not part of the default header search path, but by making it one of the `BASE_DIRS`, it will be searched. The `mytools_export.h` file is also added to the list of header files that will be installed along with the `MyTools` target. See [Section 16.2.7, “File Sets”](#) and

[Section 35.5.1, “File Sets”](#) for further details on these aspects of file sets.

If using the target name as part of the header file name or preprocessor define name is not desirable, the `BASE_NAME` option can be used to provide an alternative. It is transformed in the same way, being converted to lowercase and having `_export.h` appended for the file name, and uppercase with `_EXPORT` appended for the preprocessor define.

CMakeLists.txt

```
include(GenerateExportHeader)
generate_export_header(MyTools BASE_NAME fooBar)
```

myTools.h

```
#include "foobar_export.h"

class FOOBAR_EXPORT SomeClass
{
    // ...
};

FOOBAR_EXPORT void someFunction();
FOOBAR_EXPORT extern int myGlobalVar;
```

If a different name should be used for the file and preprocessor define, then rather than using `BASE_NAME`, the `EXPORT_FILE_NAME` and `EXPORT_MACRO_NAME` options can be given. Unlike `BASE_NAME`, the names provided by these two options are used without any modification.

CMakeLists.txt

```
include(GenerateExportHeader)
generate_export_header(MyTools
    EXPORT_FILE_NAME export_myTools.h
    EXPORT_MACRO_NAME API_MYTOOLS
)
```

myTools.h

```
#include "export_myTools.h"

class API_MYTOOLS SomeClass
{
    // ...
};

API_MYTOOLS void someFunction();
API_MYTOOLS extern int myGlobalVar;
```

The `generate_export_header()` function provides more than just this one preprocessor define. It also provides other preprocessor definitions which can be used to mark symbols as deprecated, or to explicitly specify that a symbol should never be exported. The latter can be useful to prevent exporting parts of a class that is otherwise exported, such as a public member function intended for internal use within the shared library, but not by code outside it. By default, the name of this preprocessor definition consists of the target name (or `BASE_NAME` if it is specified) with `_NO_EXPORT` appended, but an alternative name can be provided with the `NO_EXPORT_MACRO_NAME` option if desired.

CMakeLists.txt

```
include(GenerateExportHeader)
generate_export_header(MyTools
```

```
    NO_EXPORT_MACRO_NAME REALLY_PRIVATE  
)
```

myTools.h

```
#include "mytools_export.h"  
  
class MYTOOLS_EXPORT SomeClass  
{  
public:  
    REALLY_PRIVATE void doInternalThings();  
    // ...  
};
```

The function's deprecation support works in a similar way, providing a preprocessor definition with the uppercased target (or `BASE_NAME`) name followed by `_DEPRECATED`, or allowing a custom name to be specified via the `DEPRECATED_MACRO_NAME` option. The `DEFINE_NO_DEPRECATED` option can also be given, which will result in an additional preprocessor define being provided with a name consisting of the usual uppercased target or `BASE_NAME` followed by `_NO_DEPRECATED`. Like the other preprocessor defines, this name can also be overridden with the `NO_DEPRECATED_MACRO_NAME` option. With some compilers, symbols marked as deprecated can result in compile-time warnings which draw attention to their use. This can be a helpful mechanism to encourage developers to update their code to no longer use the deprecated symbols. The following shows how the deprecation mechanisms can be used.

CMakeLists.txt

```
option(OMIT_DEPRECATED "Omit deprecated parts of MyTools")
if(OMIT_DEPRECATED)
    set(deprecatedOption "DEFINE_NO_DEPRECATED")
else()
    unset(deprecatedOption)
endif()

include(GenerateExportHeader)
generate_export_header(MyTools
    NO_DEPRECATED_MACRO_NAME OMIT_DEPRECATED
    ${deprecatedOption}
)
```

myTools.cpp

```
#include "myTools.h"

#ifndef OMIT_DEPRECATED
void SomeClass::oldImpl() { ... }
#endif
```

myTools.h

```
#include "mytools_export.h"

class MYTOOLS_EXPORT SomeClass
{
public:
#ifndef OMIT_DEPRECATED
    MYTOOLS_DEPRECATED void oldImpl();
#endif
    // ...
};
```

The above example provides a CMake cache variable to determine whether to compile the deprecated items. The developer can make this choice without editing any files, so verifying behavior with or without the deprecated part of an

API is easy to do. This can be particularly useful if continuous integration builds have been set up to test both with and without deprecated parts of a library. It can also be useful in situations where the project is being used as a dependency of another project. The consuming project's developers can test whether their code uses the deprecated symbols just by changing the CMake cache variable.

A less common but nevertheless important case also deserves special mention. Some projects may wish to build both shared and static versions of the same library. In this case, the same set of source code needs to allow symbol exports to be enabled for the shared library build, but disabled for the static library build (also see [Section 23.6, “Mixing Static And Shared Libraries”](#) for why this won't always be the case). When both forms of library are required in the one build, they need to be different build targets, but the `generate_export_header()` function writes a header that is closely tied to a single target. To support this scenario, the generated header includes logic to check for the existence of one further preprocessor define before populating the export definition. The name of this special define follows the usual pattern once again, this time being the uppercase target or `BASE_NAME` followed by `_STATIC_DEFINE`, or having a custom name provided by the `STATIC_DEFINE` option. When this special preprocessor definition is defined, the export definition is forced to expand to nothing, which is typically what is needed when the target is being built as a static library.

Without the special preprocessor definition, the `export` define has the usual contents and works as expected when building a shared library target.

When both shared and static libraries are being built for the same set of source files, the `generate_export_header()` function should be given the target that corresponds to the shared library. The special preprocessor define is then set only on the static library's target. The `BASE_NAME` option will also typically be used to make the various symbols intuitive to either form of the library rather than being specific to the shared library only. The following demonstrates the structure needed to achieve the desired result:

```
# Same source list, different library types
add_library(MyShared SHARED ${mySources})
add_library(MyStatic STATIC ${mySources})

# Shared target used for generating export header
# with the name mytools_export.h, which will be suitable
# for both the shared and static targets
include(GenerateExportHeader)
generate_export_header(MyShared BASE_NAME MyTools)

# Static target needs special preprocessor define
# to prevent symbol import/export keywords being added
target_compile_definitions(MyStatic PRIVATE
    MYTOOLS_STATIC_DEFINE
)
```

As discussed earlier, the `generate_export_header()` function defines a number of different preprocessor definitions. There

are opportunities for different targets to accidentally try to use the same names for at least some of these. To help reduce name collisions, the `PREFIX_NAME` option allows an additional string to be specified which will be prepended to the names of each preprocessor definition. When used, this option would typically be something related to the project as a whole, effectively putting all of a project's generated preprocessor names into something like a project-specific namespace.

The last option not yet discussed is `CUSTOM_CONTENT_FROM_VARIABLE`, which was only added in CMake 3.7. It allows arbitrary content to be appended to the generated header. When used, it must be given the name of a variable whose contents should be injected, not the content itself.

```
string(TIMESTAMP now)
set(customContents /* Generated: ${now} */)

generate_export_header(MyTools
    CUSTOM_CONTENT_FROM_VARIABLE customContents
)
```

23.5.3. Additional Complications With C++20 Modules

A common misconception among developers is that C++20 modules replace the need to handle symbol visibility. The expectation is that modules should simplify this aspect, but in

fact, the opposite is true. Modules still require symbol visibility control, just like non-module code. The added layer adds to the complexity rather than replacing it.

One point of confusion is that the C++20 modules concept of *reachability* is unrelated to the previously discussed concept of symbol visibility. Reachability refers to whether a particular symbol can be accessed at *compile* time (the rules around that are not discussed here). Symbol visibility relates to whether a particular symbol can be seen at *link* time.

The other main point of confusion relates to a false expectation that modules are always part of a shared library's public API. A library or executable is allowed to use modules internally for its own purposes. It is not required that all modules be part of a shared library's public API. Thus, there needs to be a way for the code to indicate whether to make the module (or parts of it) available in the library's public API, which is what symbol visibility is all about.

If a module is only for use within a shared library, the recommended practice of hiding symbols by default is sufficient. Symbols from a module obey the same rules as non-module symbols in this regard. For a module intended to be part of a shared library's public API, the project must annotate the module's code just like for the non-module case. The `generate_export_header()` command can be used with module code in more or less the same way as non-module code.

CMakeLists.txt

```
set(CMAKE_CXX_VISIBILITY_PRESET hidden)
set(CMAKE_VISIBILITY_INLINES_HIDDEN TRUE)

add_library(Algo SHARED)
target_sources(Algo
    PRIVATE
        algo-impl.cpp
    PUBLIC
        FILE_SET CXX_MODULES
        FILES
            algo-interface.cppm
)
target_compile_features(Algo PUBLIC cxx_std_20)

include(GenerateExportHeader)
generate_export_header(Algo)
target_sources(Algo
    PUBLIC
        FILE_SET HEADERS
        BASE_DIRS ${CMAKE_CURRENT_BINARY_DIR}
        FILES
            ${CMAKE_CURRENT_BINARY_DIR}/algo_export.h
)
```

algo-interface.cppm

```
module;

#include <algo_export.h>

export module algo;

export class ALGO_EXPORT Algo
{
public:
    Algo() = default;
    ~Algo() = default;
    void helloworld();
};
```

algo-impl.cpp

```
module;

#include <iostream>

module algo;

void Algo::helloWorld()
{
    std::cout << "hello world\n";
}
```

The `algo-interface.cppm` file is similar to an `algo.h` header from a non-modules arrangement. This is the file the build system will compile into a BMI (built module interface) for the `algo` module. The `algo_export.h` header is included in the global module fragment (after the first `module` keyword, but before the `export module algo`). This provides the definition of `ALGO_EXPORT`, which is used in the class declaration for `Algo` in the same way as one would do for the case without modules.

Separating a class' interface and its implementation into separate files is still generally desirable for classes that are exported from a module. For the trivial example above, the implementation of `helloWorld()` could have been inlined in the same file as the class definition. For more real-world cases, the class implementation can be non-trivial, or it might contain private details that should remain hidden. The file that defines a module's interface must be installed along with the shared library so that the consumer can compile its own BMI. Any files

the module's interface file depends on must also be installed, like `algo_export.h` in the above example. The module's interface file and other files it depends on should not contain large or sensitive implementations. Thus, the same recommended separation of interface from implementation for non-module code also applies to module code. This aspect is discussed further in [Section 35.6, “Installing C++20 Modules”](#).

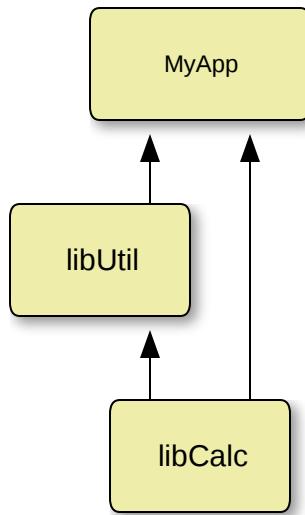
23.6. Mixing Static And Shared Libraries

When a project builds all its libraries as static, the build may appear to be a bit more forgiving about library link dependencies. The project may neglect to specify that one target requires another, but when various static libraries are linked into a final executable, the missing library dependencies are satisfied because they are explicitly listed for the executable in the required order. The build then succeeds, but probably only after a period of trial and error doing builds, having the linker complain about missing symbols, adding in more missing libraries or reordering the existing ones, etc.

This scenario results in success more by good fortune than by good design, but it is surprisingly common, especially with projects that define many small libraries. If link dependencies are specified for at least some static libraries, CMake automatically handles transitively linking those dependencies. So even if the PRIVATE/PUBLIC nature of the dependency is

specified incorrectly, with a static library, it is always treated as PUBLIC anyway. This sometimes makes builds work, even though the link dependency isn't accurately described.

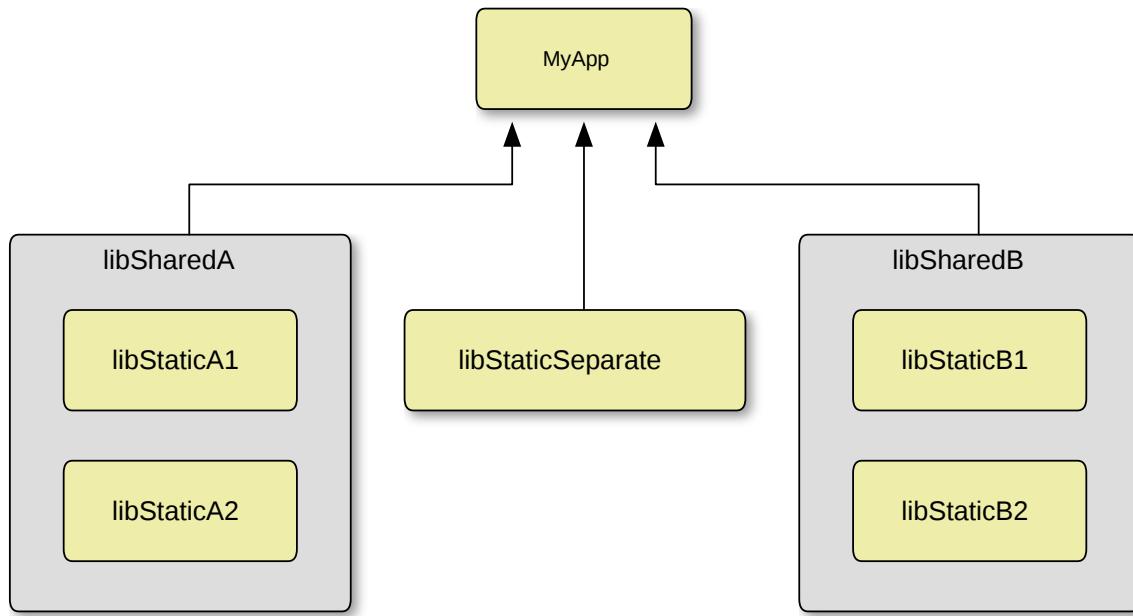
When library targets are defined as a mix of shared and static, the correctness of link dependencies becomes much more important. Consider the following set of targets:



If `libUtil` and `libCalc` are static libraries, the above link dependency relationships are safe. If `libUtil` is a shared library, then the above link dependency arrangement opens up the possibility of duplicating data expected to have only one instance across a whole application. If `libCalc` defines global data, such as might be common for a singleton or static data of a class, it may be possible for both `MyApp` and `libUtil` to have their own separate instances of that data. This becomes possible

because both `MyApp` and `libUtil` require the linker to resolve symbols, so both invocations may decide the global data is required and set up an internal instance of it within that executable or shared library. If the global data is not an exported symbol, the linker won't see the instance already created in `libUtil` when it goes to link `MyApp`. The result is that a second instance is created in `MyApp`, which is almost certain to cause hard-to-trace runtime issues. A typical manifestation of this is a variable magically appearing to change values across a function call from one executable or shared library into another shared library.

Situations similar to the above scenario can appear in a number of different forms, but the same underlying principle applies in each case. If a static library is linked into a shared library, that shared library should not be combined with any other library or executable that also links to that same static library. Ideally, if shared and static libraries are being mixed, the static libraries should only be linked exclusively into one shared library. Anything that needs something from one of those static libraries should link to the shared library instead. The shared library essentially has its own API, and the static libraries may contribute to it.



Using static libraries to build up shared library content like this presents its own set of issues when it comes to symbol visibility. Ordinarily, the code from the static libraries would not be exported, so it would not appear as part of the shared library's exported symbols. One way to address this is to use the `generate_export_header()` function on the shared library as normal, then make the static library re-use the same export definitions. The key to making this work is to ensure the static library has a compile definition for the name of the shared library target with `_EXPORTS` appended, which is how the generated header detects whether the code is being built as part of the shared library or not.

CMakeLists.txt

```

add_library(MyShared SHARED shared.cpp)
add_library(MyStatic STATIC static.cpp)

include(GenerateExportHeader)
generate_export_header(MyShared BASE_NAME mine)

target_link_libraries(MyShared PRIVATE MyStatic)
target_include_directories(MyShared
    PUBLIC ${CMAKE_CURRENT_BINARY_DIR})
)
target_include_directories(MyStatic
    PUBLIC ${CMAKE_CURRENT_BINARY_DIR})
)

# This makes the static library code appear to be part of
# the shared library as far as the generated export header
# is concerned
target_compile_definitions(MyStatic
    PRIVATE MyShared_EXPORTS
)

```

shared.h

```

#include "mine_export.h"

MINE_EXPORT void sharedFunc();

```

static.h

```

#include "mine_export.h"

MINE_EXPORT void staticFunc();

```

The other factor to consider is whether the linker will discard code or data defined in the static library when it comes to linking the shared library. If it determines that nothing is using a particular symbol, the linker may discard it as an

optimization. Special steps may need to be taken to prevent it from doing this.

One choice is to make the shared library explicitly use every symbol to be retained from the shared libraries. This has the advantage that it would work for all compilers and linkers, but it may not be feasible for non-trivial projects. The alternative essentially requires linker-specific flags to be added, such as `--whole-archive` for the `ld` linker on Unix systems, or `/WHOLEARCHIVE` with Visual Studio. The `$<LINK_LIBRARY:WHOLE_ARCHIVE,...>` generator expression may be used to add the necessary flags with CMake 3.24 or later, as shown below (see [Section 18.2, “Customize How Libraries Are Linked”](#) for further details). Be aware though that such functionality may not be available for all linkers. If the above strategies are not suitable, it may be worth considering turning those static libraries into shared instead.

```
target_link_libraries(MyShared
    PRIVATE $<LINK_LIBRARY:WHOLE_ARCHIVE,MyStatic>
)
```

If a shared library only links to static libraries in a private fashion (meaning none of the static libraries' symbols need to be exported), then the situation is considerably easier. On some platforms, no further action is needed other than simply linking the shared library to the static libraries. On others, one or two minor wrinkles may arise which need to be addressed. On

many 64-bit Unix systems, for example, code has to be compiled as *position independent* if it is to go into a shared library, whereas there is no such requirement for static libraries. If, however, a shared library links to a static library, then the static library *does* have to be built as position independent.

CMake provides the POSITION_INDEPENDENT_CODE target property as a way of transparently handling position independent behavior on those platforms that require it. When set to true, this causes that target's code to be built as position independent. By default, the property is ON for SHARED and MODULE libraries and OFF for all other types of targets. The default can be overridden by setting the CMAKE_POSITION_INDEPENDENT_CODE variable, in which case it will be used to initialize the POSITION_INDEPENDENT_CODE target property when the target is created.

```
add_library(MyShared SHARED shared.cpp)
add_library(MyStatic STATIC static.cpp)
target_link_libraries(MyShared PRIVATE MyStatic)

set_target_properties(MyStatic PROPERTIES
    POSITION_INDEPENDENT_CODE ON
)

set(CMAKE_POSITION_INDEPENDENT_CODE ON)
add_library(MyOtherStatic STATIC other.cpp)
target_link_libraries(MyShared PRIVATE MyOtherStatic)
```

23.7. Recommended Practices

Use `MODULE` libraries for optional plugins to be loaded on demand and `SHARED` libraries for linking against. Use shared libraries where the symbols to be exposed to consumers of the library must be tightly controlled, either for API purposes, or to hide sensitive implementation details. If aiming to deliver a library as part of a release package, shared libraries tend to be preferred over static libraries in most cases.

If a target uses something from a library, it should always link directly to that library. Even if the library is already a link dependency of something else the target links to, do not rely on an indirect link dependency for something a target uses directly. If that other target changes its implementation and it no longer links against the library, the main target will no longer build. Furthermore, express the right type of link dependency; `PRIVATE`, `PUBLIC`, or `INTERFACE`. This ensures CMake correctly handles transitive link dependencies for both shared and static libraries. Specifying all the direct dependencies with the correct level of visibility is essential for ensuring CMake constructs a reliable linker command line with correct library ordering.

Using the correct link visibility has the added benefit that consuming targets don't have to know about all the different library dependencies used internally. They only need to link to a library and let that library define its own dependencies.

CMake then takes care of ensuring all required libraries are specified in the correct order on the final linker command line.

Resist the temptation to simply make all link dependencies PUBLIC. That would extend the visibility of otherwise private libraries into places where it may be undesirable. It can also potentially force consumers to install additional packages that shouldn't have been needed just to do a successful build. This becomes particularly important when packaging up a project for release or distribution.

Consider using a library versioning strategy as early as possible. Once a library has been released into the wild, the version number has some very specific meanings with regard to binary compatibility. Make use of the VERSION and SOVERSION target properties to specify the library version, even if initially these are set to some basic placeholders early in the life of the project. In the absence of any other strategy, one reasonable option is to start version numbering at 0.1.0. People tend to interpret 0.0.0 as a default value, or the version mistakenly not having been set, while 1.0.0 is sometimes taken to imply the first public release. Give strong consideration to adopting semantic versioning for handling version changes thereafter. Also keep in mind that changes in library versions can have a surprisingly strong influence on things like release processes, packaging, etc. Developers need time to learn the implications of changing version numbers for shared libraries well in advance of those

libraries being released publicly. Consider also whether the project version and library version should have any relationship to each other or not. It can be very difficult to change such a relationship once the first release is made, so be wary of linking them unless they have a strong association. A project delivering a coherent set of libraries as an SDK would be one such example of a strong association.

Some projects can optionally provide certain functionality if a particular supporting toolkit, library, etc. is available. To allow other parts of the build or indeed other consuming projects to detect or check consistency with that optional functionality or feature, interface compatibility details can be provided. Consider whether the feature in question needs to have visibility beyond the library, such as allowing consuming targets to detect whether the feature is supported, or confirming whether the selected implementation provides all the capabilities required. Also consider whether the added complexity of specifying and using interface compatibilities brings with it sufficient benefits to make it worthwhile, as the deeper the library dependency hierarchy becomes, the harder it can be to use interface compatibilities effectively.

Give consideration to symbol visibility as early in the life of a project as possible, as it can be very difficult to go back and retrofit a project with symbol visibility details later. When creating libraries, develop the mindset of always thinking about

whether a particular class, function, or variable should be accessible to anything outside the library. Think of anything that has external visibility as being very hard to change, whereas internal things can be more freely modified between releases as needed. Use hidden visibility as the default, and explicitly mark each individual entity to be exported, ideally with macros provided by the `generate_export_header()` function so that CMake handles the various platform differences. Also consider using the deprecation macros provided by that function to clearly identify those parts of a library's API that have been deprecated, and which parts may be removed in a future version.

Take extra care when mixing shared and static libraries. Where possible, prefer to use one or the other rather than both. This avoids some difficulties associated with symbol visibility control and ensuring consistency of build settings. Where it makes sense to mix both library types, try to ensure that static libraries only get linked into one shared library and no other targets link to those static libraries. Treat the static libraries as being subgroups within the shared library, with outside targets only ever linking to the shared library. Even better though, consider pulling the code up from the static libraries into the shared library directly instead, getting rid of the static libraries altogether. The techniques presented in [Section 43.5.1, “Building Up A Target Across Directories”](#) demonstrate how to add sources to an existing target progressively, allowing the

target sources to be conveniently accumulated across subdirectories.

24. TOOLCHAINS AND CROSS COMPILING

When considering the process of building software and the tools involved, developers typically think about the compiler and linker. While these are the primary tools that developers are exposed to, there are a number of other tools, libraries and supporting files that also contribute to the process. Loosely speaking, this broader set of tools and other files is collectively referred to as the *toolchain*.

For desktop or traditional server applications, there usually isn't a great need to think too deeply about the toolchain. In most cases, deciding which release of the prevailing platform toolchain to use is about as complicated as it gets. CMake usually finds the toolchain without needing much help and the developer can get on with the task of writing software. For mobile or embedded development, however, the situation is quite different. The toolchain will normally need to be specified in some way by the developer. This can be as simple as specifying a different target system name, or it can be as complex as specifying the paths to individual tools and a target

root file system. Special flags may also need to be set to make the tools produce binaries that will support the right chipset, have the required performance characteristics and so on.

Once a toolchain has been selected, CMake performs quite a bit of processing internally to test the toolchain to determine the features it supports, set various properties and variables, etc. This is the case even for a traditional build where the default toolchain is used, not just for builds that are cross-compiling. The results of these tests can be seen in CMake's output the first time it is run for a given build directory. An example for GCC may look something like this:

```
-- The C compiler identification is GNU 9.3.0
-- The CXX compiler identification is GNU 9.3.0
-- Detecting C compiler ABI info
-- Detecting C compiler ABI info - done
-- Check for working C compiler: /usr/bin/cc - skipped
-- Detecting C compile features
-- Detecting C compile features - done
-- Detecting CXX compiler ABI info
-- Detecting CXX compiler ABI info - done
-- Check for working CXX compiler: /usr/bin/c++ - skipped
-- Detecting CXX compile features
-- Detecting CXX compile features - done
```

The bulk of this processing usually occurs at the point where the first `project()` command is called and the results of the toolchain tests are then cached. The `enable_language()` command also triggers such processing when it enables a previously non-enabled language, as would another `project()`

call that adds a previously non-enabled language. Once a language has been enabled, its cached details will always be used rather than re-testing the toolchain, even for subsequent CMake runs. This has at least two important consequences:

- Once a build directory has been configured with a particular toolchain, it cannot (safely) be changed. In certain situations, CMake may detect that the toolchain has been modified and discard its previous results, but this only discards cached details directly related to the toolchain. Any other cached quantities based on the cached toolchain details outside the ones CMake knows about will not be reset. Therefore, the build directory should be completely cleared before changing the toolchain. It may not be enough to just remove the `CMakeCache.txt` file, since other details may be cached in different locations.
- Different toolchains cannot be mixed directly within the one project. CMake fundamentally sees a project as using a single toolchain throughout. To use multiple toolchains, one has to structure the project to perform parts of the build as external sub-builds (a technique discussed in [Chapter 38, *ExternalProject*](#) and [Section 43.1, “Superbuild Structure”](#)).

24.1. Toolchain Files

If the default toolchain is not suitable, then the recommended way of specifying the desired toolchain details is with a

toolchain file. This is just an ordinary CMake script that typically contains mostly `set(...)` commands. These would define the variables that CMake uses to describe the target platform, the location of the various toolchain components, and so on. The name of the toolchain file is passed to CMake through the special cache variable `CMAKE_TOOLCHAIN_FILE` like so:

```
cmake -DCMAKE_TOOLCHAIN_FILE=myToolchain.cmake path/to/src
```

CMake 3.21 and later also support a `--toolchain` command-line option, or a fallback to a `CMAKE_TOOLCHAIN_FILE` environment variable, but the result is ultimately the same (the `CMAKE_TOOLCHAIN_FILE` cache variable is set).

```
cmake --toolchain myToolchain.cmake path/to/src
```

```
# Set once for the current shell
export CMAKE_TOOLCHAIN_FILE=myToolchain.cmake

# No toolchain specified, uses the environment variable
cmake path/to/source
```

An absolute or a relative path can be used. For a relative path like in the above examples, CMake first looks relative to the top of the build directory, then if not found there, relative to the top of the source directory. This toolchain file must be specified the first time CMake is run for the build directory, it cannot be added later or changed to point to a different toolchain. Since

the variable itself is cached, there is no need to specify it again for subsequent CMake runs.

The toolchain file is read by the first call to the `project()` command, possibly more than once. The number of times it is read in subsequent runs may also be different to the first run. The toolchain file may also be read by temporary subprojects that CMake sets up internally to test the toolchain when a language is enabled for the first time (see [Section 24.5, “Compiler Checks”](#)). Given these factors, a toolchain file should support being included multiple times, and it should not contain logic that assumes it is being read only by the main project.

Developers should aim to make toolchain files minimal, setting only the things needed and making as few assumptions about what the project does as possible. Toolchain files should ideally be completely decoupled from the project and should even be reusable across different projects. They should only be describing the toolchain, not how the toolchain interacts with a particular project.

Toolchain file contents vary, but the main things they may need to do include:

- Describe basic details of the target system.
- Provide paths to tools (often just to the compilers).

- Set the default flags for tools (usually just for compilers and perhaps linkers).
- Set the location of a target platform's root file system in the case of cross-compilation.

It is quite common to see other logic included in toolchain files as well, especially for influencing the behavior of the various `find_()` commands (see [Chapter 34, Finding Things](#)). While there are situations where such logic may be appropriate, one can mount an argument that such logic can and should be part of the project instead in most cases. Only the project knows what it is trying to find, so the toolchain should not make assumptions about what the project wants to do.

24.2. Defining The Target System

The fundamental variables that describe the target system are:

- `CMAKE_SYSTEM_NAME`
- `CMAKE_SYSTEM_PROCESSOR`
- `CMAKE_SYSTEM_VERSION`

Of these, `CMAKE_SYSTEM_NAME` is the most important. It defines the type of platform being *targeted*, as opposed to `CMAKE_HOST_SYSTEM_NAME` which defines the platform on which the build is being *performed*. CMake itself always sets `CMAKE_HOST_SYSTEM_NAME`, but `CMAKE_SYSTEM_NAME` can be (and often

`CMAKE_SYSTEM_NAME` is set by toolchain files. One can think of `CMAKE_SYSTEM_NAME` as being what `CMAKE_HOST_SYSTEM_NAME` would be set to if CMake was run directly on the target platform. Thus, typical values include Linux, Windows, QNX, Android or Darwin, but for certain situations (e.g. bare metal embedded devices), a system name of Generic may be used instead. There are also variations on the typical platform names which can be appropriate in some situations, such as `WindowsStore` and `WindowsPhone`. If `CMAKE_SYSTEM_NAME` is set in a toolchain file, then CMake will also set the `CMAKE_CROSSCOMPILING` variable to true, even if it has the same value as `CMAKE_HOST_SYSTEM_NAME`. If `CMAKE_SYSTEM_NAME` is not set, it will be given the same value as the auto-detected `CMAKE_HOST_SYSTEM_NAME`.

`CMAKE_SYSTEM_PROCESSOR` is intended to describe the hardware architecture of the target platform. If not specified, it will be given the same value as `CMAKE_HOST_SYSTEM_PROCESSOR`, which is automatically populated by CMake. In cross-compiling scenarios or when building for a 32-bit platform on a 64-bit host of the same system type, this will result in `CMAKE_SYSTEM_PROCESSOR` being incorrect. Therefore, it is advisable to set `CMAKE_SYSTEM_PROCESSOR` if the architecture doesn't match the build host, even if the project seems to build okay without it. Wrong decisions based on an incorrect `CMAKE_SYSTEM_PROCESSOR` value can lead to subtle problems that may not be easy to detect or diagnose.

The `CMAKE_SYSTEM_VERSION` variable has different meanings depending on what `CMAKE_SYSTEM_NAME` is set to. For example, with a system name of Windows, WindowsStore, WindowsPhone or WindowsCE, CMake 3.26 and earlier will use the system version to determine which Windows SDK to use. As another example, if `CMAKE_SYSTEM_NAME` is set to Android, then `CMAKE_SYSTEM_VERSION` will typically be interpreted as the default Android API version and must be a positive integer. For other system names, it is not unusual to see `CMAKE_SYSTEM_VERSION` set to something arbitrary like 1, or to not be set at all. The toolchains section of the CMake documentation provides examples of different uses of `CMAKE_SYSTEM_VERSION`, but the meaning and the set of allowable values for the variable are not always clearly defined. For this reason, projects are advised to exercise caution if implementing logic that depends on the value of `CMAKE_SYSTEM_VERSION`.

Normally, these `CMAKE_SYSTEM_...` variables fully describe the target system, but there are exceptions:

- With CMake 3.13 and earlier, all Apple platforms use Darwin for the `CMAKE_SYSTEM_NAME`, even for iOS, tvOS, or watchOS. The actual target system is then selected by the `CMAKE OSX_SYSROOT` variable, which selects the base SDK to be used for the build. The target device is determined based on the SDK chosen, but the developer can still choose between device or simulator at build time. Support for the dedicated `CMAKE_SYSTEM_NAME` values iOS, tvOS, and watchOS was added in CMake 3.14 to

better distinguish the different platforms and make them more consistent with how other platforms are handled. Support for visionOS was added in CMake 3.28. See [Section 25.5.1, “SDK Selection”](#) for further discussion.

- `CMAKE_SYSTEM_PROCESSOR` and `CMAKE_SYSTEM_VERSION` are not particularly meaningful for Apple platforms and usually remain unset.
- The `CMAKE_SYSTEM_PROCESSOR` variable is typically not set when targeting Android platforms. This is discussed further in [Section 24.7, “Android”](#) below.

Furthermore, some project generators support their own native platform names. For such generators, instead of setting the `CMAKE_SYSTEM_NAME` variable, a native platform name can be specified via a few different methods. The simplest and most direct is to specify the native platform along with the generator details on the `cmake` command line using the `-A` option. For example, the Visual Studio generator can be instructed to target the `x64` platform like so:

```
cmake -G "Visual Studio 16 2019" -A x64 ...
```

The chosen platform will be available to projects through the `CMAKE_GENERATOR_PLATFORM` CMake variable. Alternatively, developers may choose to use a toolchain file and to set the `CMAKE_GENERATOR_PLATFORM` CMake variable directly (projects should never set this CMake variable themselves). If using

CMake 3.15 or later, another choice is to provide the platform via the `CMAKE_GENERATOR_PLATFORM` environment variable instead.

When targeting a Windows platform, it is generally advisable to build with the latest available Windows SDK version associated with the target platform version. For example, the Visual Studio documentation recommends using Windows SDK 8.1 if building for Windows 7 or Windows Vista. If targeting Windows 10, the Windows SDK 10.0 (or a later minor version) should be used. In general, CMake selects the latest Windows SDK version it can find, but the logic and the controls over that logic have changed over different releases. Some controls also only apply when using one of the Visual Studio generators. The interested reader should consult the CMake documentation for policy `CMP0149`, and the following variables:

- `CMAKE_GENERATOR_PLATFORM`
- `CMAKE_VS_WINDOWS_TARGET_PLATFORM_VERSION`
- `CMAKE_VS_WINDOWS_TARGET_PLATFORM_VERSION_MAXIMUM`

The minimum Windows version of the target platform (the version required at run time) is not directly controlled by the SDK version selection discussed above. While the SDK used at build time must support the desired minimum deployment version, the deployment version is controlled by compiler definitions. In general, the `_WIN32_WINNT` compiler definition needs to be set to the appropriate value before any Windows

headers are included. Depending on the SDK used, `WINVER` may also need to be set, but it will usually be populated from `_WIN32_WINNT` if not set directly. The supported values are described in the Visual Studio documentation. It is common to define `_WIN32_WINNT` directly in the `.c` or `.cpp` source files, but it can also be set as a compiler flag using commands like `target_compile_definitions()` or `add_compile_definitions()`. If using precompiled headers (see [Section 26.2, “Precompiled Headers”](#)), it should be set on the whole target to ensure correct behavior.

Embed a minimum version requirement in a C++ source file

```
#ifndef _WIN32_WINNT  
// Set Windows 7 as the minimum deployment version  
#define _WIN32_WINNT 0x0601  
#endif  
  
#include <Windows.h>
```

Set a minimum version requirement for a whole target

```
if(MSVC  
    target_compile_definitions(SomeTarget PRIVATE  
        _WIN32_WINNT=0x0601  
    )  
endif()
```

The `VS_WINDOWS_TARGET_PLATFORM_MIN_VERSION` target property may also appear to be relevant if using a Visual Studio generator, but be aware of its true behavior. Its purpose within CMake is to set a Visual Studio project property which appears to control the deployment version too. However, the Visual

Studio documentation states that the underlying project property does not actually enforce anything for C++ projects. It only enforces the requirement for other languages like C# or JavaScript. See the Visual Studio documentation on the general project properties for authoritative comments on this specific topic. For most projects, the `VS_WINDOWS_TARGET_PLATFORM_MIN_VERSION` target property and its associated `CMAKE_VS_WINDOWS_TARGET_PLATFORM_MIN_VERSION` variable will not be useful and should remain unset.

24.3. Tool Selection

Of all the tools used in the build, the compiler is probably the most important from the developer's perspective. The path to the compiler is controlled by the `CMAKE_<LANG>_COMPILER` variable, which can be set in a toolchain file or on the command line to manually control the compiler used. It can also be omitted, in which case CMake will choose one automatically based on an internal set of defaults for the target platform and generator. If the name of an executable is provided manually without a path, CMake will search for it using `find_program()` (covered in [Section 34.2, “Finding Programs”](#)). If a full path to a compiler is provided, it will be used directly.

From CMake 3.19, `CMAKE_<LANG>_COMPILER` can be a list. The first item in the list is the compiler to use, just as described above.

The remaining list items are compiler options that have to be present for the compiler to work. Do not add non-mandatory options via this variable. Note also that `CMAKE_<LANG>_COMPILER` should not be changed after the first CMake run.

For most languages, the compiler can be set with an environment variable instead of setting `CMAKE_<LANG>_COMPILER`. These usually follow common conventions, such as `CC` for a C compiler, `CXX` for a C++ compiler, `FC` for a Fortran compiler, and so on. These environment variables will only have an effect the first time CMake runs in a build directory, and only if the corresponding `CMAKE_<LANG>_COMPILER` variable is not set by a toolchain file or on the CMake command line.

Some generators support their own separate toolset specifications which work differently to the above methods. These toolsets can be selected using the `-T` option on the `cmake` command line, or if using CMake 3.15 or later, by setting the `CMAKE_GENERATOR_TOOLSET` environment variable. They can also be selected in a toolchain file by setting the `CMAKE_GENERATOR_TOOLSET` CMake variable (projects should never set this variable themselves). The available toolsets and the supported syntax are specific to each generator, but the following examples demonstrate some of the possibilities.

- Build 32-bit executables but use 64-bit compiler and linker tools:

```
cmake -G "Visual Studio 16 2019" -A Win32 -T host=x64 ...
```

- Use the clang-cl compilers from the Visual Studio built-in LLVM distribution:

```
cmake -G "Visual Studio 16 2019" -T ClangCL ...
```

For some generators, having multiple instances of the build tool installed may mean the developer needs to specify which instance to use. A typical example is a developer trying out a preview version of Visual Studio and then later installing the release version without deleting the preview version. When using CMake 3.11 or later, the `CMAKE_GENERATOR_INSTANCE` variable may be set in a toolchain file to control the specific instance that will be used. With CMake 3.15 or later, the `CMAKE_GENERATOR_INSTANCE` environment variable can be set instead. Few generators support this feature, currently only those for Visual Studio 2017 or later.

With the toolchain specified, CMake will identify the compiler and try to determine its version. This compiler information will be made available through the `CMAKE_<LANG>_COMPILER_ID` and `CMAKE_<LANG>_COMPILER_VERSION` variables respectively. The compiler ID is a short string used to differentiate one compiler from another, with common values being `GNU`, `Clang`, `AppleClang`, `MSVC` and `Intel`. The CMake documentation for `CMAKE_<LANG>_COMPILER_ID` gives the full list of supported IDs. If

the compiler version can be determined, it will have the usual *major.minor.patch.tweak* form, where not all version components need to be present (e.g. 4.9 would be a valid version). With CMake 3.26 or later, a separate `CMAKE_VS_VERSION_BUILD_NUMBER` variable will also be defined when using a Visual Studio toolchain. This has the form *major.minor.date.build*, where `major` and `minor` are the same as those values reported in `CMAKE_<LANG>_COMPILER_ID`, `date` is a five digit number of the form `MMMDD`, and `build` is a build number for that date. The `MMM` is relative to an epoch that Microsoft define, not the numerical month of the year.

Related to the `CMAKE_<LANG>_COMPILER_ID` and `CMAKE_<LANG>_COMPILER_VERSION` variables, analogous generator expressions without the leading `CMAKE_` part are also supported. Either the variables or the generator expressions can be used to conditionally add content only for certain compilers or compiler versions. For example, GCC 7 introduced a new `-fcode-hoisting` option and the following shows both ways of adding it for C++ compilation only if it is available:

```
# Conditionally add -fcode-hoisting option using variables
if(CMAKE_CXX_COMPILER_ID STREQUAL "GNU" AND
CMAKE_CXX_COMPILER_VERSION VERSION_GREATER_EQUAL 7)
    target_compile_options(SomeTarget PRIVATE
        -fcode-hoisting
    )
endif()

# Same thing using generator expressions instead
```

```
set(isGNU ${CXX_COMPILER_ID:GNU})
set(newEnough
    ${VERSION_GREATER_EQUAL:${CXX_COMPILER_VERSION},7}
)
target_compile_options(SomeTarget PRIVATE
    ${${AND:${isGNU},${newEnough}}:-fcode-hoisting}
)
```

The compiler ID is the most robust way to identify the compiler used. One case projects may need to be aware of is that prior to CMake 3.0, the Apple Clang compiler was treated the same as the upstream Clang, and both had the compiler ID Clang. From CMake 3.0 onward, Apple's compiler has the compiler ID AppleClang instead so that it can be differentiated from upstream Clang. Policy CMP0025 was added to allow the old behavior to be used for those projects that require it.

CMake also identifies the linker and works out various details about it. Depending on the CMake generator and toolchain used, the linker may be invoked directly, or it may be invoked via the compiler (also called the "front end" in this context). The linker used can also be different depending on the source language(s) of the object files to be linked. CMake 3.29 and later makes some linker details available through a set of `CMAKE_<LANG>_COMPILER_LINKER...` variables. These are not normally needed by most projects, but may be useful when experimenting with different linkers (see [Section 26.7, “Alternative Linkers”](#)).

Once the compiler and linker details have been determined, CMake is able to work out the appropriate set of default flags for both. These are made available to the project through the variables `CMAKE_<LANG>_FLAGS`, `CMAKE_<LANG>_FLAGS_<CONFIG>`, `CMAKE_<TARGETTYPE>_LINKER_FLAGS` and `CMAKE_<TARGETTYPE>_LINKER_FLAGS_<CONFIG>`, which were covered back in [Section 16.6, “Compiler And Linker Variables”](#). Developers can add their own flags into the set of default values for these using variables of the same name, but with `_INIT` appended. These `..._INIT` variables are only ever used to set the initial defaults. They have no effect once CMake has been run once, after which the actual values will have been saved in the cache.

A common mistake is to set the non-`...INIT` variables in a toolchain file (i.e. setting `CMAKE_<LANG>_FLAGS` rather than `CMAKE_<LANG>_FLAGS_INIT`). This has the undesirable effect of discarding or hiding changes the developer makes to these variables in the cache. Setting the `...INIT` variables instead ensures that only the initial default values are affected and any subsequent changes to the non-`...INIT` variables via any method are retained.

As an example, consider a toolchain file a developer might use to build with special compiler flags for debugging. This can be a useful way of re-using complex developer-only logic across

multiple projects. The following chooses GNU compilers and adds flags that enable most warnings:

```
set(CMAKE_C_COMPILER    gcc)
set(CMAKE_CXX_COMPILER  g++)

set(extraOpts "-Wall -Wextra")
set(CMAKE_C_FLAGS_DEBUG_INIT  ${extraOpts})
set(CMAKE_CXX_FLAGS_DEBUG_INIT ${extraOpts})
```

Unfortunately, there are some inconsistencies in how CMake combines developer-specified ..._INIT options with the defaults it normally provides. In most cases, CMake will append further options to those specified by ...INIT variables, but with some platform/compiler combinations (particularly older or less frequently used ones), developer-specified ..._INIT values can be discarded. This stems from the history of these variables, which used to be for internal use only and always unilaterally set the ..._INIT values. From CMake 3.7, the ..._INIT variables were documented for general use and the behavior was switched to appending rather than replacing for the commonly used compilers. The behavior for very old or no longer actively maintained compilers was left unmodified.

Some compilers act more as compiler drivers and expect a command line argument specifying the platform/architecture to compile for (Clang and QNX qcc are two such examples). For compilers that CMake recognizes as requiring such arguments, the CMAKE_<LANG>_COMPILER_TARGET variable can be set in a

toolchain file to specify the target. Where supported, this should be used instead of trying to manually add the flags with `CMAKE_<LANG>_FLAGS_INIT`.

Another less common situation is where the compiler toolchain does not include other supporting utilities like archivers or linkers. These compiler drivers typically support a command line argument that can be used to specify where these tools can be found. CMake provides the `CMAKE_<LANG>_COMPILER_EXTERNAL_TOOLCHAIN` variable which can be used to specify the directory in which these utilities are located.

24.4. System Roots

In many cases, the toolchain is all that is needed, but sometimes projects may require access to a broader set of libraries, header files, etc. as they would be found on the target platform. A common way of handling this is to provide the build with a cut down version (or even a full version) of the root filesystem for the target platform. This is referred to as a *system root* or just *sysroot* for short. A sysroot is basically just the target platform's root file system mounted or copied to a path that can be accessed through the host's file system. Toolchain packages often provide a minimal sysroot containing various libraries, etc. needed for compiling and linking.

CMake has fairly extensive and easy-to-use support for sysroots. Toolchain files can set the `CMAKE_SYSROOT` variable to the sysroot location, and with that information alone, CMake can find libraries, headers, etc. preferentially in the sysroot area over same-named files on the host. This is covered in detail in [Section 34.1.2, “Cross-compilation Controls”](#). In many cases, CMake will also automatically add the necessary compiler/linker flags to the underlying tools to make them aware of the sysroot area. For more complex scenarios where different sysroots need to be provided for compiling and linking (e.g. as used by the Android NDK with unified headers), toolchain files can set `CMAKE_SYSROOT_COMPILE` and `CMAKE_SYSROOT_LINK` instead when using CMake 3.9 or later.

In some arrangements, developers may choose to mount the full target file system under a host mount point and use that as their sysroot. This could be mounted as read-only, or if not it may still be desirable to leave it unmodified by the build. Therefore, when the project has been built, it may need to be installed to somewhere else rather than writing to the sysroot area. CMake provides the `CMAKE_STAGING_PREFIX` variable which can be used to set a staging point below which any install commands will install to (see [Section 35.1.2, “Base Install Location”](#) for a discussion of this area). This staging area could be a mount point for a running target system, and the installed binaries could then be tested immediately after installation. Such an arrangement is particularly useful when cross

compiling on a fast host for a target system that would otherwise be slow to build on (e.g. building on a desktop machine for a Raspberry Pi target). [Section 34.1.2, “Cross-compilation Controls”](#) also discusses how `CMAKE_STAGING_PREFIX` affects the way CMake searches for libraries, headers, and so on.

24.5. Compiler Checks

When a `project()` or `enable_language()` call triggers testing of compiler and language features, the `try_compile()` command is called internally to perform various checks. If a toolchain file has been provided, it is read by each `try_compile()` invocation, so the test compilation will be configured in a similar way to the main build. CMake will pass through some relevant variables automatically, such as `CMAKE_<LANG>_FLAGS`, but toolchain files may want other variables to be passed through to the test compilation as well. Since the main build will read the toolchain file first, the toolchain file itself can define which variables should be passed through to test compilations. This is done by adding the names of the variables to the `CMAKE_TRY_COMPILE_PLATFORM_VARIABLES` variable (do not set this in the project, only in a toolchain file). Use `list(APPEND)` rather than `set()` so that any variables added by CMake are not lost. It won’t matter if `CMAKE_TRY_COMPILE_PLATFORM_VARIABLES` ends up containing duplicates, it only matters that the desired variable names are present.

The `try_compile()` command normally compiles and links test code to produce an executable. In some cross compiling scenarios, this can present a problem if running the linker requires custom flags or linker scripts, or is otherwise not desirable to invoke. Cross compiling for a bare metal target platform often has such a restriction. If using CMake 3.6 or later, the command can be told to create a static library instead by setting `CMAKE_TRY_COMPILE_TARGET_TYPE` to `STATIC_LIBRARY`. This variable should be set in the toolchain file, not in the project. Setting the variable to `STATIC_LIBRARY` avoids the need for the linker, but it still requires an archiving tool. `CMAKE_TRY_COMPILE_TARGET_TYPE` can also have the value `EXECUTABLE`, which is the default behavior anyway if no value is set. Prior to CMake 3.6, the now deprecated `CMakeForceCompiler` module had to be used to prevent `try_compile()` from being invoked at all, but CMake now relies heavily on these tests to work out what features a compiler supports. The use of `CMakeForceCompiler` is now actively discouraged.

While it is not invoked during compiler checks, the `try_run()` command is closely related to `try_compile()`, and its behavior is affected by cross-compilation. `try_run()` is effectively a `try_compile()` followed by an attempt to run the executable just built. When `CMAKE_CROSSCOMPILING` is set to true, CMake modifies its logic for running the test executable. If the `CMAKE_CROSSCOMPILING_EMULATOR` variable is set, CMake will

prepend it to the command that would otherwise have been used to run the executable on the target platform and uses that to run the executable on the host platform. If `CMAKE_CROSSCOMPILING_EMULATOR` is not set when `CMAKE_CROSSCOMPILING` is true, CMake requires the toolchain or project to manually set some cache variables. These variables provide the exit code and the output from `stdout` and `stderr` that would be obtained had the executable been able to run on the target platform. Having to provide these manually is clearly inconvenient and error-prone, so projects should generally try hard to avoid calling `try_run()` in cross-compiling situations where `CMAKE_CROSSCOMPILING_EMULATOR` cannot be set. For cases where these manually defined variables cannot be avoided, the CMake documentation for the `try_run()` command provides the necessary details regarding the variables to be set. Further uses of `CMAKE_CROSSCOMPILING_EMULATOR` are also discussed in [Section 27.5, “Cross-compiling, Emulators, And Launchers”](#).

24.6. Examples

The examples that follow have been selected to highlight the concepts discussed in this chapter. The toolchains section of the CMake reference documentation contains further examples for a variety of different target platforms.

24.6.1. Raspberry Pi

Cross compiling for the Raspberry Pi is a good introduction to the way CMake handles cross compilation in general. The first step is to obtain the compiler toolchain, a common way being to use a utility like crosstool-NG. The rest of this example will use `/path/to/toolchain` to refer to the top of the toolchain directory structure.

A typical toolchain file for the Raspberry Pi might look something like this:

```
set(CMAKE_SYSTEM_NAME      Linux)
set(CMAKE_SYSTEM_PROCESSOR ARM)

set(CMAKE_C_COMPILER
    /path/to/toolchain/bin/armv8-rpi3-linux-gnueabihf-gcc
)
set(CMAKE_CXX_COMPILER
    /path/to/toolchain/bin/armv8-rpi3-linux-gnueabihf-g++
)
set(CMAKE_SYSROOT
    /path/to/toolchain/armv8-rpi3-linux-gnueabihf/sysroot
)
```

If the host has a mount point for a running target device, it could be used to make testing the binaries built by the project relatively straightforward. For example, assume `/mnt/rpiStage` is a mount point that attaches to a running Raspberry Pi. This would preferably point to some local directory rather than the system root so that it could be wiped or otherwise modified in arbitrary ways without destabilizing the running system. A

toolchain file would specify this mount point as a staging area like so:

```
set(CMAKE_STAGING_PREFIX /mnt/rpiStage)
```

The project's binaries could then be installed to this staging area and run directly on the device (see [Section 35.1.2, “Base Install Location”](#)).

24.6.2. GCC With 32-bit Target On 64-bit Host

GCC allows 32-bit binaries to be built on 64-bit hosts by adding the `-m32` flag to both the compiler and linker commands. The following toolchain example still allows the GCC compilers to be found on the PATH, adding just the extra flag to the initial set used by the compilers and linker. Depending on one's point of view, this arrangement could be seen as cross-compiling or not. Therefore, setting `CMAKE_SYSTEM_NAME` could also be seen as optional, since setting it forces `CMAKE_CROSSCOMPILING` to have the value true. Either way, the `CMAKE_SYSTEM_PROCESSOR` should still be set since the goal of this toolchain file is specifically to target a processor different to that of the host.

```
set(CMAKE_SYSTEM_NAME      Linux)
set(CMAKE_SYSTEM_PROCESSOR i686)

set(CMAKE_C_COMPILER      gcc)
set(CMAKE_CXX_COMPILER    g++)
```

```
set(CMAKE_C_FLAGS_INIT -m32)
set(CMAKE_CXX_FLAGS_INIT -m32)

set(CMAKE_EXE_LINKER_FLAGS_INIT -m32)
set(CMAKE_SHARED_LINKER_FLAGS_INIT -m32)
set(CMAKE_MODULE_LINKER_FLAGS_INIT -m32)
```

One way to confirm that the build is indeed 32-bit is with the `CMAKE_SIZEOF_VOID_P` variable, which is computed by CMake automatically as part of its toolchain setup. For 64-bit builds, this will have a value of 8, whereas for 32-bit builds, it will be 4.

```
math(EXPR bitness "${CMAKE_SIZEOF_VOID_P} * 8")
message(STATUS "${bitness}-bit build")
```

24.7. Android

Cross-compiling for Android can be a bit more involved than the cases discussed above. There are a number of Android-specific settings that affect the build, not just the usual target platform, toolchain locations and flags. Some combinations of CMake and Android NDK versions also have compatibility issues, so developers need to select their tools and toolkits carefully.

24.7.1. Historical Context

CMake has its own built-in support for Android, but the Android NDK also has its own expectations around how the build should be set up. Both CMake and the NDK developed their respective support for each other more or less

independently and in parallel. This resulted in problems at various points where incompatibilities emerged.

The NDK r19 release introduced changes that broke CMake's built-in Android support. CMake 3.16.0 contained changes which restored the ability to use the built-in Android support again, but some issues remained in certain scenarios. With the NDK r23 release and CMake 3.21 or later, these incompatibilities have finally been resolved. The interested reader is directed to the following for details on the above:

- <https://gitlab.kitware.com/cmake/cmake/issues/18787>
- <https://github.com/android-ndk/ndk/issues/463>

Users should be able to reliably use the toolchain file provided by the NDK r23 or later when using CMake 3.21 or later. Developers who must use NDK releases in the range r18—r22 are advised to prefer using CMake 3.20 or later where possible. The 3.20 release contained fixes relevant to these NDK versions.



The rest of the Android-related material in the sections that follow assume NDK r23 or later and CMake 3.21 or later are being used.

24.7.2. Using The NDK

The recommended way to build for Android is to use the toolchain file provided by the Android NDK. The name of the

file is typically something like `android.toolchain.cmake`. Depending on the host platform and how the NDK has been installed, the toolchain file can be found in a variety of locations. A typical arrangement would see the file placed in the `build/cmake` subdirectory below the base install directory of the NDK.

The toolchain file takes care of setting a number of things. `CMAKE_SYSTEM_NAME` will always be set to Android. The Clang compilers provided by the NDK will be used (NDK r18 removed the ability to select the gcc toolchain). `CMAKE_SYSROOT` will be set to the appropriate directory within the NDK.

The architecture and ABI can be left at defaults chosen by the NDK, but it is recommended that the developer explicitly set them. This ensures it is very clear what is being built for. This can be done by setting the `CMAKE_ANDROID_ARCH_ABI` variable to one of the following values (others may be supported, check the NDK documentation or toolchain file):

- `armeabi-v7a`
- `arm64-v8a`
- `x86`
- `x86_64`

If `armeabi-v7a` is selected, the following two variables are also relevant:

- `CMAKE_ANDROID_ARM_NEON` can be set to true to enable building with NEON support, or false to build without it. If this variable is not set, NEON support will be enabled by default.
- `CMAKE_ANDROID_ARM_MODE` controls the type of processor to build for. Set it to true to build for 32-bit ARM processors, otherwise the build will target 16-bit Thumb processors.

CMake will set `CMAKE_SYSTEM_PROCESSOR` to an appropriate value based on the above and information provided by the NDK.

The Android API level is controlled by a variable named `ANDROID_PLATFORM` (note the lack of any `CMAKE_` prefix). If `ANDROID_PLATFORM` is not set, the API level is set to the minimum level supported by the NDK. Note that this minimum version may be unsuitable for the chosen architecture and ABI, so it is advisable not to rely on it. Instead, the API level should be specified as a number to ensure the API used is well-defined. It is recommended that an API level of 23 or higher be used to avoid potential reliability issues with Android PackageManager's native library loading (see <https://github.com/KeepSafe/ReLinker>). The special string `latest` can also be used, which selects the latest API level supported by the NDK, but this is less clear and not as traceable.

`CMAKE_ANDROID_STL_TYPE` specifies the C++ STL implementation to be used. Earlier NDK releases supported a range of different options, but projects should now use either `c++_shared` or

`c++_static`. Only use the latter if your application consists of a single shared library. If the application does not use the C++ STL at all, the value `none` can be used instead, but this would be unusual.

`CMAKE_ANDROID_RTTI` and `CMAKE_ANDROID_EXCEPTIONS` control whether to enable rtti and exceptions respectively. They are boolean variables whose defaults are determined by the choice of STL implementation. The NDK toolchain file in r23 contains a bug which means `CMAKE_ANDROID_EXCEPTIONS` might not be set correctly in some circumstances, if not set directly by the developer. Therefore, always set this variable to ensure the expected behavior is obtained.

Starting with r27, the NDK supports a larger 16KiB page size. Some devices may require applications to be rebuilt with this larger page size. The default page size remains 4KiB with r27, but r28 changes the default to 16KiB. With r27, set the `ANDROID_SUPPORT_FLEXIBLE_PAGE_SIZES` CMake variable to true to use a 16KiB page size. With r28 or later, set `ANDROID_SUPPORT_FLEXIBLE_PAGE_SIZES` to false to continue using the old 4KiB page size.

From the above, it can be seen that there are a number of variables that will typically need to be set before the NDK toolchain file is read. One could specify them on the `cmake` command line, like so:

```
cmake -DCMAKE_TOOLCHAIN_FILE=../../android.toolchain.cmake \
-DCMAKE_ANDROID_ABI=arm64-v8a \
-DANDROID_PLATFORM=24 \
-DCMAKE_ANDROID_STL_TYPE=c++_shared \
-DCMAKE_ANDROID_RTTI=YES \
-DCMAKE_ANDROID_EXCEPTIONS=YES \
-ANDROID_SUPPORT_FLEXIBLE_PAGE_SIZES=YES \
...
```

Alternatively, a wrapper toolchain file could be used:

my_android_toolchain.cmake:

```
set(CMAKE_ANDROID_ABI arm64-v8a)
set(ANDROID_PLATFORM 24)
set(CMAKE_ANDROID_STL_TYPE c++_shared)
set(CMAKE_ANDROID_RTTI YES)
set(CMAKE_ANDROID_EXCEPTIONS YES)
set(ANDROID_SUPPORT_FLEXIBLE_PAGE_SIZES YES)

include(/.../android.toolchain.cmake)
```

```
cmake -DCMAKE_TOOLCHAIN_FILE=my_android_toolchain.cmake ...
```



CMake caches information computed during the first run in a build directory. If any of the variables mentioned in this section need to be changed, the build directory contents should be deleted first. If this is not done, the compiler flags may not be updated to reflect the new settings in the changed variables.

24.7.3. Android Studio

Certain tools may enforce the use of their own internal toolchain file, making it potentially harder for developers to specify any of the above settings. Android Studio is one such example, forcing a particular toolchain file which overrides much of CMake's own logic. The gradle builds are set up to create an external CMake build that uses the Ninja generator and the NDK provided through the Android SDK manager. While direct access to the toolchain file is not enabled, the gradle build does provide a range of gradle variables which are translated into their CMake equivalents. Developers should consult the tool's documentation to understand how different CMake versions can be used and how to influence the behavior of the CMake build.

24.7.4. ndk-build

For developers using `ndk-build` (which is essentially just a wrapper around GNU `make`) rather than `gradle`, CMake 3.7 added the ability to export an `Android.mk` file as part of the CMake build using `export()` or as part of the install step with `install()`. Exporting during the build is straightforward:

```
export(TARGETS target1 [target2...] ANDROID_MK fileName)
```

The `fileName` will typically be `Android.mk` with some path prepended to put it at the location required by `ndk-build`. Each of the named targets will be included in the generated file along with the relevant usage requirements such as include flags,

compiler defines, etc. This is typically what a project will want to do if it needs to support being part of a parent `ndk-build`. For the case where the CMake project will be packaged up and wants to make itself easy to incorporate into any `ndk-build`, the `install()` command offers the required functionality (see [Section 35.3, “Installing Exports”](#)).

24.7.5. Visual Studio Generators

The Ninja and Makefiles generators integrate well with the NDK toolchain file. When using a Visual Studio generator, CMake 3.19 and later supports the NDK as well. Setup should work reasonably smoothly for NDK versions installed directly via the Visual Studio installer, but these tend to be quite old and are therefore of limited usefulness. The Ninja and Makefiles generators are likely to give better results if using more recent NDK versions installed outside of Visual Studio.

For earlier CMake versions, Android support in Visual Studio required the use of the Nvidia Nsight Tegra Visual Studio Edition. This method has been essentially unmaintained for quite a few CMake releases, so its reliability may be questionable. Developers are encouraged to use the NDK instead.

24.8. Recommended Practices

Toolchain files can seem a little intimidating at first, but much of this comes from many examples and projects putting too much logic in them. Toolchain files should be as minimal as possible to support the required tools, and they should generally be reusable across different projects. Logic specific to a project should be in the project's own `CMakeLists.txt` files.

When writing toolchain files, developers should ensure that the contents do not assume they will only be executed once. CMake may process the toolchain file multiple times depending on what the project does (e.g. multiple calls to `project()` or `enable_language()`). The toolchain file may also be used for temporary builds "off to the side" as part of `try_compile()` calls, so they should make no assumptions about the context in which they are being used.

Avoid using the deprecated `CMakeForceCompiler` module to set the compiler to be used in the build. This module was popular when using older CMake versions, but newer versions rely heavily on testing the toolchain and working out the features it supports. The `CMakeForceCompiler` module was mainly intended for cases where the compiler was not known to CMake, but use of such compilers with recent CMake versions will likely result in non-trivial limitations. It is recommended to work with the CMake developers to add the required support for such compilers.

Be careful not to discard or mishandle the contents of variables that may already be set by the time the toolchain file is processed. A common error is to modify variables like `CMAKE_<LANG>_FLAGS` rather than `CMAKE_<LANG>_FLAGS_INIT`. This can discard values manually set by developers, or interact poorly with values already populated when the toolchain file is processed multiple times.

When targeting Android platforms, prefer to use the NDK and the toolchain file it provides, or a simple wrapper around that toolchain file. To ensure a fully working, reliable build, use NDK r23 or later and CMake 3.21 or later. Earlier versions had incompatibilities between the two and setup was more involved. Avoid the once popular *taka-no-me* toolchain file frequently referred to by online examples. It is overly complicated, has known issues, and has not been maintained for a number of years. Also use Android API 23 or later to avoid known issues with the Android PackageManager's native library loader.

Projects should generally avoid using the `CMAKE_CROSSCOMPILING` variable for any of its logic. This variable can be misleading, since it can be set to true even when the target and host platform are the same, or false when they are different. The inconsistency of its value makes it unreliable. Project authors should also be aware that the Xcode generator allows the target platform to be selected at build time. Any CMake logic based

around whether cross-compiling or not needs to be written very carefully to handle the different situations in which the project may be generated.

Toolchain files often contain commands to modify where CMake searches for programs, libraries, and other files. See [Chapter 34, *Finding Things*](#) for recommended practices related to this area.

25. APPLE FEATURES

Apple platforms have a number of unique characteristics which directly affect the way software is built. While simple command-line applications for macOS can be built in similar ways to other Unix-based platforms, those applications with a graphical user interface are usually provided in an Apple-specific format known as an *application bundle* (or just *app bundle*). These bundles are more than a single executable file, they are a standardized directory structure containing a variety of files associated with the application. These app bundles are intended to be self-contained, able to be moved around as a unit and placed anywhere on a user's file system.

There is an analogous situation for libraries too. Standalone static and shared libraries can be created much like those on other Unix-based platforms, but they can also be built as part of a *framework*, which is essentially the library equivalent of an app bundle. Frameworks have their own standardized directory structure and may contain files other than just the library binaries. They may even support multiple versions within that directory structure (an uncommon practice which is now generally discouraged). Libraries intended to be loaded at

runtime can instead be built as a loadable bundle, which corresponds to Apple's `CFBundle` functionality.

Bundles and frameworks are essential parts of the machinery used to produce content for Apple's app store. Another key aspect is code signing, a process which verifies the integrity and origin of software and is a mandatory part of app store distribution. Code entitlements are also an integral part of the build process and govern which Apple features the code may use. These entitlements are part of the information sealed by the code signing process and must be defined at build time if the default entitlement set (which is empty) is not appropriate.

Together, these features present unique challenges for CMake projects. The sections that follow provide the tools for understanding and handling these areas, or in some cases, highlight the current limitations of CMake's support. It should also be noted that formal support for tvOS and watchOS was only added in CMake 3.14 (macOS and iOS have been formally supported before that). Support for visionOS was added in CMake 3.28.

25.1. CMake Generator Selection

The technologies and tools used to produce frameworks and bundles is constantly evolving, with major Apple OS and Xcode releases often introducing new features and changing the requirements around signing, distribution, etc. The processes

and technologies are tightly integrated into Xcode as the primary tool Apple expects developers to use, with developers also typically expected to upgrade to the current Xcode release rather than staying with past major releases. Areas like resource compilation, code signing, etc. are automatically handled as part of building applications and frameworks, many aspects of which are unique to the Apple ecosystem.

For CMake projects, this means that the Xcode generator is the most reliable and most convenient for building with the Xcode toolchain. Other generators such as Unix Makefiles or Ninja lack much of the automation of the Xcode generator, and they may lag behind implementing support for some of the more recent Xcode features. With the exception of basic, unsigned desktop applications not intended for distribution through the app store, developers will be more or less required to use the Xcode generator to get a build that supports the necessary features. Also note that the fast-moving nature of Apple platforms means that developers will also generally want to be using fairly recent CMake and Xcode releases to keep up with the changes. The arrival of Apple Silicon is a good example, where CMake 3.19.2 and Xcode 12.2 should be considered the bare minimum versions when building on or for that architecture. These are also the minimum requirements for CMake to be able to use Xcode's modern build system. In practice though, projects should consider at least Xcode 14 and

CMake 3.24 as their minimum versions in order to support Apple's fast-moving requirements.

One of the unique benefits of the Xcode generator is that it supports setting arbitrary Xcode project attributes. Most project settings can be modified in a key-value fashion on a per-target basis using target properties of the form `XCODE_ATTRIBUTE_XXX`, where `XXX` is the name of an Xcode property. These names are defined in the Apple documentation, but a potentially more convenient way to find them is to open an existing Xcode project, go to the build settings of a target and select the menu item **Editor > Show Setting Names**. Alternatively, one can click on a build setting of interest and the *Quick Help* assistant editor shows the setting name along with a description. A third method is to obtain a listing of a project's build settings from the command line using `xcodebuild`:

```
xcodebuild -showBuildSettings
```

CMake also supports variables of the form `CMAKE_XCODE_ATTRIBUTE_XXX`, but their relationship to the corresponding target properties is different to the usual CMake arrangement. These variables are used to set or override global defaults in the Xcode project rather than being used to initialize target properties. They only have an effect in the top level `CMakeLists.txt` file, their value is ignored in all other directory

scopes. When a XCODE_ATTRIBUTE_XXX target property is set, it overrides the global default.

The following example shows some of the more commonly used attributes:

```
# Set the default signing identity and team ID to use for
# all targets, must be in the top level of the project
set(CMAKE_XCODE_ATTRIBUTE_CODE_SIGN_IDENTITY
    "Apple Development"
)
set(CMAKE_XCODE_ATTRIBUTE_DEVELOPMENT_TEAM
    XYZ123ABCD
)

# Target-specific settings, can be in any directory scope
set_target_properties(MyApp PROPERTIES
    XCODE_ATTRIBUTE_TARGETED_DEVICE_FAMILY      1,2
    XCODE_ATTRIBUTE_IPHONEOS_DEPLOYMENT_TARGET 10.0
)
```

This feature can also be used to set an Xcode attribute for only one particular build type by appending [variant=ConfigName] to the property name. Other suffix types can be appended to the property name too for even more specific attribute settings, but their use would be unusual. Even [variant=...] suffixes would not often be needed. The following example gives an idea of the use cases where this feature might be useful:

```
set_target_properties(MyApp PROPERTIES
    XCODE_ATTRIBUTE_VALIDATE_PRODUCT[variant=Release] YES
    XCODE_ATTRIBUTE_ENABLE_TESTABILITY[variant=Debug] YES
)
```

Some projects may require setting quite a few attributes in order to get the desired Xcode behavior and features, whereas other projects may be quite simple and require only a minimal number of additional settings. Some attributes are only needed in very specific circumstances, whereas others are so common they are (or should be) present in almost every Apple-focused project. A number of these are discussed in the rest of this chapter, including some of those used in the above examples.

With CMake 3.24 or later, an additional method is available for specifying Xcode build settings. Xcode supports *.xcconfig files, which are ordinary text files consisting of key = value assignments. These provide similar functionality to the XCODE_ATTRIBUTE_... property and CMAKE_XCODE_ATTRIBUTE_... variable. Projects moving to CMake from a traditional Xcode project may already have such files, so this method may be more familiar and simplify the transition.

In Xcode, a .xcconfig file is assigned to a build configuration, or to a target under a particular build configuration. The file may be assigned to multiple configurations and targets, as illustrated in the following example:

Configurations

Name	Based on Configuration File
Debug	3 Configurations Set
AppWithFwk	globals.debug ▾
ALL_BUILD	None ▾
AppWithFwk	app ▾
FranklyFwk	fwk.debug ▾
ZERO_CHECK	None ▾
install	None ▾
Release	3 Configurations Set
AppWithFwk	globals.release ▾
ALL_BUILD	None ▾
AppWithFwk	app ▾
FranklyFwk	fwk.release ▾
ZERO_CHECK	None ▾
install	None ▾
MinSizeRel	3 Configurations Set
RelWithDebInfo	3 Configurations Set

In the above, AppWithFwk is the global project. The interesting targets are an app named AppWithFwk and a framework named FranklyFwk. At the project level, the `globals.debug.xcconfig` file is used for the Debug configuration, whereas `globals.release.xcconfig` is used for the Release configuration. A single `app.xcconfig` file is used for AppWithFwk in all configurations, while the FranklyFwk target has `fwk.debug.xcconfig` for its Debug configuration and `fwk.release.xcconfig` for its Release configuration.

In CMake, the `CMAKE_XCODE_XCCONFIG` variable controls the global settings, while the `XCODE_XCCONFIG` target property provides the target-specific settings. Both the variable and the property

accept only a single value. Generator expressions must be used where different files are needed for different configurations. The following demonstrates how to reproduce the arrangement shown in the above screenshot:

```
cmake_minimum_required(VERSION 3.24)
project(AppWithFwkExample)

set(CMAKE_XCODE_XCCONFIG
    ${IF:$<CONFIG:Debug>,globals.debug.xcconfig,globals.release.xcconfig}
)

add_executable(AppWithFwk ...)
set_target_properties(AppWithFwk PROPERTIES
    XCODE_XCCONFIG app.xcconfig
)

add_library(FranklyFwk ...)
set_target_properties(FranklyFwk PROPERTIES
    XCODE_XCCONFIG
    ${IF:$<CONFIG:Debug>,fwk.debug.xcconfig,fwk.release.xcconfig}
)
```

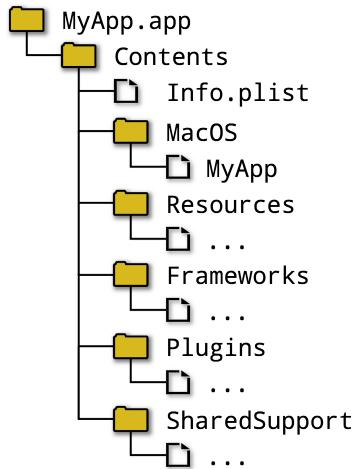
Just as for CMAKE_XCODE_ATTRIBUTE_... variables, CMAKE_XCODE_XCCONFIG only has an effect when set in the top level CMakeLists.txt file.

25.2. Application Bundles

Application bundles are a cornerstone of the Apple ecosystem. Understanding the structure of an application bundle and how this affects the way the build should be configured is essential for any developer targeting Apple platforms.

25.2.1. Bundle Structure

The structure of an application bundle for macOS is different to that for iOS, tvOS, watchOS, and visionOS. The macOS structure separates out various categories of files into different subdirectories and looks something like the following (applications might have only some of the subdirectories shown):



In contrast, the bundle structure for iOS, tvOS, watchOS, and visionOS is flattened, having very little in the way of a defined structure:



When building an app bundle, CMake somewhat abstracts away these structural differences, allowing at least some things to be handled the same way regardless of the Apple platform being built for. Developers should be aware, however, that some

areas of that abstraction have not been implemented correctly until more recent CMake releases, the handling of resources being a specific example. Therefore, using the latest CMake release is strongly advised.

An application is identified as being a bundle by adding the `MACOSX_BUNDLE` keyword to `add_executable()`:

```
add_executable(MyApp MACOSX_BUNDLE ...)
```

This sets the `MACOSX_BUNDLE` target property to true, which non-Apple platforms simply ignore. A project can alternatively set the `CMAKE_MACOSX_BUNDLE` variable to true and all subsequently defined executable targets have their `MACOSX_BUNDLE` target property set as well. But it would be more common and clearer to use the `MACOSX_BUNDLE` keyword with each `add_executable()` command instead (projects typically define only a small number of application bundles, often only one).

Somewhat confusingly, `MACOSX_BUNDLE` applies not just to macOS, but also to iOS, tvOS, watchOS, and visionOS. The keyword predates the non-desktop Apple platforms, hence the desktop-specific name. Rather than creating new keywords for each of the other platforms, the use of the existing keyword was expanded to cover all Apple platforms. This same pattern of expanding `...OSX...` keywords and variables to cover all Apple platforms can be seen in a number of other cases as well, but note that this is not universal across all `...OSX...` variables and

properties. Those for which this holds true are highlighted in this chapter.

25.2.2. Sources, Resources And Other Files

In addition to the usual C/C++ sources, Apple platforms also support Objective-C/C++ source files. These typically have a `.m` or `.mm` file suffix and can be listed as sources in `add_executable()` and `target_sources()` commands just like ordinary C or C++ files (see [Section 43.5, “Defining Targets”](#) for more on defining target sources). Most of CMake’s generators will recognize these file suffixes and compile the files appropriately, not just the Xcode generator. Starting from CMake 3.16, `OBJC` and `OBJCXX` are recognized as distinct languages and can be enabled separately from `C` and `CXX`. They also support their own language-specific sets of CMake properties and variables like `CMAKE_OBJC_FLAGS`, `CMAKE_OBJCXX_STANDARD`, and so on. See [Section 17.1, “Setting The Language Standard Directly”](#) for fallback behavior when `OBJC_STANDARD` and `OBJCXX_STANDARD` target properties are not set.

Another group of source files unique to Apple platforms are those used to define the user interface. Storyboard or interface builder files are like sources, but they require some additional handling to compile them as resources and put the compiled result in the appropriate place in the app bundle ([Section 25.5.2, “Info.plist Files”](#) also covers aspects of this topic). Only the Xcode generator implements this automatic compilation and

copying to the appropriate location, so the use of Makefile or Ninja generators is generally not recommended when an app bundle has these files.

Storyboard and interface builder sources need to be listed as sources in `add_executable()` or `target_sources()`. To get them to be automatically compiled and copied to the appropriate location in the bundle, they also need to be listed in the RESOURCE target property or have their `MACOSX_PACKAGE_LOCATION` source property set to Resources (another potential condition is discussed later in this section). The main difference between these two approaches is what happens if the target is installed ([Chapter 35, *Installing*](#) is dedicated to this broad topic). Any file listed in the RESOURCE target property will be copied to the RESOURCE destination given in the `install(TARGET)` command, regardless of what type of source file it is. This is usually undesirable for source files that need to be compiled, but is suitable for other arbitrary files to be added to the app bundle. On the other hand, source files that have their `MACOSX_PACKAGE_LOCATION` set to Resources will not be installed if Xcode recognizes them as source files that should be compiled. All other types of source files will be installed.

```
set(compileRes
    Base.lproj/Main.storyboard
    Base.lproj/LaunchScreen.storyboard
    Assets.xcassets  ①
)
```

```

set(directCopyRes
    defaultConfig.xml
    inventoryDb.dat
)
add_executable(MyApp MACOSX_BUNDLE
    AppDelegate.m
    AppDelegate.h
    ViewController.m
    ViewController.h
    main.m
    ${compileRes}
    ${directCopyRes}
)
set_target_properties(MyApp PROPERTIES
    RESOURCE "${directCopyRes}" ②
)
set_source_files_properties(${compileRes} PROPERTIES
    MACOSX_PACKAGE_LOCATION Resources
)

```

- ① While CMake doesn't officially support listing directories as sources, it is an important technique for allowing things like asset catalogs to be compiled.
- ② Note the quotes to ensure the list of files is passed as a single value for the RESOURCE property.

A special case applies when setting the MACOSX_PACKAGE_LOCATION to a path starting with Resources and the target is being built for iOS, tvOS, watchOS, or visionOS. Because app bundles for these platforms use a flattened structure, CMake will strip off the Resources part of the path. Prior to CMake 3.9, this behavior was implemented incorrectly, and it was not always possible to get a file into the desired location.

For cases where source files need to be copied into the app bundle with some sort of directory structure, or where they need to be located somewhere other than the Resources directory, the MACOSX_PACKAGE_LOCATION method must be used. For example:

```
set(sharedRes defaultConfig.xml defaultInventoryDb.dat)

add_executable(MyApp MACOSX_BUNDLE ... ${sharedRes})

set_source_files_properties(${sharedRes} PROPERTIES
    MACOSX_PACKAGE_LOCATION SharedSupport/defaults
)
```

When building for macOS, Xcode 14 or later might not automatically compile asset catalogs or storyboard files added using the methods described above. Explicitly linking the app target to Cocoa or AppKit may fix that problem. [Section 25.10, “Linking Frameworks”](#) discusses different ways of linking a framework, but the following example shows the preferred method when using CMake 3.24 or later:

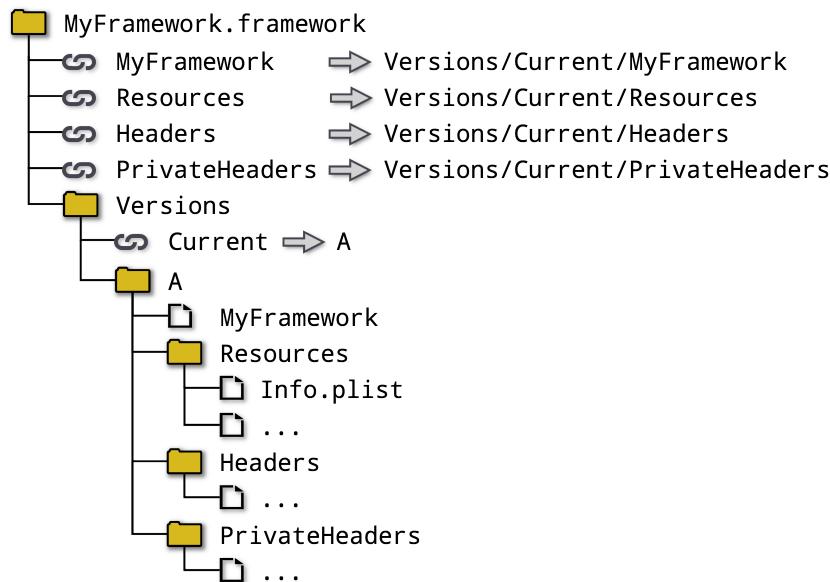
```
# This may be necessary with Xcode 14 or later to ensure
# the asset catalogs and storyboard files are compiled
target_link_libraries(MyApp
    PRIVATE $<LINK_LIBRARY:FRAMEWORK,AppKit>
)
```

25.3. Frameworks

Frameworks share some similarities with application bundles, but they also have a number of unique features. A framework contains a main library, but unlike an application bundle, on macOS there may be multiple versions of the library. In addition to the usual resources, frameworks also support headers, and in the case of macOS, both the resources and headers are version-specific.

25.3.1. Framework Structure

A typical example of the macOS framework structure looks something like this.

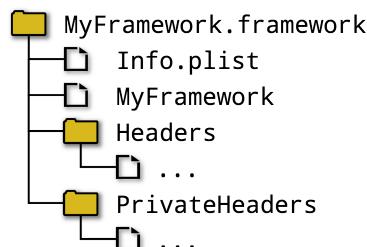


The top level of the framework always has a name that ends with `.framework`, and typically the only non-symlinked contents in that top level directory is the `Versions` subdirectory (umbrella frameworks being the exception, but those are outside the scope of framework support being considered here). Everything

else at that level is usually a symlink to something in the current version's subdirectory.

Within the `Versions` directory, each version of the library gets its own subdirectory, but this version support is mostly a historical feature. In practice, almost every framework contains just one version, and by convention, the version subdirectory name is usually `A`. Rather than providing multiple versions in one framework, it is generally preferred to provide a completely separate framework and let the consumer choose which one they want to use. Regardless of the style of versioning, a symlink called `Current` points to the most recent version. The symlink acts like a default version for the framework. Each version is expected to have a `Resources` directory that contains at least an `Info.plist` file, which provides configuration details about that particular version (discussed further below). There will also be a library (which is usually a shared library, but it can be static), and often `Headers` and potentially `PrivateHeaders` subdirectories as well.

In comparison, the structure on iOS, tvOS, watchOS, and visionOS is flattened, and it does not typically support versions:



CMake supports the creation of frameworks (single-version only in the case of macOS), and it provides features for handling the version details. Like app bundles, frameworks also require an `Info.plist` file (discussed in detail in [Section 25.5.2, “Info.plist Files”](#)).

The first step is to define a library in the usual way and then mark it as a framework by setting the `FRAMEWORK` target property to true. With CMake 3.15 or later, the `FRAMEWORK` target property is initialized with the value of the `CMAKE_FRAMEWORK` variable, while for 3.14 and earlier, the target property is initially unset. Most frameworks are defined as shared libraries, but as of CMake 3.8, static libraries can also be built as frameworks. The `FRAMEWORK` target property is ignored on non-Apple platforms.

For macOS only, the framework version can be specified using the `FRAMEWORK_VERSION` target property. If omitted, a default version of A will be set. Non-macOS Apple platforms will ignore the `FRAMEWORK_VERSION` property if it is set, producing the same flattened, unversioned framework structure produced by Xcode when it creates frameworks for these platforms.

```
add_library(MyFramework SHARED foo.cpp)

set_target_properties(MyFramework PROPERTIES
    FRAMEWORK      TRUE
    FRAMEWORK_VERSION 5
)
```

25.3.2. Headers

Frameworks often contain the headers associated with the framework's library. This allows the framework to be treated as a self-contained bundle which other software can build against. Framework headers are separated into public and private groups, with only public headers intended to be directly included or imported by consuming projects. The private headers are usually needed as internal implementation details by the public headers and frameworks often do not include any private headers at all.

CMake supports specifying the set of public and private headers with the `PUBLIC_HEADER` and `PRIVATE_HEADER` target properties respectively. Both properties contain a list of header files, and all files mentioned must also be explicitly listed as sources for the target or they won't be copied into the framework. Files listed in `PUBLIC_HEADER` will be copied into the framework's `Headers` directory with paths stripped, while files listed in `PRIVATE_HEADER` will be copied into the `PrivateHeaders` directory, again with any paths stripped. If paths need to be preserved, these target properties cannot be used and the headers have to be added using techniques such as via `MACOSX_PACKAGE_LOCATION`, as described in [Section 25.2.2, “Sources, Resources And Other Files”](#).

```
add_library(MyFramework SHARED  
    foo.cpp  
    foo.h
```

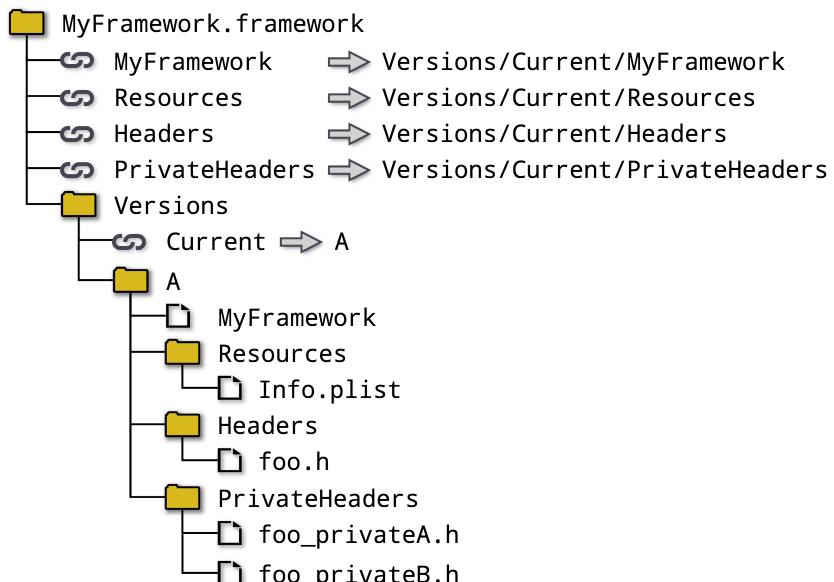
```

foo_privateA.h
nested/foo_privateB.h
)

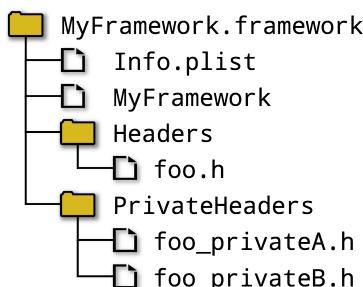
set_target_properties(MyFramework PROPERTIES
    FRAMEWORK      TRUE
    PUBLIC_HEADER  foo.h
    PRIVATE_HEADER "foo_privateA.h;nested/foo_privateB.h"
)

```

The above example would result in the following structure on macOS:



The same example on iOS would result in a more flattened structure:



Note that the PUBLIC_HEADER and PRIVATE_HEADER target properties are also used when installing targets on non-Apple platforms (see [Section 35.5.2, “Explicit Public And Private Headers”](#)).

25.4. Loadable Bundles

In addition to application bundles and frameworks, Apple also supports loadable bundles for macOS. These are often used as plugins or to provide optional features which might or might not be supported at run time. The structure of a loadable bundle is the same as that of an application bundle, but the top level directory usually has the extension .bundle or .plugin (any extension is technically permitted). CMake supports the creation of loadable bundles through the MODULE library type and the BUNDLE target property. By default, loadable bundles will be given the extension bundle, but this can be overridden with the BUNDLE_EXTENSION target property.

```
add_library(MyBundle MODULE ...)
set_target_properties(MyBundle PROPERTIES
    BUNDLE      TRUE
    BUNDLE_EXTENSION plugin
)
```

All the target properties relating to application bundles can also be used for loadable bundles.

25.5. Build Settings

When building a project for Apple platforms, a number of variables and properties must be set to obtain a working build, many of which are unique to the Apple ecosystem. For example, the toolchain is closely associated with the SDK used, which in turn is closely related to the target architecture. The name and version details of an app or framework are also quite different for Apple platforms.

Unlike other CMake generator types, the Xcode generator allows some of these things to be specified at build time by the developer rather than being known at configure time. For single-configuration generators, the target device is known exactly at configure time, but for Xcode, some platforms support both the device and device simulators. Furthermore, some of these devices have multiple architectures. In the case of iOS, this can mean up to five different target platform combinations. To allow developers to switch between different device targets and SDKs at build time, CMake projects must be careful not to over-specify or incorrectly specify these details.

25.5.1. SDK Selection

The selection of the SDK for iOS, tvOS, and watchOS is one area where many online examples exhibit considerable complexity. They also often suffer from locking the developer out of being able to switch between device and simulator builds without re-running CMake. With recent versions of CMake and Xcode, specifying the SDK should be relatively straightforward. This is

especially so with improvements added in CMake 3.14, with potentially the only required setup being to set the `CMAKE_SYSTEM_NAME` variable to `iOS`, `tvOS`, or `watchOS` (CMake 3.28 extended this further to support `visionOS` as well). A toolchain file may not even be needed, `CMAKE_SYSTEM_NAME` can be set directly on the `cmake` command line. Other methods exist for CMake 3.13 and earlier, using variables like `CMAKE OSX_SYSROOT` to achieve a working build, but they are no longer a practical approach with today's project needs.

With `CMAKE_SYSTEM_NAME` set to the desired target platform, Xcode will choose the latest SDK for that platform and allow switching between device and simulator builds without having to re-run CMake. Furthermore, Xcode can automatically populate the set of supported architectures based on the chosen SDK, so the project shouldn't need to specify them directly (see [Section 25.8.2, “Intel And Apple Silicon Binaries”](#) for more on this topic). This gives the developer the most control over what they want to build without having to re-run CMake.

The `-sdk` option can be given to choose the device or simulator at build time. For example, if `CMAKE_SYSTEM_NAME` was set to `iOS`, then building for the simulator could be done like so:

```
xcodebuild -sdk iphonesimulator
```

For the curious, the available SDKs can be obtained by running the following command:

```
xcodebuild -showsdk
```

25.5.2. Info.plist Files

Every application bundle or framework must have an `Info.plist` file. That file provides a lot of information about the app or framework, and it controls many aspects of how the app or framework is built. Even a very basic app or framework needs quite a bit of information to be provided before it can be built and executed successfully.

The most appropriate way to provide an `Info.plist` file depends on the minimum Xcode version the project must support. Xcode 14 introduced the ability to generate the `Info.plist` file, optionally merging in settings from an existing `Info.plist` file. For earlier Xcode versions, the project is fully responsible for providing the `Info.plist` file.

By default, CMake will provide a basic `Info.plist` from a template file shipped with CMake itself. This template may be acceptable for a framework, but it will typically be too simple for all but the most trivial of application bundles. When using this template file, CMake will substitute a few specific target properties, but a number of these are now either deprecated or ignored completely by Xcode. Therefore, projects should migrate away from using that mechanism and either provide their own `Info.plist` file or let Xcode generate it.

If supporting Xcode 13 or earlier, the appropriate target property should be used to specify the location of a suitable Info.plist file. That property is `MACOSX_BUNDLE_INFO_PLIST` for application bundles and `MACOSX_FRAMEWORK_INFO_PLIST` for frameworks. If some details need to be populated from the `CMakeLists.txt` file (e.g. the project version), the project can use `configure_file()` with the `@ONLY` keyword to safely substitute any necessary values, then provide the destination of that `configure_file()` call as the value for the `MACOSX_BUNDLE_INFO_PLIST` or `MACOSX_FRAMEWORK_INFO_PLIST` target property. Avoid using any of the `${MACOSX_BUNDLE_...}` variable substitutions CMake supports with this file (see the official CMake documentation for the `MACOSX_BUNDLE_INFO_PLIST` and `MACOSX_FRAMEWORK_INFO_PLIST` target properties for details of those substitutions). Historically, these substitutions used to be the recommended approach, but the names of the substitution variables can be confusing, and they have not been updated for more recent Xcode functionality.

If the project only needs to support Xcode 14 or later, a typically more convenient approach is to let Xcode generate the final Info.plist file. This is enabled by setting the `XCODE_ATTRIBUTE_GENERATE_INFOPLIST_FILE` target property to YES. Xcode will then create the Info.plist file based on other build settings provided via `XCODE_ATTRIBUTE_INFOPLIST_KEY_...` attributes (see below). The `XCODE_ATTRIBUTE_INFOPLIST_FILE`

target property should be set to the location of an initial Info.plist file, which Xcode will merge with the project's build settings. If no initial Info.plist needs to be provided, set XCODE_ATTRIBUTE_INFOPLIST_FILE to an empty string, or set it to the absolute path to an Info.plist file with no keys or values. This will prevent CMake's default Info.plist template file from being used.

Xcode 14 supports providing many individual Info.plist fields through build settings with names of the form INFOPLIST_KEY_xxx. These can be set by the project just like any other Xcode build setting, using target properties of the form XCODE_ATTRIBUTE_INFOPLIST_KEY_xxx. The xxx is the case-sensitive field name as it would appear in the Info.plist file. Not all valid Info.plist keys can be specified this way, only those for which Xcode offers an INFOPLIST_KEY_xxx build setting (which it does for many). The following example shows some settings which would typically be set for an application bundle on macOS:

```
set_target_properties(MyApp PROPERTIES
    # App bundles and frameworks would both set these
    XCODE_ATTRIBUTE_PRODUCT_NAME
        "MyApp"
    XCODE_ATTRIBUTE_PRODUCT_BUNDLE_IDENTIFIER
        "com.example.myapp"
    XCODE_ATTRIBUTE_MARKETING_VERSION
        "${PROJECT_VERSION}"
    XCODE_ATTRIBUTE_CURRENT_PROJECT_VERSION
        "${BUILD_VERSION}"
    XCODE_ATTRIBUTE_GENERATE_INFOPLIST_FILE
        YES
```

```
XCODE_ATTRIBUTE_INFOPLIST_FILE  
""  
XCODE_ATTRIBUTE_INFOPLIST_KEY_CFBundleDisplayName  
"My Cool Game"  
XCODE_ATTRIBUTE_INFOPLIST_KEY_LSAplicationCategoryType  
"public.app-category.games"  
XCODE_ATTRIBUTE_INFOPLIST_KEY_NSPrincipalClass  
"NSApplication"  
XCODE_ATTRIBUTE_INFOPLIST_KEY_NSMainStoryboardFile  
"Main"  
XCODE_ATTRIBUTE_INFOPLIST_KEY_NSHumanReadableCopyright  
"(c)2023 Example Co."  
)
```

An advantage of using these build settings is that Xcode uses some of them to populate other parts of its UI. Specifying the same settings directly in the Info.plist file will sometimes result in those other parts of the Xcode UI not being updated in the same way. CFBundleDisplayName and LSAplicationCategoryType are two examples of this.

The example above also demonstrates a few cases where Xcode provides a dedicated build setting for something that could be provided via a field in the Info.plist file. The PRODUCT_NAME, PRODUCT_BUNDLE_IDENTIFIER, MARKETING_VERSION and CURRENT_PROJECT_VERSION build settings are alternatives to their respective Info.plist fields CFBundleName, CFBundleIdentifier, CFBundleShortVersionString and CFBundleVersion. In some cases, Xcode will warn if both the dedicated build setting and the corresponding Info.plist entry are specified and they do not match. In general, where such dedicated build settings exist,

they should be used instead of the Info.plist field. Xcode will then populate the generated Info.plist with a reference to that build setting using the Xcode variable form `$(VAR_NAME)`. This ensures consistent values are used throughout.

The Apple requirements around app and framework version numbers have evolved over time. The latest documented requirements specify that the *major.minor.patch* format should be used for both the MARKETING_VERSION and the CURRENT_PROJECT_VERSION. In the case of CURRENT_PROJECT_VERSION, only the *major* part is required and the *minor* and *patch* version components are optional. One strategy is to set CURRENT_PROJECT_VERSION to the job number from a continuous integration system, which will ensure that subsequent builds for the same MARKETING_VERSION during the pre-release phase will have unique and increasing build numbers. When updating an already installed app with the same MARKETING_VERSION, this will ensure the operating system sees the latest build as a newer version. The following CMake code shows one way to provide version numbers that meet Apple's requirements:

```
cmake_minimum_required(VERSION 3.24)
project(Example VERSION 2.4.7)

# CI systems typically provide some form of job ID as an
# environment variable. This example works for gitlab, but
# other CI systems are likely to be similar. When not run
# under CI, this will leave BUILD_VERSION set to 0.
set(BUILD_VERSION $ENV{CI_JOB_ID})
```

```

if(BUILD_VERSION STREQUAL "")
    # This is a local build, not through CI system
    set(BUILD_VERSION 0)
endif()

add_executable(MyApp MACOSX_BUNDLE ...)

set_target_properties(MyApp PROPERTIES
    XCODE_ATTRIBUTE_MARKETING_VERSION
    "${PROJECT_VERSION}"
    XCODE_ATTRIBUTE_CURRENT_PROJECT_VERSION
    "${BUILD_VERSION}"
)

```

Note the unfortunate different meaning for PROJECT_VERSION between Xcode and CMake. The MARKETING_VERSION is the main user-visible version number, which likely corresponds to the version given in CMake's project() command. The CURRENT_PROJECT_VERSION in Xcode is really more a build version number, for which CMake has no direct equivalent. This build version number normally comes from the environment in which CMake is called. The above example shows one such way a build number might be provided.

When using Storyboard or interface builder files, the Info.plist file should contain one of the keys NSMainStoryboardFile, NSMainNibFile or UIMainStoryboardFile (see the Apple documentation for details on the meaning and appropriate use of these keys). Such an entry tells the operating system which UI element to use when launching the app. In the earlier example, the NSMainStoryboardFile field has the value Main, which

specifies that a `Main.storyboard` UI will be used when the app starts.

25.5.3. Deployment Target

By default, the project's minimum deployment target version will be set to the most recent one the SDK or host system supports. This will often be undesirable, since projects typically want to remain compatible with a specific minimum OS version.

The `CMAKE OSX_DEPLOYMENT_TARGET` variable specifies the minimum operating system version the project's applications and libraries can run on. Despite its name, the variable supports all platforms when using CMake 3.11 or later, not just macOS. CMake will transform the variable's value to the appropriate `<platform>_DEPLOYMENT_TARGET` build setting in the Xcode project. For earlier CMake versions, it only applies to macOS.

The `CMAKE OSX_DEPLOYMENT_TARGET` variable should be set before the first `project()` command is called. It should be set as a cache variable for at least three reasons:

- The project may be built as part of a larger project with higher minimum deployment version requirements. It may be desirable to allow the user or script driving the project to override the project's default setting, enabling it to use newer

SDK features or avoid warnings about mixing deployment versions.

- The platform initialization performed as part of the first `project()` call will try to set `CMAKE OSX DEPLOYMENT TARGET` as a cache variable. The value of the variable will be used when performing compiler checks as part of enabling a language for the first time. This can affect the default set of flags selected for the toolchain.
- If set as a non-cache variable, that value will be discarded if policy `CMP0126` is not set to `NEW`. The project can avoid this by specifying a minimum CMake version of 3.21 or higher, but setting a cache variable to begin with avoids this subtle problem.

```
cmake_minimum_required(VERSION 3.21)

set(CMAKE OSX_DEPLOYMENT_TARGET 12.2 CACHE STRING
    "Minimum operating system version for deployment"
)

project(MyProj)
```

Do not rely on the user setting `CMAKE OSX DEPLOYMENT TARGET` through a toolchain file or on the command line. They may choose to do that, but the project should still define a default value for this cache variable which makes clear its minimum deployment requirements. Users should not be expected to

know what those minimum requirements are and provide them for every build they set up.

If required, the minimum deployment version can be overridden on individual targets by setting the relevant XCODE_ATTRIBUTE_<platform>_DEPLOYMENT_TARGET property, where <platform> can be MACOSX, IPHONEOS, TVOS, WATCHOS, or XROS.

```
set_target_properties(MyApp PROPERTIES  
    XCODE_ATTRIBUTE_IPHONEOS_DEPLOYMENT_TARGET 11.0  
)
```

Keep in mind that doing so will take away the ability of the user to override the minimum deployment version. Therefore, only do this for projects where it is known the user will not need to do that, such as in private company projects.

Also be aware that the minimum deployment version can interact with the architectures requested by the CMAKE_OSX_ARCHITECTURES variable in ways that can cause CMake configuration to fail. See [Section 25.8, “Universal Binaries”](#) for discussion of examples where this can occur.

25.5.4. Device Families

In the case of iOS, projects will also likely want to specify the device families being targeted. Apple denotes devices with integer values specified in the TARGETED_DEVICE_FAMILY attribute. For iOS, common values are 1 for iPhone (and technically iPod

touch too), and 2 for iPad. If the app should support both iPhone and iPad, then specify both values separated by a comma. If this attribute is not set, it will default to 1. Xcode will use this value to add a `UIDeviceFamily` entry in the app's `Info.plist` file automatically, so avoid setting this entry in any custom `Info.plist` supplied by the project.

```
# An iOS app that supports only iPad
add_executable(MyiPadApp MACOSX_BUNDLE ...)
set_target_properties(MyiPadApp PROPERTIES
    XCODE_ATTRIBUTE_TARGETED_DEVICE_FAMILY 2
)

# An iOS app that supports both iPhone and iPad
add_executable(RunEverywhereApp MACOSX_BUNDLE ...)
set_target_properties(RunEverywhereApp PROPERTIES
    XCODE_ATTRIBUTE_TARGETED_DEVICE_FAMILY 1,2
)
```

25.5.5. Other Helpful Build Settings

The defaults for a project created by CMake will have some differences to a similar project created directly in Xcode. Some of these differences are subtle and less important, but some can be unexpected and hard to track down.

Settings for Clang are a prime example where differences can have a strong impact on the way the project is defined and built. A project with Objective-C code will probably have been written with the assumption that automatic reference counting is enabled, but this has to be explicitly requested for a CMake

project by setting the XCODE_ATTRIBUTE_CLANG_ENABLE_OBJC_ARC target property to YES. The somewhat related XCODE_ATTRIBUTE_CLANG_ENABLE_OBJC_WEAK property may also need to be set to YES if the code has any manual retain-release logic.

Projects created directly in newer Xcode versions will have auto-linking of system frameworks enabled by default, but CMake-generated projects will not. More accurately, CMake-generated projects do not enable Clang modules, which is a prerequisite for the framework auto-linking. Having auto-linking disabled means the project has to explicitly link to all system frameworks it uses directly, with typical examples being UIKit, CoreFoundation, and so on. For many developers, this is surprising. It is usually desirable to enable this module support, and therefore enable auto-linking, which can be achieved by setting the XCODE_ATTRIBUTE_CLANG_ENABLE_MODULES target property to YES.

```
set_target_properties(SomeApp PROPERTIES
    XCODE_ATTRIBUTE_CLANG_ENABLE_OBJC_ARC YES
    XCODE_ATTRIBUTE_CLANG_ENABLE_OBJC_WEAK YES
    XCODE_ATTRIBUTE_CLANG_ENABLE_MODULES YES
)
```

If using Xcode 14.3 or later, the Apple documentation also recommends enabling the module verifier for framework targets. This turns on various checks for common problems and inconsistencies in how a framework is defined and implemented. It is specifically focused on uncovering problems

that don't normally show up at build time, they show up only when the framework is used by a consumer. Setting XCODE_ATTRIBUTE_ENABLE_MODULE_VERIFIER to YES turns this on, but a couple of other settings also need to be provided. The XCODE_ATTRIBUTE_MODULE_VERIFIER_SUPPORTED_LANGUAGES target property should be a space-separated list of languages. The supported values are objective-c, objective-c++, c, and c++. The XCODE_ATTRIBUTE_MODULE_VERIFIER_SUPPORTED_LANGUAGE_STANDARDS property is closely related to the CXX_STANDARD and CXX_EXTENSIONS target properties. Valid values include gnu99, c11, c++11, gnu++17, c++20, and so on. Make sure to set these three properties to a consistent set of values.

```
set_target_properties(SomeFwk PROPERTIES
    XCODE_ATTRIBUTE_ENABLE_MODULE_VERIFIER YES
    XCODE_ATTRIBUTE_MODULE_VERIFIER_SUPPORTED_LANGUAGES "c++"
    XCODE_ATTRIBUTE_MODULE_VERIFIER_SUPPORTED_LANGUAGE_STANDARDS "c++20"
    CXX_STANDARD 20
    CXX_EXTENSIONS NO
)
```

25.5.6. Compiler Test Workarounds

When building for Apple platforms other than macOS, the compiler checks performed by CMake and any `try_compile()` invocations initiated by the project have the potential to trigger a variety of problems. Many of these problems come from code signing being enabled during compiler checks or `try_compile()` invocations, but signing is usually not necessary nor desirable

in those contexts. The steps to avoid these problems depend on the combination of the Xcode and CMake versions used, but in almost all cases, the workarounds are most easily implemented with a toolchain file. A better solution though is to use at least CMake 3.24 and Xcode 14, in which case no workarounds should be needed.

Xcode 11 changed the handling of certain signing-related project options, among other things. To be able to build successfully with Xcode 11 for iOS, watchOS, or tvOS, use CMake 3.18.2 or later. CMake 3.14 or later can still be used (earlier versions will fail), but the `CMAKE_XCODE_ATTRIBUTE_CODE_SIGNING_ALLOWED` variable needs to be set to false inside `try_compile()` calls to prevent signing. This variable should *not* be set for the main part of the build, since the main build's targets will likely need to be signed. CMake 3.18.2 and later needs no such workaround, since it automatically sets `CMAKE_XCODE_ATTRIBUTE_CODE_SIGNING_ALLOWED` to false inside `try_compile()` calls. The following toolchain file demonstrates how this workaround can be implemented:

```
# Any of these platforms can be used with this approach
#set(CMAKE_SYSTEM_NAME watchOS)
#set(CMAKE_SYSTEM_NAME tvOS)
set(CMAKE_SYSTEM_NAME iOS)

if(CMAKE_VERSION VERSION_LESS 3.18.2)
    # Only disable code signing for try_compile() calls.
    # Leave signing details alone for the main build.
    get_property(__in_try_compile GLOBAL
```

```
PROPERTY IN_TRY_COMPILE
)
if(__in_try_compile)
  set(CMAKE_XCODE_ATTRIBUTE_CODE_SIGNING_ALLOWED NO)
endif()
unset(__in_try_compile)
endif
```

25.6. Signing And Capabilities

The above covers the main build-related settings that need to be defined for most Apple projects. For simple, unsigned macOS apps, they may be enough on their own, but most projects will need further configuration to sign the build products and specify the capabilities they are allowed to use before they can be useful.

Xcode's code signing functionality has evolved with each successive major Xcode release. The move toward automatic management of code signing and provisioning has made it easier to get signed applications built with CMake, but it still requires an understanding of the signing process to set the appropriate properties and variables. In practice, if a project must sign its build products, the latest Xcode release should generally be used. The previous major release may still remain functional for a while, but anything older than that is likely to cause problems. Apple generally expects developers to develop and sign apps with the latest Xcode release.

25.6.1. Signing Identity And Development Team

For signing and provisioning to work, the app must have a valid bundle ID and at least two other key pieces of information: the development team ID and the code signing identity. These need to be specified as Xcode attributes, which follow the usual pattern of being set on individual targets through target properties or through CMake variables to specify global defaults. Since both quantities would typically need to be the same throughout the build, it is generally advisable to set them as variables at the top of the project rather than per target.

The `XCODE_ATTRIBUTE_DEVELOPMENT_TEAM` target property, or alternatively the corresponding `CMAKE_XCODE_ATTRIBUTE_DEVELOPMENT_TEAM` variable, should be set to the development team ID. This is a short string typically of around 10 characters. The most convenient approach is usually to set the `CMAKE_XCODE_ATTRIBUTE_DEVELOPMENT_TEAM` variable very early in the very top `CMakeLists.txt` file, usually just after the first `project()` command. Depending on the project, the developer might or might not need the ability to change this value. For example, if the project is company software that will always be built by an employee, the team ID will likely never change, whereas an open source project available to the public will almost certainly be built by developers with their own development team ID. For cases where the team ID should

never change, defining `CMAKE_XCODE_ATTRIBUTE_DEVELOPMENT_TEAM` as an ordinary variable is sufficient, but where it is expected that the developer may need to change it, it should be defined as a cache variable. This ensures there is a default value, but developers can override it without editing the `CMakeLists.txt` file.

Similarly, the `XCODE_ATTRIBUTE_CODE_SIGN_IDENTITY` target property or the corresponding `CMAKE_XCODE_ATTRIBUTE_CODE_SIGN_IDENTITY` variable specifies the signing identity. In the past, this should almost always have been the string `Mac Developer` for macOS applications or `iPhone Developer` for iOS, tvOS or watchOS applications. Starting with Xcode 11, the string `Apple Development` should be used instead and will work for all platforms. These values will direct Xcode to select the most appropriate signing identity for the specified development team.

In unusual circumstances, the signing identity may need to be set to a string which identifies a particular code signing identity in the developer's keychain. The onus is then on the developer to ensure that this identity belongs to the specified development team. The team ID for a signing identity can be confirmed using these steps:

- Open the Keychain Access app and select "My Certificates".

- Right-click on the certificate corresponding to the desired signing identity and select "Get Info".
- The team ID for that certificate will be listed as the "Organisational Unit" in the "Subject Name" section at the top.

Note that part of the "Common Name" for the certificate may contain a string that looks like a team ID. It will commonly have the form "Apple Development: FirstName LastName (XXXXXXXXXXXX)", but that XXXXXXXXXXXX may be different to the team ID. Always check the "Organisational Unit" for the certificate, as that is what the team ID must be set to.

The following example shows how a CMakeLists.txt might be structured for a macOS application which allows the developer to change the team ID and the signing identity:

```
cmake_minimum_required(VERSION 3.24)
# Other build settings omitted from here...
project(macOSexample)

set(CMAKE_XCODE_ATTRIBUTE_DEVELOPMENT_TEAM
    "ABC12345DE" CACHE STRING ""
)
set(CMAKE_XCODE_ATTRIBUTE_CODE_SIGN_IDENTITY
    "Apple Development" CACHE STRING ""
)
```

For an iOS application where the team ID is not expected to be changed, but where the developer might still want control over the signing identity (e.g. to test a different identity in their keychain), only the identity would need to be a cache variable:

```
cmake_minimum_required(VERSION 3.24)
# Other build settings omitted from here...
project(iOSexample)

set(CMAKE_XCODE_ATTRIBUTE_DEVELOPMENT_TEAM "ABC12345DE")
set(CMAKE_XCODE_ATTRIBUTE_CODE_SIGN_IDENTITY
    "Apple Development" CACHE STRING ""
)
```

One might be tempted to move the code signing details into a toolchain file to avoid having to set CMAKE_XCODE_ATTRIBUTE_CODE_SIGN_IDENTITY altogether. Beware of potential problems with `try_compile()` calls though, as mentioned in [Section 25.5.6, “Compiler Test Workarounds”](#). If code signing is enabled during the try-compile test CMake performs as part of the first `project()` command, it would then require a valid provisioning profile, which in turn would require a valid bundle ID. It is not generally going to be desirable to have such bundle IDs and provisioning profiles being created in the team account. The try-compile tests do not need to perform code signing, so a toolchain file should not be used to enable signing globally.

If the app links to shared frameworks that are also built by the project, do not enable code signing for those frameworks. The recommended way to add such frameworks to an app bundle is to embed them with the *Code sign on copy* option enabled. This is discussed in [Section 25.11, “Embedding Frameworks And Other Things”](#).

25.6.2. Provisioning Profiles

When configured as described in the preceding section, Xcode will automatically select an appropriate provisioning profile. If an appropriate profile doesn't exist, the Xcode IDE can automatically create one. The `xcodebuild` command line tool also provides the `-allowProvisioningUpdates` option for Xcode 9 or later. Automatic provisioning can be more convenient compared to the manual process of earlier Xcode versions where provisioning profiles had to be created manually through the online developer portal. For automatic provisioning to work, the developer still needs an account on Apple's developer portal. This can be a problem for continuous integration builds or for team environments where individual developers might not have such an account. In those situations, manual provisioning may still be preferred.

The `XCODE_ATTRIBUTE_PROVISIONING_PROFILE_SPECIFIER` target property allows the provisioning profile to be specified directly. It should be given the provisioning profile's name rather than its UUID because the profile will need to be updated from time to time, such as when a device or developer certificate is added, updated or removed. The profile's name will remain constant, but its UUID will change with each update. The name to use is the one shown for the profile in the developer portal.

25.6.3. Entitlements

Apple applications also have an associated set of entitlements. These control which features the operating system will allow the app to use, such as Siri, push notifications and so on. In the project settings within the Xcode IDE, users are able to go to the *Signing & Capabilities* tab of an app target and enable or add the required capabilities. The associated entitlements are then enabled in the plist file that Xcode automatically generates, the target is linked to any required frameworks, and the capability is added to the app ID in the team account. With a CMake-generated project, the capabilities part of the *Signing & Capabilities* tab is effectively bypassed. Instead, the CMake project must provide its own entitlements plist file if the default entitlements are not sufficient. The project must also handle linking of any required frameworks itself, and no changes are made to the app ID in the team account. In practice, for many applications, these are fairly mild restrictions, with only framework linking presenting some wrinkles.

Specifying entitlements is done by setting the `XCODE_ATTRIBUTE_CODE_SIGN_ENTITLEMENTS` target property to the name of an appropriate entitlements file like so:

```
set_target_properties(MyApp PROPERTIES
    XCODE_ATTRIBUTE_CODE_SIGN_ENTITLEMENTS
    ${CMAKE_CURRENT_LIST_DIR}/MyApp.entitlements
)
```

As an example, an entitlements file which adds Siri to the default entitlements can be quite simple:

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN"
 "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
  <key>com.apple.developer.siri</key>
  <true/>
</dict>
</plist>
```

25.7. Creating And Exporting Archives

To distribute an app via the App Store, an Enterprise distribution portal, or other supported avenues, an archive must be created. CMake doesn't provide a build target for creating such an archive, but the `xcodebuild` tool can be used with a project generated by CMake to accomplish the task. The archive build action requires only a few options to build the necessary targets for release and create an archive. There are a few ways to specify what to archive, but a fairly simple approach is to name the project, scheme, and the name of the output, which can be done like so:

```
xcodebuild archive \
-project MyProject.xcodeproj \
-scheme MyApp \
-archivePath MyApp.xarchive
```

CMake creates the `.xcodeproj` file when using the Xcode generator. Prior to CMake 3.9, the user then had to load the project in the Xcode IDE to create the build schemes. This

presented a problem for headless continuous integration builds where the IDE cannot be accessed, so to address this situation, CMake 3.9 introduced the `CMAKE_XCODE_GENERATE_SCHEME` variable. When this variable is set to true, CMake will also generate schemes for the project. Subsequent CMake versions added support for a variety of `XCODE_SCHEME_...` target properties and associated `CMAKE_XCODE_SCHEME_...` variables which can be used to customize scheme properties. See the CMake documentation for the set of supported properties and variables.

With scheme generation enabled, the name of the app target can be specified for the `-scheme` option to `xcodebuild` and the archive task has all the information it needs. The above command will build the `MyApp` target for the `Release` configuration for all supported architectures, sign it (still with the developer signing identity), and then create an archive named `MyApp.xcarchive` in the current directory. It is not required to use a distribution signing identity at this stage, as the archive will be re-signed in the next step, exporting the archive.

While an archive may support multiple architectures, it will normally only support one platform. For example, with a project set up to target iOS, the command shown above would produce an archive for devices, but not simulators. The `-destination` argument can be used to specify the desired platform:

```
xcodebuild archive \
    -project MyProject.xcodeproj \
    -scheme MyApp \
    -destination "generic/platform=iOS Simulator" \
    -archivePath MyApp-iOS_Simulator.xcarchive
```

The list of available destinations can be found by running `xcodebuild` with the `-showdestinations` option. The `-project` and `-scheme` options are needed so it can work out the supported destinations.

Archiving may fail if certain install attributes are not set appropriately. The Apple developer documentation contains a few troubleshooting guidelines which may help overcome some of the more common situations. For example, ensure the target's `INSTALL_PATH` and `SKIP_INSTALL` attributes are set correctly for the target type. In a CMake project aimed at producing a signed application for distribution, a target's `XCODE_ATTRIBUTE_SKIP_INSTALL` property must be set to `YES` for libraries and embedded frameworks, and to `NO` for applications. Where it is set to `NO`, the `XCODE_ATTRIBUTE_INSTALL_PATH` must also be provided, and it should generally be given the value `$(LOCAL_APPS_DIR)`. Failure to follow this advice will typically result in the archiving step producing a generic archive rather than an application archive.

```
# Apps must have the install step enabled
set_target_properties(macOSApp PROPERTIES
    XCODE_ATTRIBUTE_SKIP_INSTALL NO
```

```
XCODE_ATTRIBUTE_INSTALL_PATH "$(LOCAL_APPS_DIR)"  
)
```

After the application archive has been created, it needs to be exported for distribution. This is achieved by running the `xcodebuild` tool again, this time providing the archive just created, an export options plist file, and the location to write the output to. The basic form of the command is as follows:

```
xcodebuild -exportArchive \  
-archivePath MyApp.xcarchive \  
-exportOptionsPlist exportOptions.plist \  
-exportPath Products
```

The `-archivePath` option points to the archive file created by the earlier invocation of `xcodebuild`, and the `-exportPath` option specifies the directory in which to create the final output file. Everything else about the export step is defined by the plist file given to the `-exportOptionsPlist` option. The full set of supported keys can be found in the tool's help documentation (`xcodebuild -help`), but a minimal plist file might look like this:

```
<?xml version="1.0" encoding="UTF-8"?>  
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN"  
"http://www.apple.com/DTDs/PropertyList-1.0.dtd">  
<plist version="1.0">  
<dict>  
    <key>method</key>  
    <string>app-store</string>  
</dict>  
</plist>
```

The *method* specifies the intended distribution channel. Valid values have evolved over time, but all possible values can be found in the output of a `xcodebuild --help` command. Some important ones to be aware of include:

app-store

Export the archive for normal distribution through the Apple app store.

developer-id

Export a macOS app, plugin or installer package for distribution to end users outside the Apple app store. This would be the appropriate method when distributing to the general public via a company's own website. It is recommended that the exported app be notarized before making it available.

enterprise

Export an iOS app for distribution within an organization. This method requires membership in the Apple Enterprise Development Program.

ad-hoc

Distribute an iOS app to testers with known devices.

development

Distribute a macOS app directly to testers with known devices outside the Apple app store.

When exporting an archive, an appropriate distribution signing certificate and provisioning profile must be available. Depending on the selected method and the way the app was built, these may be found automatically by the exporting tool, or they may need to be specified manually in the export options plist file. Since a provisioning profile is associated with a specific signing certificate, providing just the provisioning profile should be sufficient. The following example demonstrates an ad-hoc export options plist with a manually specified provisioning profile (the key is the app ID and the string associated with the key must match the profile name as set in the Apple developer portal):

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN"
 "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
  <key>method</key>
  <string>app-store</string>
  <key>provisioningProfiles</key>
  <dict>
    <key>com.example.myapp</key>
    <string>iOS ad hoc</string>
  </dict>
</dict>
</dict>
</plist>
```

25.8. Universal Binaries

When targeting Apple platforms, it is common to build for multiple architectures. For a given platform, there may be multiple generations of CPU type, and it would usually be desirable to provide binaries for each architecture. For example, iOS supports some combination of armv7, armv7s, arm64 and arm64e, depending on the SDK used and the deployment version targeted. For macOS, Intel (x86_64) and Apple Silicon (arm64) architectures may need to be supported. Device platforms also typically come with a set of simulators for development and testing. These simulators run on the host machine, so again there may be more than one architecture to build.

There are two main scenarios where it is desirable to build for multiple architectures:

- Producing an archive for the App Store, or a release package for direct distribution. An app bundle should preferably contain slices for each architecture supported by the platform. For example, an iOS app targeting deployment to iOS 11 or later may have both arm64 and arm64e slices in its binaries. A macOS app bundle may include slices for both x86_64 and arm64.
- Producing a framework or XCFramework for other projects to use in their builds. A shared framework targeting iOS 11 or later would likely want to include slices for arm64 and arm64e

in device builds. For simulators, `x86_64` and `arm64` slices should be included.

Historically, a third common scenario was to combine slices for both device and simulator architectures in the one universal binary. With the arrival of the M1 chip, this could no longer support all cases because the `arm64` architecture was supported for both device and simulator platforms, and a universal binary cannot distinguish between those two cases. Apple now recommends including support for only a single platform within a universal binary (device and simulator are considered different platforms). They recommend using XCFrameworks to then bring together the different platform binaries.

25.8.1. Device-only Bundles

For an app bundle without any embedded frameworks, producing a universal binary doesn't require any additional changes to the project's `CMakeLists.txt` files or specifying any new cache variables. It can be achieved just by indicating which architectures to build for on the build command line and overriding the `ONLY_ACTIVE_ARCH` setting. The final app bundle with the combined binaries will be signed using the same settings as if doing a single architecture build. In the following two examples, both commands are essentially equivalent:

```
# Building via CMake
cmake --build . --config Release -- \
    ONLY_ACTIVE_ARCH=NO \
```

```
-arch arm64 \
-arch arm64e
```

```
# Invoking xcodebuild directly
xcodebuild -configuration Release \
ONLY_ACTIVE_ARCH=NO \
-arch arm64 \
-arch arm64e
```

When building via `cmake`, all options after the `--` are passed directly to the underlying build tool (`xcodebuild` when using the Xcode generator). If building from within the Xcode IDE, the `ONLY_ACTIVE_ARCH` build setting for the app bundle's target can be set to `NO` and the build is then performed in the usual way.

When producing an archive, `cmake --build` cannot be used and the `xcodebuild` tool must be invoked directly. The same architecture information needs to be given when producing an archive as well. The following extends the example from [Section 25.7, “Creating And Exporting Archives”](#) to build an archive as a universal binary:

```
xcodebuild archive \
-project MyProject.xcodeproj \
-scheme MyApp \
-archivePath MyApp.xcarchive \
ONLY_ACTIVE_ARCH=NO \
-arch arm64 \
-arch arm64e
```

The archive can then be exported and uploaded in the same way as for a single architecture app.

In practice, it is recommended to use the `-destination` option instead of specifying individual architectures. If building for iOS, the above example could be written in the more recommended way:

```
xcodebuild archive \
    -project MyProject.xcodeproj \
    -scheme MyApp \
    -archivePath MyApp.xcarchive \
    ONLY_ACTIVE_ARCH=NO \
    -destination "generic/platform=iOS"
```

It is very common to see online tutorials and examples recommend setting the architectures in the project's `CMakeLists.txt` files or as cache variables on the `cmake` command line. They set the `CMAKE_OSX_ARCHITECTURES` variable and sometimes also set `CMAKE_XCODE_ATTRIBUTE_ONLY_ACTIVE_ARCH` to false. These have the effect of changing the default behavior of the build to always produce universal binaries with the specified architectures. For example:

```
cmake -G Xcode \
    -D CMAKE_TOOLCHAIN_FILE=../toolchain.cmake \
    -D "CMAKE_OSX_ARCHITECTURES:STRING=arm64;arm64e" \
    -D CMAKE_XCODE_ATTRIBUTE_ONLY_ACTIVE_ARCH:BOOL=NO \
    path/to/source
```

Whether this is desirable will depend on the situation. For day-to-day development, it is likely that the developer will only need to build one architecture. In that case, it would be a nuisance if the project hard-coded the architectures and forced building

universal binaries, since it would build more than the developer needs each time. Instead, the project should omit those details and let the developer decide if they want that behavior by default or not. The above example shows how the developer or an automated script can set the defaults using CMake cache variables alone. One could make the argument that the project could specify the set of architectures, but still leave the developer to choose whether to set `CMAKE_XCODE_ATTRIBUTE_ONLY_ACTIVE_ARCH` or not. If the project does this, it should not force the value of `CMAKE OSX ARCHITECTURES`, but rather set it as a cache variable which can still be overridden if the developer or a script driving the build needs to.

Developers should be aware of a side effect of setting `CMAKE OSX ARCHITECTURES`. With one exception (see next section), the compiler checks will test the architectures listed in that variable instead of just the default architecture. This not only increases the configure time, it can break the configure step if the deployment version used by those compiler checks is incompatible with any of the architectures requested. If not specified globally through a cache variable set before the first `project()` command, the latest version supported by the SDK will be used for the deployment version. In the case of iOS, the deployment version is required to be 10 or less for the `armv7` architecture, which means using any reasonably current Xcode version will break by default without explicitly setting the

deployment version. Adding something like `-DCMAKE OSX_DEPLOYMENT_TARGET=10` to the `cmake` command line may be needed to overcome this situation.

25.8.2. Intel And Apple Silicon Binaries

With a recent CMake and Xcode, producing macOS universal binaries with slices for Intel and Apple Silicon is very similar to the device-only case. In fact, it can be handled the same way, by setting `CMAKE OSX_ARCHITECTURES` to the desired architectures. Instead of listing the individual architectures though, it may be more convenient to use the special Xcode variable `$(ARCHS_STANDARD)`. This will expand to the full set of architectures supported by that particular version of Xcode for the selected SDK (macOS by default). When using at least CMake 3.19.2 and Xcode 12.2, the following is sufficient to produce a universal binary containing Intel and Apple Silicon slices:

```
cmake -G Xcode \
-D "CMAKE OSX_ARCHITECTURES:STRING=$(ARCHS_STANDARD)" \
path/to/source
```

CMake 3.19 also ensures that the initial compiler checks only test the host architecture when targeting the macOS platform with the Xcode generator. This is in contrast to targeting one of the device platforms, where all architectures specified by `CMAKE OSX_ARCHITECTURES` would be tested.

If `CMAKE OSX ARCHITECTURES` is not set, CMake will only build for one architecture by default. The choice may be influenced by the host machine's architecture, by whether CMake is running under Rosetta, and by whether CMake itself has been built as a universal binary. With CMake 3.19.2 or later, the official CMake packages contain universal binaries. The default architecture is then chosen by which slice is being executed. On an Intel host, this will be the Intel slice. On an Apple Silicon host, this will normally be the Apple Silicon slice, but if CMake is being forced to run under Rosetta, it will select the Intel architecture instead. If required, the user can override the default choice by setting a CMake cache variable named `CMAKE APPLE SILICON PROCESSOR` to either `x86_64` or `arm64`. Alternatively, a `CMAKE APPLE SILICON PROCESSOR` environment variable can be used in the same way instead. Avoid CMake versions before 3.19.2 if building on an Apple Silicon host.

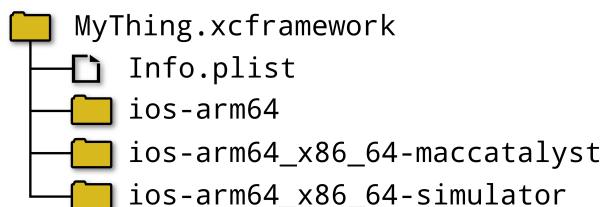
25.8.3. Combined Device And Simulator Binaries

The methods of the previous sections are suitable when only a single SDK is needed for the build. When building for both a device and its simulators, there are two SDKs involved. As mentioned earlier, it used to be commonplace to produce universal binaries supporting both devices and simulators. Apple now actively discourages such practices. CMake provides the `IOS_INSTALL_COMBINED` target property for supporting that

workflow, but it is now deprecated, and it doesn't work at all with Xcode 15 or later. Projects still using that property or its associated `CMAKE_IOS_INSTALL_COMBINED` variable should migrate to using XCFrameworks instead, which are discussed in the next section.

25.9. XCFrameworks

CMake 3.28 and later supports using an XCFramework, which is like an umbrella over a set of platform-specific frameworks usually of the same name. The top level of an XCFramework typically has a structure like the following:



Each directory at the first level is expected to be for a single platform. Below each of those, the platform-specific framework may contain universal binaries supporting multiple architectures for that platform. The `Info.plist` file contains all the details of what each subdirectory provides, acting like a table of contents for tools to find what they need.

In the above example, note how each of the platforms provided relates to iOS, but they are different variants. The device and simulator are considered distinct platforms, as is Mac Catalyst. This is important, because all three may contain binaries that

support the same architecture, such as arm64, so they cannot be merged into a single platform. There's no reason other platforms like macOS, tvOS or watchOS could not also be added to the XCFramework, assuming the platform-specific frameworks support them.

Incorporating an existing XCFramework into a project is very similar to an ordinary framework. An imported library target represents the XCFramework, and that target's IMPORTED_LOCATION property is set to the .xcframework directory:

```
add_library(MyThing SHARED IMPORTED)
set_target_properties(MyThing PROPERTIES
    IMPORTED_LOCATION /path/to/MyThing.xcframework
)
```

See [Section 25.10, “Linking Frameworks”](#) for discussion of how XCFrameworks can be consumed by other targets.

CMake does not currently provide any support for generating an XCFramework, but it can produce the individual frameworks that may go into one. An XCFramework is expected to be created by running `xcodebuild -create-xcframework ...`, listing the set of frameworks it should contain. The Apple documentation describes this process in detail here:

<https://developer.apple.com/documentation/xcode/creating-a-multi-platform-binary-framework-bundle>

25.10. Linking Frameworks

App bundles often link against frameworks (and more recently, XCFrameworks) to re-use functionality. These frameworks could be provided by the SDK, by external providers, or they could be built by the project.

Frameworks and XCFrameworks provided by the Xcode SDK are the most straightforward to handle. Xcode automatically adds the relevant search path for the SDK's frameworks. And if the `XCODE_ATTRIBUTE_CLANG_ENABLE_MODULES` build setting is set to YES, as recommended in [Section 25.5.5, “Other Helpful Build Settings”](#), then auto-linking of SDK frameworks should be enabled. The project then won't need to explicitly link to any SDK frameworks. This is the simplest arrangement and provides arguably the best developer experience.

If auto-linking is not enabled, or it is unable to find a framework for some reason, they can be robustly linked using the generator expression `$<LINK_LIBRARY:FRAMEWORK,FrameworkName>`. This was introduced back in [Section 18.2.2, “Link Library Features”](#) and requires CMake 3.24 or later. It is also the recommended approach for frameworks provided by external parties. Such frameworks might be found using `find_library()` or `find_package()` (see [Chapter 34, *Finding Things*](#)).

If CMake 3.23 or earlier needs to be supported, frameworks can be linked using the form `-framework FrameworkName` instead. To prevent CMake from erroneously merging these options, quoting must be used to keep the option together with the name of the framework to link.

```
# Workaround for CMake 3.23 and earlier
target_link_libraries(MyApp PRIVATE
    "-framework ARKit"
    "-framework HomeKit"
)
```

It gets more complicated when linking a framework built by the project. When creating an archive, Xcode uses completely different paths to build the project compared to an ordinary build. The frameworks built during the archive process will not be at the locations CMake expects them to be. When using CMake 3.19 or later, the linker command lines are constructed in such a way that the full path to the framework isn't used directly. This allows the usual `target_link_libraries()` command to be used and linking will succeed despite the different paths.

For CMake 3.18 and earlier, the wrong path breaks archive builds, so linking needs to be done without referring to the CMake target directly. The `-framework` linker option can once again be used for this, following it with the output name of the framework. This output name is usually the same as the target name, but can be changed with the `OUTPUT_NAME` target property.

Some kind of dependency also needs to be added to ensure the framework is built before the executable is linked. The following example assumes the default output name for simplicity:

```
# Workaround for CMake 3.18 and earlier
target_link_libraries(MyApp PRIVATE "-framework MyFwk")
add_dependencies(MyApp MyFwk)
```

A drawback to losing the direct linking to the CMake target is that usage requirements will not be propagated from the framework target to the executable target. None of the framework's PUBLIC or INTERFACE properties will be applied to the executable target. If these are relevant, the project will need to find another way to achieve this. One method would be to create a separate interface library that both the framework and the executable targets link to. That is fairly fragile and inconvenient, so prefer to use CMake 3.19 or later where possible.

The technique outlined above can be extended to cases where a framework links against another framework:

```
add_executable(MyApp ...)
add_library(MyFwk ...)
add_library(OtherFwk ...)

target_link_libraries(MyFwk PRIVATE "-framework OtherFwk")
target_link_libraries(MyApp PRIVATE "-framework MyFwk")

add_dependencies(MyFwk OtherFwk)
add_dependencies(MyApp MyFwk)
```

The same caveat applies regarding loss of usage requirements propagating from OtherFwk to MyFwk using this approach.

CMake 3.19 introduced support for using Xcode's *Link Binary With Libraries* build phase. A new target property XCODE_LINK_BUILD_PHASE_MODE can be used to control the way CMake links libraries and frameworks into some target types. The default value of this property results in the same behavior as earlier CMake versions, except it no longer embeds paths in linker flags in a way that would break an xcodebuild archive operation. This is why the above fragile workaround can be avoided with CMake 3.19 or later.

A more familiar Xcode experience can be obtained by setting a target's XCODE_LINK_BUILD_PHASE_MODE property to BUILT_ONLY. Any other CMake targets that are built by the project and linked into the target will then be linked via the *Link Binary With Libraries* build phase instead of using raw linker flags. The property can alternatively be set to KNOWN_LOCATION, in which case any item CMake knows the path to will be linked via this build phase, not just CMake targets built by the project. Examples of items that would only be linked via the build phase using KNOWN_LOCATION but not BUILT_ONLY include imported targets and externally provided libraries specified as full paths.



When building frameworks for any of the Apple device platforms, be aware that a long-standing bug in CMake versions before 3.20.1 caused mishandling of a framework's install name. The full absolute path to the framework would be embedded in the framework's binary, but that path wouldn't exist on the device. Any app using that framework would therefore be unable to run. Use CMake 3.20.1 or later to avoid this problem. For further details, see the discussions in [Section 35.2.2, “Apple-specific Targets”](#).

25.11. Embedding Frameworks And Other Things

For shared frameworks, there are further steps to consider beyond linking. The project will need to embed the shared framework into the app bundle so that it is available at run time. CMake 3.20 added direct support for this with the Xcode generator, and CMake 3.28 extended that support to XCFrameworks. Projects can specify a list of frameworks and XCFrameworks to embed with the `XCODE_EMBED_FRAMEWORKS` target property. These can be CMake targets or paths to frameworks (they can also be paths to bare libraries, but that would be unusual and not consistent with normal practice of using frameworks). Xcode will copy the frameworks to a standard location within the bundle by default, extracting the platform-specific framework as necessary in the case of an XCFramework. If required, the project can override this

location with the XCODE_EMBED_FRAMEWORKS_PATH property, but that should not normally be necessary.



A bug in CMake leads to a fatal error if an imported framework *target* is listed in XCODE_EMBED_FRAMEWORKS. Until that bug is fixed, set XCODE_LINK_BUILD_PHASE_MODE to KNOWN_LOCATION, and list the full path to the framework or XCFramework in XCODE_EMBED_FRAMEWORKS. Details of the issue can be found in the following bug report:

<https://gitlab.kitware.com/cmake/cmake/-/issues/25487>

When embedding a framework, the project needs to decide whether it wants the framework headers to be included or not. When embedding into an application bundle, the headers would likely be unnecessary and should be excluded. On the other hand, when embedding into a framework, then it may be reasonable or even expected to include the headers. The project can specify the behavior it wants with the boolean XCODE_EMBED_FRAMEWORKS_REMOVE_HEADERS_ON_COPY property on the target being embedded into. It will apply to all frameworks being embedded into that target.

Similarly, the project will likely want to indicate whether to code-sign the frameworks as part of embedding them. This can be done with the boolean XCODE_EMBED_FRAMEWORKS_CODE_SIGN_ON_COPY property on the target being embedded into. If enabling this feature, ensure that

the frameworks are not signed when they are built or else Xcode will complain about trying to sign an already-signed framework.

The following example demonstrates how to apply the above for an application with a single embedded framework:

```
set(CMAKE_BUILD_WITH_INSTALL_RPATH YES)

add_library(MyFwk SHARED ...)
add_executable(MyApp MACOSX_BUNDLE ...)
target_link_libraries(MyApp PRIVATE MyFwk)

set_target_properties(MyFwk PROPERTIES
    FRAMEWORK           TRUE
    XCODE_ATTRIBUTE_CODE_SIGNING_ALLOWED FALSE
    ...
)

set_target_properties(MyApp PROPERTIES
    # CMake 3.20 or later required
    XCODE_EMBED_FRAMEWORKS           MyFwk
    XCODE_EMBED_FRAMEWORKS_CODE_SIGN_ON_COPY   TRUE
    XCODE_EMBED_FRAMEWORKS_REMOVE_HEADERS_ON_COPY TRUE
    ...
)
```

Further tweaks to the above example are needed to complete the full picture. Target properties like XCODE_ATTRIBUTE_SKIP_INSTALL and XCODE_ATTRIBUTE_INSTALL_PATH need to be set appropriately, as discussed in [Section 25.7, “Creating And Exporting Archives”](#). The binaries also need to be able to find each other at run time, which requires embedding further details in the binaries themselves. That topic is

addressed in [Section 35.2.1, “RPATH”](#) and [Section 35.2.2, “Apple-specific Targets”](#).

Embedding frameworks with CMake 3.19 and earlier is much less straightforward. More manual (and more fragile) steps are needed to achieve a similar result. When using the Xcode generator, a workaround is available by also listing the shared frameworks as sources for the app bundle’s executable target. They need to be specified in an unusual way to support all use cases robustly though, and it gets more complicated when embedding a shared framework built as part of the same project. It is recommended that projects instead use CMake 3.20 or later rather than implementing the unusual workarounds needed to embed frameworks with earlier versions.

Later CMake releases added support for embedding other types of content. Each content type supports a set of `XCODE_EMBED_<type>...` properties that work as discussed above for frameworks. The

`XCODE_EMBED_<type>_REMOVE_HEADERS_ON_COPY` properties are the main exception, as different content types may have different defaults for that property. See the official CMake documentation for specific details on embedding each type of content.

Embedded Content Type	Target Properties	CMake Version
Frameworks	<code>XCODE_EMBED_FRAMEWORKS...</code>	3.20

Embedded Content Type	Target Properties	CMake Version
App extensions	XCODE_EMBED_APP_EXTENSIONS...	3.21
Plugins	XCODE_EMBED_PLUGINS...	3.23
ExtensionKit extensions	XCODE_EMBED_EXTENSIONKIT_EXTENSIONS...	3.26
Resources	XCODE_EMBED_RESOURCES...	3.28
XPC services	XCODE_EMBED_XPC_SERVICES...	3.29

The XCODE_EMBED_RESOURCES properties may at first seem like an alternative to the resource-copying techniques discussed in [Section 25.2.2, “Sources, Resources And Other Files”](#), but it is intended for a different purpose. Only CMake targets or directories can be listed in XCODE_EMBED_RESOURCES, not individual files. Furthermore, no compilation or other automatic handling is performed on resources embedded with XCODE_EMBED_RESOURCES, so it can't be used to add things like Base.lproj or Assets.xcassets directories.

25.12. Limitations

CMake's handling of entitlements is fairly rudimentary. It falls short of the automation that the Xcode IDE provides in the *Signing & Capabilities* target properties tab, where adding or enabling a particular capability also takes care of adding any required frameworks and automatically updates app ID details

as needed. CMake's support still allows all entitlements to be specified, but the process is entirely manual. The project is responsible for defining the entitlements in raw plist format, and it must also manually link in any required frameworks itself. Nonetheless, the handling of entitlements is at least possible without the workarounds or steps becoming too burdensome. Any frameworks required by the entitlements are system-provided, so they do not need to be embedded with the application.

On a more practical, day-to-day level, a word of caution is in order regarding a CMake behavior that isn't always obvious. With the Xcode generator, when CMake writes the Xcode project, it creates a utility target called `ZERO_CHECK`. Most other targets in the project depend on `ZERO_CHECK`, whose sole purpose is to work out if CMake needs to be re-run before doing the rest of the build. Unfortunately, if CMake is re-run by `ZERO_CHECK`, the rest of that build still uses the old project details. This can result in subtle errors due to targets being built with out-of-date settings. Rebuilding a second time should always ensure any such incorrectly built targets are rebuilt properly, but it can be easy to miss. Developers may want to explicitly build the `ZERO_CHECK` target or re-run CMake first after modifying `CMakeLists.txt` files or anything else that would cause CMake to be re-run automatically, or simply build twice.

A more subtle problem related to `ZERO_CHECK` exists if the project contains multiple calls to the `project()` command. Targets defined below the second or later `project()` calls may not have their dependency on `ZERO_CHECK` set up correctly. The `CMAKE_XCODE_GENERATE_TOP_LEVEL_PROJECT_ONLY` variable can be set to true to prevent this problem. This will also have the useful side effect of speeding up the CMake stage. Support for this variable was added in CMake 3.11.

25.13. Recommended Practices

CMake is able to handle projects targeting Apple platforms, but the limitations need to be considered carefully. If an app bundle needs to embed shared frameworks, the framework-embedding features available for the Xcode generator since CMake 3.20 are by far the simplest solution. Use CMake 3.20.1 or later to avoid an RPATH-related bug if targeting iOS, tvOS, or watchOS. Use CMake 3.28 or later if support for XCFrameworks or visionOS is required. Using older CMake versions will require more work to set up, and the steps involved are not intuitive.

If shared frameworks are not needed, then CMake's support from 3.14 onward is potentially enough to automate the process without too much effort, again as long as the Xcode generator is used. For Xcode 12 or later though, CMake 3.19.2 should be considered the bare minimum, while for Xcode 14, at least CMake 3.24 should be used. Other generators such as Makefiles

or Ninja are fine for building an unsigned macOS application, but for other platforms or for signed applications, these generators typically lack some of the features needed to easily produce the final package for distribution. Except for unsigned macOS application development, use of the Xcode generator for Apple development is strongly advised.

Much of the information available in online tutorials and examples is relatively out of date when it comes to using CMake for Apple platforms. In particular, it is very common to see fairly complex toolchain files for iOS, but much of the logic contained in such toolchain files is either questionable or should be moved to the project itself. Developers are strongly encouraged to set their minimum CMake version no lower than 3.14 (ideally 3.24) and take advantage of the improved support for Apple platforms. This makes toolchain files vastly simpler or even unnecessary—just setting `CMAKE_SYSTEM_NAME` to `iOS`, `tvOS`, or `watchOS` would often be sufficient. Logic related to Xcode project settings, device- or platform-specific configuration, etc. should go in the project itself.

One of the things that tutorials and examples often do is specify the target architecture by setting the `CMAKE_OSX_ARCHITECTURES` variable. When using the Xcode generator with projects targeting any of the device platforms, this can prevent the developer from being able to switch freely between device and simulator builds. The target architecture is selectable at build

time when working in the Xcode IDE or when building at the command line. Projects should generally avoid setting `CMAKE OSX ARCHITECTURES` to a specific list of architectures. Instead, let Xcode supply the standard set of architectures based on the selected SDK. When using the Xcode generator, this can be achieved by setting `CMAKE OSX ARCHITECTURES` to `$(ARCHS_STANDARD)`, but it likely already has the correct value by default. If a project wants to specify the architectures for the convenience of its developers, it should do so as a cache variable and not force overwriting an existing value. This will ensure that developers still have control.

When using CMake 3.14 or later, prefer to select the platform by setting `CMAKE SYSTEM NAME` to the appropriate value (e.g. `iOS`, `tvOS`, or `watchOS`). Older tutorials and examples intended for CMake 3.13 or earlier may show `CMAKE OSX SYSROOT` being set instead, but that variable is now handled automatically when setting `CMAKE SYSTEM NAME` with CMake 3.14 or later. Avoid setting `CMAKE OSX SYSROOT` directly.

The minimum deployment version for an app or framework is controlled by the `CMAKE OSX DEPLOYMENT TARGET` cache variable, or perhaps by Xcode-specific target properties like `XCODE ATTRIBUTE IPHONEOS DEPLOYMENT TARGET`. It is the deployment target that ultimately determines whether the application will be able to run on the target, and this is independent of the SDK used to build it (assuming the SDK

supports that deployment target). Since the latest available version of the SDK will be used by default, there is generally little to be gained by trying to use anything else.

Some examples also set `CMAKE_XCODE_ATTRIBUTE_ONLY_ACTIVE_ARCH` to true to only build the currently selected architecture in the Xcode IDE. Again, this is a decision that should typically be left up to the developer at build time rather than being enforced by the project. The default value of `CMAKE_XCODE_ATTRIBUTE_ONLY_ACTIVE_ARCH` depends on whether `CMAKE OSX ARCHITECTURES` has been explicitly set or not, but in general the developer should set this according to their own needs. They can do so within the project in the Xcode IDE, or they can override the project setting when building on the command line with the `-arch` option to `xcodebuild`. The `-arch` option can be specified multiple times to build more than one architecture and have `xcodebuild` generate universal binaries for those architectures automatically. The `-destination` option may be a better alternative than specifying multiple `-arch` options.

Some projects contain targets that link to libraries or frameworks that do not provide universal binaries (i.e. they were only built for a single target platform and architecture). In such situations, it may make sense to restrict the build to just one architecture and platform, since the project can only be built for that specific combination. Similarly, when using

`find_library()` or `find_package()` (covered in [Chapter 34, “Finding Things”](#)), these commands mostly assume they are building for a single platform, so they do not attempt to define the things they find in a way that supports switching between multiple target platforms (except `find_library()`, which supports XCFrameworks with CMake 3.28 or later).

Some projects may choose to use CMake’s install functionality rather than assume Xcode does everything needed for a distributable bundle at build time. The `IOS_INSTALL_COMBINED` target property used to be used for such cases, but that is now deprecated and should be avoided. It does not work with Xcode 15 or later. To produce a framework that supports more than one platform (where device, simulator, and Mac Catalyst are all considered different platforms), an XCFramework should be produced instead. This may require separate builds to produce each platform’s framework, followed by a manual step to run `xcodebuild -create-xcframework ...` to stitch them all together (this may be the part that runs at install time, specified using `install(SCRIPT)` or `install(CODE)`).

The build output from Xcode can be quite verbose, so developers may choose to use a tool like `xcbeautify` or `xcpretty` to hide much of the detail (this is more common for scripted builds to reduce log sizes). Unfortunately, these particular tools will typically hide the output of any CMake custom post-build steps, even if those custom steps cause a build error. When such

custom steps fail, it can be challenging to work out the cause of the failure. Therefore, it is advisable to either avoid the use of these tools, or at least make it easy to switch them off in scripts to help diagnose build problems. The `-quiet` option to the `xcodebuild` command may be an alternative to reduce log output without hiding warnings or errors, but it may also hide too much detail.

26. BUILD PERFORMANCE

For larger projects, build times can be non-trivial, extending out to hours in extreme cases. The impact of a long build time can go beyond mere annoyance, it can drive developer behavior toward undesirable practices and discourage experimentation of new ideas. Long builds can also cause difficulties with continuous integration systems, causing job delays and increasing requirements on hardware resources to cope with the high build volumes.

A variety of factors can contribute to long build times. Poor project structure can lead to the same source files being compiled multiple times with the same settings for different targets. Appropriate use of libraries can usually eliminate such problems, although this may require some refactoring to decouple parts of the code.

Specifying linking relationships between targets that don't actually need to be linked is another source of inefficiency. It reduces the ability of the build tool to execute build tasks in parallel and it expands the set of targets that have to be relinked whenever the dependee is rebuilt.

Exposing private details in public headers of C or C++ projects is another example of how code structure can cause more things to be rebuilt than necessary when a change is made. Reducing coupling between code is one of the most effective ways to reduce incremental build times when making changes during development. The material covered in [Section 22.2, “Source Code Access To Version Details”](#) is a prime example of using code structure to minimize rebuild times.

When seeking to improve build performance, addressing structural problems such as those mentioned above should be the first priority. Specifying correct relationships between entities is a pre-requisite for many other techniques to be robust or effective. With those areas addressed, attention can turn to the techniques discussed in the remainder of this chapter.

26.1. Unity Builds

A unity build (also sometimes referred to as a *jumbo* build) is where source files that would normally be compiled individually are effectively concatenated to produce a smaller number of larger files. If each of the source files includes similar sets of headers, then the compiler would normally be processing those headers multiple times, one for each source file. When the individual sources are concatenated into a single combined source file, the compiler can avoid processing each

header more than once. If the header processing time is non-trivial, this can lead to meaningful savings in build time.

CMake 3.16 and later supports automatically converting a target's sources to a unity build. By setting the `UNITY_BUILD` target property to true, CMake will take care of combining sources into one or more unity sources and building those instead of the originals. This process is transparent to the project, requiring nothing more than enabling the feature via the target property.

CMake does not support unity builds for all languages. CMake 3.16 and later supports them for C and C++, CMake 3.29 added support for Objective-C (`OBJC`) and Objective-C++ (`OBJCXX`), and CMake 3.31 added support for CUDA. The sources for other languages will be left as they are and compiled individually. Sources will only be combined with other sources of the same language.

The `UNITY_BUILD` target property is initialized by the `CMAKE_UNITY_BUILD` variable when the target is created. Setting that variable to true can be an effective way to enable unity builds across the entire project, although it should usually be a cache variable to allow developers to easily switch it off if they need to. Making it a non-cache variable could cause problems in hierarchical builds, since the developer would not be able to easily disable unity builds in dependency subprojects.

In practice, it may take more than simply turning on the unity build feature to get a worthwhile or even buildable result. There are some restrictions to be aware of when combining source files in this way:

- Source files often define their own local file scope entities, such as types, variables, pre-processor macros and so on. When each source file is built individually, these file-scope entities are kept separate, but when combined in a unity build, they can clash between files.
- Source files may already be quite large. This can be especially common for sources produced by code generation tools. If combining sources results in an excessively large unity source file, the compiler may run out of memory or exceed other internal limits during processing.

Strategies like using a naming convention to avoid duplicating symbol names of file scope entities can help with the first of the above points. Sometimes, that may not be practical or there may be other constraints preventing such changes. For the second point, large source files should be excluded from unity builds, since there is little to gain when they are already of a substantial size.

CMake provides a few controls which may help in situations like the above. If a small number of sources are problematic, they can be excluded from being combined with other sources

on a case-by-case basis. This is done by setting the SKIP_UNITY_BUILD_INCLUSION property on the problematic source files to true. Those sources will then never be combined with others in a unity build. Note that CMake already excludes any source file which isn't normally compiled (e.g. header files) or any source file which has any of the following source properties defined:

- COMPILE_OPTIONS
- COMPILE_DEFINITIONS
- COMPILE_FLAGS
- INCLUDE_DIRECTORIES

For resolving name clashes, especially for symbols in C++ anonymous namespaces, the UNITY_BUILD_UNIQUE_ID target property available with CMake 3.20 or later may be useful. Its official documentation contains a description of the types of problems it is intended to solve, details of its usage and a simple example. In general though, prefer to rework the source code to avoid the name clashes if possible, as it will be simpler and much easier to understand.

With CMake 3.18 or later, the UNITY_BUILD_MODE target property specifies the method for choosing which sources to combine together. If defined, this property may hold the values BATCH or

GROUP. If the property is not defined or if using CMake 3.17 or earlier, the behavior is the same as BATCH.

26.1.1. BATCH Mode

In BATCH mode, CMake combines sources based on the order in which they were added to the target. The `UNITY_BUILD_BATCH_SIZE` target property controls the maximum number of sources which may be combined. The first `UNITY_BUILD_BATCH_SIZE` files for a particular language will be combined into one unity source, the next `UNITY_BUILD_BATCH_SIZE` sources will be combined into another unity source, and so on until all original sources have been included or skipped for reasons discussed above. This property is initialized by the `CMAKE_UNITY_BUILD_BATCH_SIZE` variable if that variable is defined, otherwise it is given an initial value of 8.

This method is suitable when none of the sources are particularly big. If some sources are much larger than others, the large sources can be listed away from each other as a crude way of minimizing the likelihood that they will be combined together. This is not particularly robust, but may be good enough for some projects.

```
option(CMAKE_UNITY_BUILD "Enable unity builds")
add_executable(MyApp
    someBigSource.cpp
    little1.cpp)
```

```

little1.h          ①
little2.cpp
little2.h          ①
# -----
anotherBigSource.cpp
customFlags.cpp    ②
mustBeSeparate.cpp ③
small1.cpp
# -----
differentLang1.c
differentLang2.c
)
set_target_properties(MyApp PROPERTIES
    UNITY_BUILD_BATCH_SIZE 3
)
set_source_files_properties(customFlags.cpp PROPERTIES
    COMPILE_DEFINITIONS
    COMPVER=${CMAKE_CXX_COMPILER_VERSION}
)
set_source_files_properties(mustBeSeparate.cpp PROPERTIES
    SKIP_UNITY_BUILD_INCLUSION YES
)

```

- ① Headers are not compiled, so they are not added to unity sources.
- ② Source files with certain source properties set are automatically excluded from being added to unity sources.
- ③ Source file explicitly excluded from unity sources due to having its SKIP_UNITY_BUILD_INCLUSION source property set to true.

The two big source files someBigSource.cpp and anotherBigSource.cpp are kept separate by limiting the unity batch size to 3 and ensuring that there are enough source files listed between these two that they are at least 3 sources apart in the source list. CMake will combine someBigSource.cpp, little1.cpp and little2.cpp into the first unity source, then anotherBigSource.cpp and small1.cpp into a second unity source.

Note also that `differentLang1.c` and `differentLang2.c` are not combined with the other C++ sources, they are placed in their own unity source because they are a different language. The actual names of the unity sources are an internal implementation detail, projects should not attempt to refer to them directly.

26.1.2. GROUP Mode

When more precise control is needed over how sources should be combined, GROUP mode is more appropriate. When `UNITY_BUILD_MODE` is set to GROUP, each source file in the target needs to specify the name of the unity group it belongs to with the `UNITY_GROUP` source file property. Any source that does not define this property will not be added to a unity source and will be compiled directly (i.e. as though unity builds were not enabled).

No batch size limits are applied to unity groups, the `UNITY_BUILD_BATCH_SIZE` property is ignored. The project is in full control over which sources are combined. There could be different strategies for how the project groups sources. It could be based on file size, on the set of headers that are included, on keeping related code together to maximize optimization opportunities, etc. The following shows an alternative way of grouping the sources of the previous example:

```
option(CMAKE UNITY_BUILD "Enable unity builds")
add_executable(MyApp
```

```

someBigSource.cpp
anotherBigSource.cpp
little1.cpp
little1.h
little2.cpp
little2.h
small1.cpp
customFlags.cpp
mustBeSeparate.cpp
differentLang1.c
differentLang2.c
)
set_source_files_properties(customFlags.cpp PROPERTIES
    COMPILE_DEFINITIONS
        COMPVER=${CMAKE_CXX_COMPILER_VERSION}
)
set_target_properties(MyApp PROPERTIES
    UNITY_BUILD_MODE GROUP
)
set_source_files_properties(
    little1.cpp little2.cpp small1.cpp
    PROPERTIES UNITY_GROUP small
)
set_source_files_properties(
    differentLang1.c differentLang2.c
    PROPERTIES UNITY_GROUP different
)

```

In the above, only some of the source files have a group defined. Those that don't will be compiled individually, which is convenient in this case since `someBigSource.cpp`, `anotherBigSource.cpp` and `mustBeSeparate.cpp` should all be excluded from unity builds. The `customFlags.cpp` source is also excluded (it has to be since it has its `COMPILE_DEFINITIONS` source property set).

As the above example shows, the project can sometimes provide more appropriate grouping than the BATCH method. The extra verbosity and maintenance burden it introduces should be weighed against any overall gain in build performance.

26.2. Precompiled Headers

Another technique that can sometimes improve build times is to employ precompiled headers to cache some of the work done by the compiler. For cases where header file processing is a non-trivial contributor to build times, this technique can lead to a worthwhile saving.

Most major compilers support precompiled headers, but there are significant differences between the various implementations. CMake 3.16 introduced direct support for precompiled headers which takes away the burden of having to manage these differences in each project. The primary way to instruct CMake to set up precompiled headers for a target is with the `target_precompile_headers()` command. This follows the same form as all the other `target_...()` commands:

```
target_precompile_headers(targetName
    <PRIVATE|PUBLIC|INTERFACE> headers...
    [<PRIVATE|PUBLIC|INTERFACE> headers...] ...
)
```

The PRIVATE, PUBLIC and INTERFACE keywords have their usual meaning, specifying whether the headers that follow the

keyword should be applied to the specified target and/or to things linking against the target. PRIVATE headers are appended to a target property called PRECOMPILE_HEADERS, whereas INTERFACE headers are appended to the INTERFACE_PRECOMPILE_HEADERS property. PUBLIC headers are appended to both properties. CMake uses these properties to build up a set of headers that will be force-included when compiling sources for the specified target or things that link against it, as appropriate. The method used to accomplish this varies between compilers, but from a project perspective, an important point is that no source changes are required. CMake will generate files and use command line arguments to make compilers include the specified headers rather than requiring sources to be modified to explicitly include any special header.

In typical scenarios, precompile headers should be specified as PRIVATE. The main reason for supporting non-private relationships for a precompile header is to support interface libraries whose reason for existence is to collect together commonly used compiler definitions, options and so forth. Targets opt in to having these applied to themselves by linking to the interface library. The following example demonstrates such an arrangement:

```
add_library(MyCommonPCH INTERFACE)

target_precompile_headers(MyCommonPCH INTERFACE
<iostream>
<vector>
```

```

<algorithm>
[["myAlgo.h"]]
)
target_include_directories(MyCommonPCH INTERFACE
    $<BUILD_INTERFACE:${CMAKE_CURRENT_LIST_DIR}>
)

add_library(ShipBuilder ships.cpp)
add_library(CarBuilder cars.cpp)

target_link_libraries(ShipBuilder PRIVATE MyCommonPCH)
target_link_libraries(CarBuilder PRIVATE MyCommonPCH)

```

In the list of headers provided to `target_precompile_headers()`, note how lua-style brackets have been used to ensure that the quotes are included as part of the header. The delimiters around each header name are significant, as they affect how that header is treated when CMake forms the internal files used to collect the headers to be precompiled. Where a header is surrounded by angle brackets or quotes, they are used as is. The effect is as though they were preceded by `#include` and used verbatim. Such headers are expected to be found on the header search path for the source file that is using them. This is why the example also adds `CMAKE_CURRENT_LIST_DIR` to the header search path for things that link against `MyCommonPCH` (see [Section 16.3.1, “Building, Installing, And Exporting”](#) for why the `$<BUILD_INTERFACE:...>` generator expression is also used here).

Where there are no angle bracket or quote delimiters at all, the `target_precompile_headers()` command will assume headers are paths relative to the current source directory and will convert

them to an absolute path if they are not already absolute. This would make such interface libraries unsuitable for being installed, since they would have paths from the build tree embedded in their interface properties.

A potentially simpler and more efficient way to define a common set of precompile headers is to use an alternative form of the `target_precompile_headers()` command:

```
target_precompile_headers(targetName
    REUSE_FROM otherTarget
)
```

The `REUSE_FROM` keyword instructs the command to apply the precompile headers from `otherTarget` to `targetName` as well. Note that this is not copying the precompile header settings to `targetName`, it is literally reusing the precompile header configuration from `otherTarget`, including the internal files generated for it. This can lead to fewer generated files compared to using an interface library to share common settings between targets, potentially resulting in lower disk space being used. In projects with many targets sharing the same precompiled header, the savings can be significant.

An important prerequisite for the `REUSE_FROM` form is that both targets must use a compatible set of compiler flags, definitions, etc. Without this restriction, the precompiled header from `otherTarget` might be different to what should have been

generated for `targetName` with its own unique settings. Compiler flags or definitions which do not affect the precompiled header can potentially be different between the two targets, or omitted in one but not the other. Projects should aim to minimize such cases to avoid potential compiler warnings.

26.3. Build Parallelism

Each CMake generator has its own corresponding build tool which schedules and executes the required tasks at build time. Most of those build tools support executing tasks in parallel. Some build in parallel by default, while others require an explicit command line flag to turn it on. Where the generator chosen might not be known, or where it may be inconvenient to know or specify it, the generator-independent `--parallel` flag or its shorter equivalent `-j` can be used.

```
cmake --build <someDir> --parallel [limit]
cmake --build <someDir> -j [limit]
```

The optional `limit` usually means an upper limit on the number of parallel tasks, but the precise meaning is up to the build tool. If no `limit` is specified, again the behavior is generator-dependent.

In practice, while the `--parallel` flag may seem like a convenience, it is usually not the best solution. It is often not needed at all. Where a generator doesn't build in parallel by

default, a better result can sometimes be achieved by passing more appropriate tool-specific options directly. Since the optimal choice for each generator is likely to be different, there is typically not much to gain by trying to use the `--parallel` flag.

26.3.1. Makefiles Generators

Makefiles generators do not build in parallel by default. When invoking the build tool directly (for example, typing `make`), it can be enabled with the `-j` option. It is usually followed by a number specifying the maximum number of tasks allowed to execute at once. CMake's own `--parallel` option maps directly to the native build tool's `-j` option. The following are therefore all equivalent (options following `--` are passed directly to the native build tool):

```
cmake --build . --parallel 8
cmake --build . -j 8
cmake --build . -- -j 8
make -j 8
```

If the number after `-j` or `--parallel` is omitted, some build tool implementations will halt with an error, but most will just use no limit at all. For any non-trivial build, running with no limit is likely to overwhelm the system with too many parallel tasks.

Most Makefiles build tools also support another option, `-l <limit>`. This option is intended to limit the number of parallel tasks based on the system load. It would not normally be used

without `-j`. In practice, a load-based limit via `-l` usually performs very poorly. There is typically an almost unconstrained initial spike before the measured system load can ramp up, so the start of the build again typically overwhelms the system with too many tasks.

Unless there is a compelling reason that requires a Makefile-based generator to be used (e.g. using an IDE that doesn't support any other type of build tool), prefer to use the Ninja generator instead. Ninja has better behavior by default, offers better overall build performance, and can be thought of as having a superset of the capabilities available with Makefiles generators.

26.3.2. Ninja Generators

The Ninja and Multi-Config Ninja generators offer the best performance and broadest platform support among all the generators supported by CMake. They build in parallel by default, automatically select an appropriate upper limit for the host machine, and are supported on every major platform.

While Ninja supports the same `-j` and `-l` flags as the Makefiles build tools, they are not usually needed. CMake's `--parallel` option maps to `-j`, but there should be little reason to use it either. Ninja has its own algorithm for selecting the optimal value for the upper limit, and this is usually different to the number of logical CPUs on the host machine.

A key strength of Ninja is its global view of the whole build. This enables it to schedule parallel tasks very efficiently. Scheduling is determined only by the actual dependencies between tasks rather than any artificial limitations due to directory or project structure.

A capability unique to Ninja generators is the ability to assign tasks to *job pools*. Each job pool is assigned a parallel task limit, which is applied in addition to the global limit. The number of tasks from that pool that can execute simultaneously is restricted to the pool limit or less. Ninja schedules tasks across all job pools and tasks with no job pool, and it still ensures the total number of tasks doesn't exceed the global limit.

For example, consider a project that defines a set of targets and assigns them to job pool A with a limit of 5. It defines a second set of targets and assigns them to job pool B with a limit of 3. Lastly, it defines another set of targets, this time not assigned to any job pool. If the build is executed using `ninja -j 16`, it will be forced to have a global limit of 16 tasks that can run in parallel. At any time during the build, there will never be more than a total of 16 tasks running at once. In addition, there will never be more than 5 tasks from job pool A executing at once, and never more than 3 tasks from job pool B executing at once. Ninja will utilize all 16 of the available slots as much as possible, balancing the constraints between the pools and unpooled tasks throughout the build.

The first step to using Ninja job pools with CMake is to define the set of job pools and their limits. These are defined in the JOB_POOLS global property, which is expected to hold a list of pool_name=limit items. It is empty by default. The following example defines two job pools, comp and link:

```
set_property(GLOBAL PROPERTY JOB_POOLS  
    comp=10  
    link=4  
)
```

If the JOB_POOLS global property is not defined, the contents of the CMAKE_JOB_POOLS variable will be used instead. This may be a more desirable way to specify the pools, since pool limits often depend on the host machine's capabilities and need to be under the developer's control. The job pool details can then be set on the command line or in a user preset. Note though that this variable will only have an effect if the project does not set the JOB_POOLS global property.

```
cmake -G Ninja "-DCMAKE_JOB_POOLS=comp=10;link=4" ...
```

The second step is to assign targets to pools. For library and executable targets, compilation and linking tasks can be directed to use different pools. They are assigned using the JOB_POOL_COMPILE and JOB_POOL_LINK target properties. These properties are initialized by the values of the CMAKE_JOB_POOL_COMPILE and CMAKE_JOB_POOL_LINK variables, which can be specified by the developer rather than the project:

```
cmake -G Ninja \
"-DCMAKE_JOB_POOLS=comp=10;link=4" \
-DCMAKE_JOB_POOL_COMPILE=comp \
-DCMAKE_JOB_POOL_LINK=link \
...
```

In practice, it would be rare to use a job pool for compilation tasks. Those tasks normally form the vast majority of all tasks, so it is usually more convenient to control them by the global limit. A job pool for linker tasks is potentially more commonly useful though. When a compiler cache is used (see [Section 26.5, “Compiler Caches”](#)), it is not unusual for all compiler tasks to finish very quickly, leaving all the linker tasks to execute together at the end of the build. Linker tasks typically take much more memory. On machines with a high number of CPUs but only modest RAM, this can result in the linker tasks spilling over into swap, potentially even exhausting all memory in the system. The developer may therefore want to use a job pool to limit just the linker tasks without constraining the other non-linker tasks.

```
cmake -G Ninja \
-DCMAKE_JOB_POOLS=link=4 \
-DCMAKE_JOB_POOL_LINK=link \
...
```

In the absence of any other data for machine hardware specifications, a good starting point would be to aim for at least 1.5-2Gb of RAM per logical CPU. If the host machine has less than that, there is increased risk that linker task stacking as

discussed above could significantly degrade the machine's build performance. Linker job pools may provide a means of mitigation for machines that have lower RAM-to-CPU ratios.

With CMake 3.15 or later, custom targets and custom commands can also be assigned to job pools. These have no corresponding variable, they can only be set directly in the `add_custom_command()` and `add_custom_target()` calls with the `JOB_POOL` keyword. Thus, the use of job pools with custom targets and commands is effectively hard-coded into the project. This may limit the developer's ability to customize other job pools used by the build if not handled carefully.

The following example shows one way to preserve developer control, but still apply settings that allow the build to work out-of-the-box if the developer doesn't provide any job pool details. The example represents a scenario where source code is generated by some tool and where that tool is expensive to run, either in terms of memory, licensing, or some other measure. The job pool allows the number of concurrent invocations of the costly tool to be limited to no more than 2 without limiting the parallelism of the rest of the build.

```
if(NOT DEFINED CMAKE_JOB_POOLS)
    set_property(GLOBAL PROPERTY JOB_POOLS costly=2)
endif()

add_library(CostlyThings)

foreach(src IN ITEMS a.cpp b.cpp c.cpp ...)
```

```

set(genSrc ${CMAKE_CURRENT_BINARY_DIR}/gen_${src}
add_custom_command(
    OUTPUT ${genSrc}
    COMMAND costly_generation --output ${genSrc}
    JOB_POOL costly
)
target_sources(CostlyThings PRIVATE ${genSrc})
endforeach()

```

26.3.3. Visual Studio Generators

Makefiles and Ninja generators have a fairly straightforward model for executing build tasks in parallel. They schedule tasks according to the dependencies between the tasks. They don't typically have any artificial constraint between targets unless the project adds such constraints.

Visual Studio generators use MSBuild as their build tool. The interaction between MSBuild and the compiler is more complex than for the Makefiles and Ninja generators. Both the build tool and the compiler have their own support for parallel execution.

- The `cl` compiler's parallel execution is enabled by adding the `/MP` compiler flag. It controls whether source files within a single target can be compiled in parallel.
- The build tool's parallel execution is enabled by adding `/m` to the MSBuild or `cmake --build` command line (the latter after `--` to denote options meant for MSBuild, not `cmake`). If building inside the Visual Studio IDE, this is enabled by default. This option controls whether *targets* can be built in parallel. It

does not control parallel compilation of sources *within* a single target.

Both `/MP` and `/m` can optionally be followed by a number specifying the upper limit on the number of parallel tasks. When no such number is provided, they each default to the number of available logical processors.

For a CMake project with a small number of targets that each have many sources, adding the `/MP` compiler flag would typically give a significant performance gain. For a project with many targets where each target has relatively few sources, the `/m` build tool flag should give the bigger performance boost. It may be tempting to enable both to try to get the best of both worlds, but this can result in severe over-commitment of system resources. For a system with N logical cpus, it may result in up to $N \times N$ tasks running in parallel. This can slow down overall performance, or even crash the host machine in severe cases.

In practice, projects often have some targets with many sources and other targets with very few. Projects with a few main targets but many test executables match this pattern. In such cases, developers have to go through a trade-off exercise, experimenting to determine whether `/MP` or `/m` gives the better overall build throughput. With either choice, there will often be periods during the build where the CPU is under-utilized.

With Visual Studio 2019 update 16.3 or later (16.9 or later recommended), a new *Multi-ToolTask* scheduler is available which behaves more like Ninja. It has the ability to schedule and limit tasks both within and across targets (when the /m option is also used). Enabling the Multi-ToolTask scheduler disables /MP automatically, since it takes over scheduling tasks within a target.

The Multi-ToolTask scheduler can be enabled using environment variables or with Visual Studio project properties. If using environment variables, they need to be set when running MSBuild. The environment variables should be set as follows:

UseMultiToolTask=true

This enables the new scheduler, but on its own would still allow over-commitment of system resources.

EnforceProcessCountAcrossBuilds=true

This prevents resource over-commitment when the new scheduler is enabled.

In practice, using environment variables may not be as convenient as setting Visual Studio project properties. With CMake 3.13 or later, Visual Studio project properties can be set using the CMAKE_VS_GLOBALS CMake variable. It should hold a list of key=value items which will be added to the Visual Studio

project for each target. Developers can set the `CMAKE_VS_GLOBALS` variable when invoking CMake:

```
cmake -G "Visual Studio 16 2019" ... \
      "-"
CMAKE_VS_GLOBALS=UseMultiToolTask=true;EnforceProcessCountAcrossBuilds=true"
```

It can also be set by the project, in which case it should be defined before any targets are created, ideally right after the first `project()` call:

```
cmake_minimum_required(VERSION 3.13)
project(MyThings)

# NOTE: Not ideal, see text following this example
set(CMAKE_VS_GLOBALS
    UseMultiToolTask=true
    EnforceProcessCountAcrossBuilds=true
)

# Add targets here, etc.
```

One problem with hard-coding `CMAKE_VS_GLOBALS` as shown in the above example is that it prevents the developer or driving script from selecting a different parallelism strategy. In fact, because it discards any previous contents of `CMAKE_VS_GLOBALS`, it prevents setting *any* custom Visual Studio project properties from outside the CMake project. Developers may want to be able to modify this variable for their own custom purposes. In order to safely preserve any existing settings, a more careful approach is needed:

```
if(NOT CMAKE_VS_GLOBALS MATCHES
  "(^|;)UseMultiToolTask=")
  list(APPEND CMAKE_VS_GLOBALS
    UseMultiToolTask=true
  )
endif()

if(NOT CMAKE_VS_GLOBALS MATCHES
  "(^|;)EnforceProcessCountAcrossBuilds=")
  list(APPEND CMAKE_VS_GLOBALS
    EnforceProcessCountAcrossBuilds=true
  )
endif()
```

Once `CMAKE_VS_GLOBALS` is set using one of the above methods, add the `/m` option if running the build from the command line to make best use of available CPUs. The following are equivalent:

```
cmake --build <path> -- /m
```

```
msbuild /m
```

A clear advantage of using `CMAKE_VS_GLOBALS` over environment variables is that the developer can build within the Visual Studio IDE, or from the command line, and both will use the Multi-ToolTask scheduler without any additional steps. No changes to user- or system-wide settings are needed, and the IDE or command prompt do not need to be started or set up any differently to normal.

Multi-ToolTask is expected to give superior build throughput for any decent size project, with one exception. If there are only a

few targets, and those targets all have many sources, then using just the compiler parallelism (/MP) alone may be slightly faster in some cases. This is because the cost of starting a new process under Windows is quite high. The /MP-based approach re-uses processes, whereas Multi-ToolTask will create a new process for each source file compilation. Even for such projects though, using /MP may exclude using other methods that could otherwise drastically reduce build times (see [Section 26.5, “Compiler Caches”](#)).

26.3.4. Xcode Generator

Projects using the Xcode generator can be built within the Xcode IDE or from the command line. A command line build uses `xcodebuild` as the build tool. The parallel building behavior is quite similar to Visual Studio’s Multi-ToolTask arrangement, except that building in parallel is already the default behavior.

Inter-target parallelism can be enabled by adding the `-parallelizeTargets` option to `xcodebuild` (analogous to the `/m` option for Visual Studio generators). If the project has properly expressed dependencies between targets, there is little reason not to enable this. In fact, when CMake is generating for the Xcode new build system (the default behavior when using Xcode 12 or later), `cmake --build` automatically adds the `-parallelizeTargets` option when it invokes `xcodebuild`.

The global limit on parallel tasks defaults to the number of logical CPUs. This can be overridden by passing the `-jobs` option to `xcodebuild`. That should rarely be needed though, as the default limit will typically be appropriate.

26.4. Optimizing Build Dependencies

Accurately specifying dependencies is a critical piece of both build robustness and build efficiency. So far, discussions have mostly focused on ensuring no dependencies are missed. If dependencies are under-specified, stale build artifacts may be used. In parallel builds, race conditions can also occur. On the other hand, if dependencies are over-specified, consequences may include reduced build parallelism, and rebuilding more things than necessary when some build inputs change. This section focuses on reducing conservatism in the build by avoiding over-specified dependencies.

Ordinarily, a target's dependencies must be built before the target itself, but there are cases where this constraint can be relaxed, or even removed entirely. Consider the following example:

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.9)
project(simple LANGUAGES CXX)

add_library(Func func.cpp)
```

```
add_executable(App main.cpp)
target_link_libraries(App PRIVATE Func)
```

func.cpp

```
int func() { return 42; }
```

main.cpp

```
int func();
int main() { return func(); }
```

Makefiles generators will compile `func.cpp`, create the `libFunc.a` static archive library, compile `main.cpp` and finally link the `App` executable. None of these tasks can be performed in parallel, they must be performed in that order.

Since CMake 3.9, the Ninja generator recognizes that `main.cpp` can be compiled without waiting for `libFunc.a` to be built. Compilation does not depend on `libFunc.a` in this case. This relaxation is only possible when there are no custom commands associated with the `Func` target. Even with this mild condition, the improved parallelism that the Ninja generator can achieve as a result of this relaxation can be significant for some projects.

CMake 3.19 added support for the `OPTIMIZE_DEPENDENCIES` target property. When this is set to true on a static or object library target, it allows further relaxation under certain conditions (for all CMake generator types, not just Ninja). Consider this example:

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.19)
project(moreRelaxed LANGUAGES CXX)

add_library(MyStatic STATIC func.cpp)
add_library(MyShared SHARED impl.cpp)
target_link_libraries(MyStatic PRIVATE MyShared)

set_target_properties(MyStatic PROPERTIES
    OPTIMIZE_DEPENDENCIES YES
)
```

func.cpp

```
int impl();
int func() { return impl(); }
```

impl.cpp

```
int impl() { return 42; }
```

In this case, the `MyStatic` target can technically be fully built without having to compile `impl.cpp` or produce a shared library for `MyShared` at all. This is because `MyStatic` is a static library, so it doesn't need to actually link to `MyShared`. The relationship between the two library targets still exists and will be applied to any other target that links to `MyStatic`, but it doesn't affect building `MyStatic` itself.

This particular dependency relaxation can only be performed when CMake can be certain that building the static or object library does not require the dependency to be built. Examples of things that prevent this from occurring include:

- An explicit `add_dependencies()` command specifying the dependency.
- A custom command attached to the dependency.
- A generated source file for the static or object library whose custom command depends on the dependency.
- The dependency containing any generated source files.
- The dependency uses a language that produces side effects and that language is relevant to the static or object library. For more detail on this particular aspect, see the discussion in the official CMake documentation for the `OPTIMIZE_DEPENDENCIES` target property.

Rather than explicitly specifying the `OPTIMIZE_DEPENDENCIES` property on each target, it will usually be more convenient to set the `CMAKE_OPTIMIZE_DEPENDENCIES` variable project-wide. This variable is used to initialize the `OPTIMIZE_DEPENDENCIES` property when creating targets.



CMake 3.27 and older have a bug which prevents this feature from working with the Ninja generator when some dependencies are shared libraries. Projects can still safely enable the feature, it's just that the dependencies won't be optimized for affected scenarios. The bug was fixed in CMake 3.28.

The `DEPENDS_EXPLICIT_ONLY` option of `add_custom_command()` provides another opportunity for optimizing the build dependencies. Consider the following example:

```
# The find_package() command is covered later in the
# Finding Things chapter. Here, it provides the
# Python3::Interpreter target.
find_package(Python3 REQUIRED COMPONENTS Interpreter)

add_custom_command(
    OUTPUT ${CMAKE_CURRENT_BINARY_DIR}/generated.cpp
    COMMAND Python3::Interpreter
        ${CMAKE_CURRENT_SOURCE_DIR}/code_generator.py
        --input ${CMAKE_CURRENT_SOURCE_DIR}/template.yaml
        --output ${CMAKE_CURRENT_BINARY_DIR}/generated.cpp
    DEPENDS
        Python3::Interpreter
        ${CMAKE_CURRENT_SOURCE_DIR}/code_generator.py
        ${CMAKE_CURRENT_SOURCE_DIR}/template.yaml
)
add_library(Algo algo.cpp)
add_executable(MyApp
    main.cpp
    ${CMAKE_CURRENT_BINARY_DIR}/generated.cpp
)
target_link_libraries(MyApp PRIVATE Algo)
```

In this particular example, assume the Python code generator is known to only depend on the things listed in its `DEPENDS` arguments. It doesn't use `Algo` or any of `Algo`'s build outputs. There's no reason the code generator can't be run before building any other part of the project. However, with the above logic as presented, the build will wait for the `Algo` target to be built before running the code generator. This is because when

the generated.cpp file is added to the MyApp target, CMake conservatively adds the MyApp target's dependencies to the custom command used to create generated.cpp as well. If algo.cpp takes a very long time to compile, the code generator would be held up a long time too, which would also delay compiling the generated code.

With CMake 3.27 or later, the DEPENDS_EXPLICIT_ONLY option can be added to the add_custom_command() call to address this situation. This option tells CMake that the DEPENDS arguments fully specify all things the custom command depends on. No dependencies from a target the generated file is added to should be applied to the custom command. Therefore, if DEPENDS_EXPLICIT_ONLY is added to the add_custom_command() in the above example, the code generator will be able to run immediately without waiting for Algo to be built. This dependency optimization is currently only implemented for the Ninja generator. When using other generators, the DEPENDS_EXPLICIT_ONLY option can still be specified, but it will have no effect.

CMake also provides a CMAKE_ADD_CUSTOM_COMMAND_DEPENDS_EXPLICIT_ONLY variable which can be used to define the default behavior if DEPENDS_EXPLICIT_ONLY is not given. A project may set that variable to true instead of updating all calls to add_custom_command(). This may be desirable if the project must

support CMake versions earlier than 3.27. Care must be taken for the scope of the variable to ensure it doesn't apply to any `find_package()` or `FetchContent_MakeAvailable()` calls which might bring in project code not expecting the `DEPENDS_EXPLICIT_ONLY` behavior.

26.5. Compiler Caches

Significant improvements in build performance can often be achieved by using a compiler cache. These caches store built object files. If the compiler is asked to compile the exact same source file with the same set of flags, headers, and toolchain, the object file can be retrieved directly from the cache instead of having to be compiled again. A well-configured compiler cache can be one of the most effective ways to reduce build times.

Ccache is one of the most commonly used compiler cache tools when using GCC, Clang or any compiler that claims to be compatible with either of those. With Ccache 4.6.1 or later, the Visual Studio compilers are also supported. Ccache works in one of two ways:

- Replace the location of the default system compilers with symlinks to itself. Many Linux distributions employ this arrangement.
- Precede the normal compiler command line with `ccache`.

The first option provides compiler caching as the default system-wide behavior, but it has drawbacks. The main limitation is that it doesn't allow the developer to choose which compiler to use, instead locking in the choice of using the default system compiler. In many cases, the default compiler is quite old, so developers frequently want to use newer compilers installed in other locations. Another limitation is that it requires administrator access to set up if the system doesn't install Ccache that way by default. This method is also not suitable on Windows.

A much more flexible approach is to precede the usual compiler command line with `ccache`. This method allows any supported compiler to be used, not just the system default. No system-wide change is required, so the technique can be employed freely by any user. Depending on the generator used, slightly different approaches are needed to invoke Ccache appropriately. These are discussed in the subsections further below.

26.5.1. Ccache Configuration

Certain Ccache options should be set to ensure safe and efficient caching behavior. Various `CCACHE_...` environment variables can be used to set these on a per-project basis. The supported variables are detailed in the Ccache documentation, but some more important ones are:

`CCACHE_SLOPPINESS`

If precompiled headers are enabled, it is important to set this option to `pch_defines, time_macros`. The *Precompiled headers* section of the Ccache documentation explains why these settings are needed. For improved cache hit performance, it may also be desirable to add `include_file_mtime` and `include_file_ctime` to the list of sloppiness options. This comes with a theoretical risk of a race condition, but for typical scenarios, that race condition is highly unlikely (files included by the preprocessor would have to be updated while the source is being compiled). Consult the Ccache manual for details before deciding whether to add `include_file_mtime` and `include_file_ctime` to the sloppiness options.

CCACHE_PREFIX

Ccache supports being used in conjunction with another compiler command wrapper. Popular examples include tools such as `distcc`, `icecc` and `sccache-dist` which distribute compilation across multiple machines to reduce build times. When chaining multiple compiler wrappers, it is recommended to have `ccache` as the first wrapper invoked and then specify the other wrapper through the `CCACHE_PREFIX` environment variable (e.g. `CCACHE_PREFIX=distcc`). `ccache` then handles chaining to the second wrapper if the result of the compile command is not already in its cache.

If using a version of Ccache older than 3.3, set `CCACHE_CPP2=true` to avoid spurious warnings with some compilers (see the Ccache manual for details). Upgrading to a newer Ccache instead should be preferred as a better solution.

Developers should also become familiar with Ccache's different modes of operation. Direct mode, preprocessor mode, and depend mode all have their advantages and restrictions. Direct mode is the default. Pay special attention to interaction with features like precompiled headers, as problems can sometimes occur. As one example, depend mode is advisable when using precompiled headers with Clang to avoid issues with timestamps when switching branches, but changing compiler definitions may not be handled correctly in depend mode. Recent Ccache documentation also states that the `-fno-pch-timestamp` compiler flag must be used and is only recognized by Ccache 4.0 or later. As this flag is specific to the Clang compiler, it must be preceded by `-Xclang`, so it needs to be protected from flag de-duplication (see [Section 16.5, “De-duplicating Options”](#)).

```
foreach(lang IN ITEMS C CXX OBJC OBJCXX)
  if(CMAKE_${lang}_COMPILER_ID MATCHES "Clang")
    add_compile_options(
      "$<$<COMPILE_LANGUAGE:${lang}>:SHELL:-Xclang -fno-pch-timestamp>"
    )
  endif()
endforeach()
```

If using the Visual Studio toolchain, note that Ccache does not support storing debug information in a separate PDB file when

compiling. If the `/Zi` or `/ZI` compiler option is used, Ccache will fall back to invoking the compiler and perform no caching. [Section 16.8.5, “Debug Information Format Selection”](#) discussed different ways these flags may be set by default. If policy `CMP0141` is set to `OLD` or is unset, CMake adds `/Zi` to the default value of some `CMAKE_<LANG>_FLAGS_<CONFIG>` variables. If `CMP0141` is set to `NEW`, the `CMAKE_MSVC_DEBUG_INFORMATION_FORMAT` variable controls the defaults instead, but with the same result that `/Zi` will be the default for some configurations. Therefore, additional logic is needed to switch to the `/Z7` option instead. This stores debug information directly in the object files, which Ccache does support.

```
if(MSVC)
    # Disable use of separate PDB, Ccache won't cache
    # things otherwise
    foreach(lang IN ITEMS C CXX)
        foreach(config IN LISTS
            CMAKE_BUILD_TYPE CMAKE_CONFIGURATION_TYPES)
            set(var CMAKE_${lang}_FLAGS)
            if(NOT config STREQUAL "")
                string(TOUPPER "${config}" config)
                string(APPEND var "_${config}")
            endif()
            string(REGEX REPLACE "[-/]Z[iI]" "-Z7"
                ${var} "${${var}}")
        )
        set(${var} "${${var}}" PARENT_SCOPE)
    endforeach()
endforeach()

if(DEFINED CMAKE_MSVC_DEBUG_INFORMATION_FORMAT)
    string(REGEX REPLACE
        "ProgramDatabase|EditAndContinue" "Embedded"
```

```

    replaced "${CMAKE_MSVC_DEBUG_INFORMATION_FORMAT}"
)
set(CMAKE_MSVC_DEBUG_INFORMATION_FORMAT "${replaced}"
PARENT_SCOPE
)
else()
set(CMAKE_MSVC_DEBUG_INFORMATION_FORMAT
"${$<$<CONFIG:Debug,RelWithDebInfo>:Embedded>"}
PARENT_SCOPE
)
endif()
endif()

```

Note that both `/Z...` and `-Z...` forms of the compiler options may be encountered. They are both equivalent and accepted by the compiler, but the `-Z...` form is slightly more robust due to `/` being interpreted as a path separator in some environments. Most developers are accustomed to seeing the `/Z...` forms, but the above code uses `-Z7` for the most robust result.

Also note that forcing `-Z7` does not prevent a PDB file from being generated for executable or shared library targets. Generation of those PDBs is controlled by the `/DEBUG` linker option. They can be created from embedded or separated debug information produced by the compiler. See [Section 44.5, “PDB Generation”](#) for a more detailed discussion of the two PDB file types.

26.5.2. Makefiles And Ninja Generators

Starting with CMake 3.4, the `<LANG>_COMPILER_LAUNCHER` target properties can be used to specify a list of items to precede the

compiler command line in a language-specific way. This is supported only by the Ninja and Makefiles generators. The default values for these properties are taken from the corresponding `CMAKE_<LANG>_COMPILER_LAUNCHER` variables when a target is created. The variable is the typical and recommended way to use this feature. The following demonstrates how to enable Ccache for the whole build, but only after first confirming that a ccache executable is available. This ensures the build will work with or without Ccache.

```
find_program(CCACHE_EXECUTABLE ccache)
if(CCACHE_EXECUTABLE)
    set(CMAKE_C_COMPILER_LAUNCHER ${CCACHE_EXECUTABLE})
    set(CMAKE_CXX_COMPILER_LAUNCHER ${CCACHE_EXECUTABLE})
endif()
```

For most projects, the above example is too simplistic. It does not set any Ccache environment variables, it relies purely on the user-level configuration of that tool. CMake's command mode can be used to set the relevant environment variables when invoking Ccache on any platform. The following is a more realistic example:

```
find_program(CCACHE_EXECUTABLE ccache)
if(CCACHE_EXECUTABLE)
    set(ccacheEnv
        CCACHE_SLOPPINESS=pchDefines,time_macros
    )
    # NOTE: Ccache 4.2+ required for reliable CUDA support
    foreach(lang IN ITEMS C CXX OBJC OBJCXX CUDA)
        set(CMAKE_${lang}_COMPILER_LAUNCHER
            ${CMAKE_COMMAND} -E env ${ccacheEnv}
```

```
    ${CCACHE_EXECUTABLE}  
)  
endforeach()  
endif()
```

26.5.3. Xcode Generator

The above technique is suitable for the Ninja or Makefiles generators, but not for the Xcode generator. Ccache does support the AppleClang compiler, but a different method must be used to insert ccache before the compiler command and set the relevant environment variables.

When using the Xcode generator, the compilers to use for C and C++ can be overridden by setting the `CMAKE_XCODE_ATTRIBUTE_CC` and `CMAKE_XCODE_ATTRIBUTE_CXX` variables. The linkers must also be set with the `CMAKE_XCODE_ATTRIBUTE_LD` and `CMAKE_XCODE_ATTRIBUTE_LDPLUSPLUS` variables to work around a bug in some versions of the Xcode IDE where it can select the wrong linker language if only `CMAKE_XCODE_ATTRIBUTE_CC` and `CMAKE_XCODE_ATTRIBUTE_CXX` are set. Curiously, the bug is restricted to building within the IDE, any command-line builds using `xcodebuild` are not affected. Also recall that, as mentioned back in [Section 25.1, “CMake Generator Selection”](#), the `CMAKE_XCODE_ATTRIBUTE_...` variables only have an effect if set in the top level `CMakeLists.txt` file.

Each of the Xcode project variables allow specifying only a single value, but the command line needs to have multiple

options (at least the ccache executable and the real compiler to be invoked). Therefore, a separate launch script needs to be written out and the project variables pointed at them. Relevant environment variables can also be set in these launch scripts. For example:

```
# Write out launch scripts for C and C++ languages
foreach(lang IN ITEMS C CXX)
    set(launch${lang} ${CMAKE_BINARY_DIR}/launch-${lang})
    file(WRITE ${launch}${lang})
        "#!/bin/bash\n\n"
        "export CCACHE_SLOPPINESS=pchDefines,time_macros\n"
        "exec \\"${CCACHE_EXECUTABLE}\\"
            \"\\"${CMAKE_${lang}_COMPILER}\\" \"$@\\"\n"
    )
    execute_process(COMMAND chmod a+r ${launch}${lang})
endforeach()

# Redirect Xcode to use our launchers
set(CMAKE_XCODE_ATTRIBUTE_CC      ${launchC})
set(CMAKE_XCODE_ATTRIBUTE_CXX     ${launchCXX})
set(CMAKE_XCODE_ATTRIBUTE_LD      ${launchC})
set(CMAKE_XCODE_ATTRIBUTE_LDPLUSPLUS ${launchCXX})
```

26.5.4. Visual Studio Generators

Using Ccache with the Visual Studio generators requires Ccache 4.6.1 or later. The `CMAKE_<LANG>_COMPILER_LAUNCHER` variables don't support Visual Studio generators, but Visual Studio project properties can be used in conjunction with a launch script to achieve the same thing. The `CLToolPath` and `CLToolExe` project properties redirect the compile steps to use a custom compiler executable or script. The properties can be set with the

`CMAKE_VS_GLOBALS` variable (see [Section 26.3.3, “Visual Studio Generators”](#) for another closely related use of this variable).

The same compiler executable is used for C and C++ with these generators. Thus, only one launch script is needed, unlike the Xcode generator which requires one launch script per language. The following shows one way for a project to generate and use such a launch script (this should be executed after the first `project()` call):

```
cmake_path(NATIVE_PATH CCACHE_EXECUTABLE ccache_exe)
file(WRITE ${CMAKE_BINARY_DIR}/launch-cl.cmd
    "@echo off\n"
    "set CCACHE_SLOPPINESS=pchDefines,time_macros\n"
    "\"${ccache_exe}\" \"${CMAKE_C_COMPILER}\" %*\n"
)

# Remove existing settings, we will replace them
list(FILTER CMAKE_VS_GLOBALS EXCLUDE
    REGEX "^(CLTool(Path|Exe)|Track FileAccess)=.*$"
)
list(APPEND CMAKE_VS_GLOBALS
    CLToolPath=${CMAKE_BINARY_DIR}
    CLToolExe=launch-cl.cmd
    Track FileAccess=false      # See below
)
```

Like most generators, Visual Studio offers a "clean" feature which removes files created by previous builds. It's build tool (MSBuild) tracks files created or modified during compilation and removes them upon a "clean". But this also deletes artifacts from the cache, ruining Ccache's effectiveness. To avoid losing the cached artifacts, file tracking must be disabled by setting

the `Track FileAccess` project property to false. The above example includes that option in the `CMAKE_VS_GLOBALS` variable.

For Ccache to work, the `/MP` option must not be used. One can inhibit that by setting the `CMAKE_VS_NO_COMPILE_BATCHING` variable to true (requires CMake 3.24 or later). But a more effective strategy is to enable the Multi-ToolTask scheduler, as described earlier in [Section 26.3.3, “Visual Studio Generators”](#). Conveniently, in addition to giving more efficient task scheduling, that scheduler automatically disables `/MP`. It is therefore a very good choice if using Ccache.

26.5.5. Combined Generator Support

Projects can combine the various generator-specific methods discussed above to provide support for Ccache across the different generators. It may be useful to implement the logic in its own function and call it from the top level `CMakeLists.txt` file, typically just after the `project()` command. The function should do nothing if not called from the top level, since that is a requirement for the Xcode generator. It also ensures that the top level project is in control for hierarchical builds. The function can be in its own file, potentially in its own source repository, then added to the build via `FetchContent`. This is a convenient way to share the same logic across many projects.

[Appendix A, Full Compiler Cache Example](#) provides a complete combined implementation, ready for production use. The logic

from [Section 26.3.3, “Visual Studio Generators”](#) to enable the Multi-ToolTask scheduler for Visual Studio generators is also included.

26.6. Debug-related Improvements

A typical developer workflow is to make a code change, perform an incremental build to rebuild anything that depends on the change and re-run one or more executables, tests, etc. Some of these may be run under a debugger, which involves loading the relevant debug symbols for the executable and any shared libraries used by it. With many common toolchains, the default settings lead to a number of inefficiencies in this workflow.

One common default behavior is for compilers to store debug information directly in the generated object files. At the link step, the linker then processes all this debug information, even though it isn’t actually needed to produce a working binary. When creating an executable or shared library, the linker may also embed a copy of the relevant debug information, which requires the linker to process all the symbols across the object files to work out what to store, including handling multiple definitions of the same symbol. This embedding also results in multiple copies of debug information being stored across the various object files and binaries in the build. The size of this information is frequently very significant, often making up the

majority of the size of object files and binaries. All this extra processing and duplication can have a noticeable impact on the build performance. It can also lead to very high memory use during linking.

One solution to the above is to store the debug information in a separate file instead of directly in the object file, shared library or executable. Any reasonably recent version of GCC or Clang supports a feature called *split dwarf* which does exactly this, but it is not enabled by default. It can be turned on by adding the `-fsplit-dwarf` compiler option. The compiler will then create a `.dwo` file beside the object file, then record a reference to the `.dwo` in that object file instead of the full debug information. Furthermore, any executable or shared library that links in that object file will also contain a reference to its `.dwo` file instead of embedding a copy of the debug information.

To gain the most benefit from split dwarf, it should be enabled for the whole build. This ensures that all debug information for all targets will be separated from the object and binary files. Developers can add it manually to the CMake cache or set it as part of a toolchain file. This is done by appending `-fsplit-dwarf` to variables like `CMAKE_C_FLAGS_DEBUG` and `CMAKE_CXX_FLAGS_DEBUG`, or their `..._INIT` counterparts in the case of toolchain files. This requires no changes to the project and gives the developer full discretion over whether or not to use the feature.

In some cases, it may be desirable for the project itself to add the flag, such as in a company environment where the project is built in a controlled setup. When doing this, consider the advice in [Chapter 16, *Compiler And Linker Essentials*](#) and prefer to use the `add_compile_options()` command to set the relevant directory properties rather than modifying the `CMAKE_<LANG>_FLAGS_DEBUG` variables. The following example demonstrates how this can be done, including a test for whether the flag is supported or not:

```
include(CheckCCompilerFlag)
check_c_compiler_flag("-gsplit-dwarf" HAVE_SPLIT_DWARF)

if(HAVE_SPLIT_DWARF)
    # Only add for debug builds, but could also expand the
    # generator expression to add for RelWithDebInfo too
    add_compile_options("${${CONFIG}:Debug:-gsplit-dwarf}")
endif()
```

Split dwarf has some subtleties around its interaction with options like `-g`, `-g1` and so on. The interaction of these flags with Ccache in particular has caused some issues in the past, so it is advisable to use a recent Ccache release if adding this compiler flag (at least Ccache 3.7). Similarly, having the debug information split out to a separate file may also interfere with distributed compilation tools like `distcc`. Developers should check the documentation of the version of the tools they are using and ensure the tools support split dwarf before enabling it.

26.7. Alternative Linkers

As discussed in the previous section, when working with debug builds, the link time can be significant due to the debug symbol handling. The default BFD linker on many Unix systems does not perform well in this regard, but alternative linkers can do a much better job. The gold linker is relatively mature, is typically much faster than the BFD linker, and uses much less memory. The llvm linker (lld) potentially offers even better performance. The mold linker is another more recent alternative, offering superior performance over most other linkers, but supporting fewer platforms. These alternative linkers are suitable for all build types, not just Debug.

CMake 3.29 and later provides the `CMAKE_LINKER_TYPE` variable for selecting the desired linker. The following values select one of the more commonly used linkers:

- BFD
- GOLD
- LLD
- MOLD (this will be the same as SOLD when building for macOS or iOS)

Other values are supported, but the above will be the more commonly specified values when the default linker is being overridden. See the official documentation of the

`CMAKE_LINKER_TYPE` variable for other choices. A custom linker can also be specified, although this would rarely be needed. The interested reader should consult the official documentation of the `CMAKE_<LANG>_USING_LINKER_<TYPE>` set of variables for how to specify the custom details.

`CMAKE_LINKER_TYPE` is primarily used to initialize the `LINKER_TYPE` target property of executable and shared library targets. Projects should not normally manipulate that target property, nor should they set `CMAKE_LINKER_TYPE`. Linker selection should generally be under the developer's control, which allows them to experiment with different linkers and use the one that works best in their situation. Developers can set `CMAKE_LINKER_TYPE` in a toolchain file, or directly on the `cmake` command line like any other cache variable.

With CMake 3.28 and earlier, no abstraction for the linker is available and linker selection requires setting linker options directly. When using a GNU or LLVM toolchain, the alternative linkers can generally be enabled with `-fuse-ld=gold`, `-fuse-ld=lld`, or `-fuse-ld=mold`, assuming the relevant linker is installed and supported for that platform and toolchain version. If set by the developer through the CMake cache, the linker option should be appended to the `CMAKE_EXE_LINKER_FLAGS`, `CMAKE_MODULE_LINKER_FLAGS`, and `CMAKE_SHARED_LINKER_FLAGS` variables. If being set via a toolchain file, the same variables with `_INIT` appended to their names should be set. Do not select

the linker using `add_link_options()` or by adding the relevant flags to directory properties, as these will not propagate to any `try_compile()` calls made by the project or its dependencies.



If targeting Android and using the NDK, be aware of a bug in older versions of lld which breaks debugging. If using NDK r21, set the CMake variable `ANDROID_LD` to `lld` instead of adding the `-fuse-ld=lld` option (from NDK r22, `lld` is already the default linker). The NDK toolchain file will then apply the necessary workaround.

26.8. Recommended Practices

Always focus on build correctness before trying to optimize build performance. Ensure that relationships between targets are properly expressed and that dependencies in custom commands fully capture *all* dependencies. Under-specified dependencies can lead to build failures, or worse still, silently using an old binary output from a previous build due to one task not waiting for that output to be regenerated in the current build. Such problems can be notoriously hard to trace, often going undetected for a very long time before being diagnosed as the underlying cause of unreliable builds. Adding certain build optimizations into the mix before addressing such problems will likely only make the build even more unreliable. Conversely, by avoiding unnecessary dependencies between

targets, the build tool has a greater opportunity to execute parts of the build in parallel and shorten the overall build time.

One simple and relatively safe build optimization is to enable project-wide optimization of dependencies for static and object library targets. This can be done by setting the `CMAKE_OPTIMIZE_DEPENDENCIES` variable to true in the top level `CMakeLists.txt` file, a toolchain file, or via a cache variable. When using CMake 3.19 or later, this can relax dependency relationships for static and object library targets. This may improve build parallelism or reduce what has to be built during day-to-day development. Earlier CMake versions will simply ignore the variable.

When seeking to optimize build performance, be careful about assuming characteristics of the machine on which the build will be performed. Tuning values like the unity build batch size for one machine may result in poor performance on another with very different characteristics (e.g. less memory or a different number of cpus). Prefer to leave such tuning up to the developer using cache variables, except for situations where the project already knows upper limits beyond which little gain can be expected (e.g. source files that are already very large). Use the GROUP unity mode sparingly, and only where it provides a measurable improvement in build performance.

When considering unity builds for a project, start from the point of view that unity builds will be enabled project-wide

rather than trying to turn it on for specific targets. Focus instead on identifying those targets or source files that are incompatible with a unity build and disable it on just those entities. This ensures hierarchical builds have the opportunity to enable unity builds as widely as possible throughout the dependency tree.

Targets should build successfully with or without compiler support for precompiled headers. It should be considered an optimization, not a requirement. In particular, do not explicitly include a precompile header (e.g. stdafx.h) in the source code, let CMake force-include an automatically generated precompile header on the compiler command line instead. This is more portable across the major compilers and is likely to be easier to maintain. It will also avoid warnings being generated from certain code checking tools like `iwyu` (include what you use).

Precompiled headers are most effective when the headers in the precompile set rarely change. This is typically true for headers provided by the system or the compiler, but may not be the case for headers provided by the project. If adding project headers to the precompile set, measure the effect and confirm that it gives a worthwhile benefit. Avoid adding headers that change often, as this will tend to have an overall negative effect on build times due to the increased scope of rebuilds when those headers change.

Take full advantage of the parallelism available with the chosen build tool. If using Ninja, it is generally best to let it select the optimal limit on the number of concurrent tasks. If using a Makefiles generator, consider whether switching to Ninja for better build efficiency is possible, otherwise make sure to explicitly enable parallel builds (they are not parallel by default for Makefiles generators). For Visual Studio generators, consider enabling the Multi-ToolTask scheduler, especially if also using a compiler cache like Ccache.

Where possible, use Ccache on both developer and continuous integration machines. It is one of the most effective ways to reduce incremental build times when compiling code seen frequently by the compiler with the same settings (a common characteristic of continuous integration builds). Cache misses can result in an increase in compile time for that file of around 10-30%, but the gain for cache hits in typical development or continuous integration workloads more than makes up for that (order-of-magnitude improvements are not unusual).

Configure Ccache to store its cache on a fast disk such as a SSD, as the latency of that storage can have a strong effect on the cache performance. Also increase the maximum cache size well above the 5Gb default, since it is typically much too low for most real-world deployments. Ensure the cache sloppiness options include `pch_defines` and `time_macros` if using precompiled headers.

For any modest size project, consider enabling split dwarf if it is supported by the toolchain. This can drastically reduce disk space consumed by debug builds, it can speed up linking, and it can reduce memory used by some linkers. When using Ccache with split dwarf, ensure that Ccache 3.7 or later is used. Older versions were susceptible to using out-of-date .dwo files or generating more cache misses. They also used to fail to handle the combination of precompiled headers and split dwarf properly.

Avoid forcing the use of a non-default linker if there is any chance that the project may become a child dependency of another project. A parent project may have restrictions which require it to use the default linker, so it must have a way to prevent the child project from trying to use something else. A good strategy is to only try to change the linker if it is the top level project in the build, and ideally leave it for a toolchain file to specify. This follows the general recommendation that the developer should be able to enable or disable most toolchain-related features except where it is an actual requirement of a project.

IV: TESTING AND ANALYSIS

Testing and code analysis are important parts of the complete software cycle. CMake has direct support for defining test cases, which are executed with a dedicated testing tool, `ctest`. Rich features are provided for defining how tests use resources, constraints between tests, and controlling how tests execute. Reporting options include support for a dedicated dashboard server (CDash), or file output in the widely used JUnit XML format. There is even a mode for creating separate builds off to the side, which can be useful for testing things like SDKs or packages. The chapters in this part of the book go through each of these areas, demonstrating how to get the most out of what CMake and `ctest` provide.

Support is also provided for the popular GoogleTest framework. While GoogleTest can be used standalone, `ctest` can drive the tests defined with the GoogleTest framework, taking over how tests are scheduled to run and the environment they run in. The ability to mix GoogleTest tests with other test cases opens up a range of testing strategies. While the chapter on testing frameworks focuses on GoogleTest, it also briefly introduces a

couple of other alternative frameworks which operate in a very similar manner.

CMake also has direct support for a number of popular static code analysis tools, including clang-tidy, cppcheck, cpplint, and include-what-you-use. These complement tests by providing additional verification of the code quality, adherence to relevant standards, and catching common programming problems. Some of these tools also have the potential to improve build performance. Dynamic code analysis is also possible with CMake projects. Both sanitizers and code coverage are discussed in detail in this part of the book.

27. TESTING FUNDAMENTALS

A natural follow-on to building a project is to test the artifacts it created. The CMake software suite includes the `ctest` tool, which can be used to automate the testing phase. This chapter covers the fundamental aspects of testing. It discusses how to define tests and execute them using the `ctest` command-line tool. Subsequent chapters discuss other ways of using `ctest` and related topics.

27.1. Defining And Executing A Simple Test

The first step to defining tests in a CMake project is to call `enable_testing()` somewhere in the top level `CMakeLists.txt` file. This would typically be done early, soon after the first `project()` call. The effect of this function is to direct CMake to write out a `ctest` input file in the `CMAKE_CURRENT_BINARY_DIR`, which will contain details of all the tests defined in the project (more accurately, those tests defined in the current directory scope and below). `enable_testing()` can be called in a subdirectory without error, but without a call to `enable_testing()` at the top

level, the `ctest` input file will not be created at the top of the build tree where it is normally expected to be.

Defining individual tests is done with the `add_test()` command:

```
add_test(NAME testName
          COMMAND command [arg...]
          [CONFIGURATIONS config1 [config2...]]
          [WORKING_DIRECTORY dir]
          [COMMAND_EXPAND_LISTS]  # CMake 3.16 or later
      )
```

By default, the test will be deemed to pass if the command returns an exit code of 0, but more flexible pass/fail handling is supported (see the next section). Prior to CMake 3.19, the `testName` should not contain any spaces, quotes or other special characters. With CMake 3.19 or later, these constraints are removed when policy `CMP0110` is set to `NEW`. CMake 3.18.0 originally introduced the same capability, but it was reverted in 3.18.1 after it was found to break some projects. The capability was reintroduced again in 3.19.0, this time with a policy to ensure backward compatibility for projects that relied on the old behavior.

The command can be a full path to an executable, or it can be the name of an executable target defined in the project. When a target name is used, CMake automatically substitutes the real path to the executable. This is particularly useful when using multi-configuration generators like Xcode, Visual Studio, or

Ninja Multi-Config, where the location of the executable will be configuration-dependent.

```
cmake_minimum_required(VERSION 3.0)
project(CTestExample)
enable_testing()

add_executable(TestApp testapp.cpp)
add_test(NAME noArgs COMMAND TestApp)
```

The automatic substitution of a target with its real location does not extend to the command arguments, only the command itself supports such substitution. If the location of a target needs to be given as a command line argument, generator expressions can be used. For example:

```
add_executable(App1 ...)
add_executable(App2 ...)

add_test(NAME WithArgs COMMAND App1 ${TARGET_FILE:App2})
```

When running the tests, the user can specify which configuration should be tested. When the project is using a single-configuration generator, the configuration does not have to match the build type. In particular, if no configuration is provided, an empty configuration is assumed. Without the optional CONFIGURATIONS keyword, the test will be run for all configurations regardless of the build type or which configuration has been requested by the user. If the CONFIGURATIONS keyword is given, the test will only be run for the configurations specified. Note that an empty configuration

is still considered valid, so for the test to run in that scenario, an empty string would have to be one of the CONFIGURATIONS listed.

For example, to add a test that should only be executed for configurations that have debug information, the Debug and RelWithDebInfo configurations can be listed. Adding the empty string also makes the test run when no configuration is specified when running the tests:

```
add_test(NAME DebugOnly
    COMMAND TestApp
    CONFIGURATIONS Debug RelWithDebInfo ""
)
```

In most cases, the CONFIGURATIONS keyword is not needed, and the test would be executed for all configurations, including the empty one.

By default, the test will run in the CMAKE_CURRENT_BINARY_DIR directory. The WORKING_DIRECTORY option can be used to make the test run in some other location. An example of where this can be useful is to run the same executable in different directories to pick up different sets of input files, without having to specify them as command-line arguments.

```
add_test(NAME Foo
    COMMAND TestApp
    WORKING_DIRECTORY ${CMAKE_CURRENT_LIST_DIR}/Foo
)
add_test(NAME Bar
    COMMAND TestApp
```

```
WORKING_DIRECTORY ${CMAKE_CURRENT_LIST_DIR}/Bar  
)
```

If specifying a working directory, always use an absolute path. If a relative path is given, it will be interpreted as being relative to the directory in which `ctest` itself was launched, but that might not be the top of the build tree. To ensure the working directory is predictable, projects should avoid using a relative `WORKING_DIRECTORY`.

If the specified working directory does not exist when the test is run, CMake versions 3.11 and earlier will not issue an error message and will still run the test, even though it fails to change the working directory. CMake 3.12 and later will catch the error and treat the test as failed. Regardless of what version of CMake is used, it is the project's responsibility to ensure the working directory exists and has appropriate permissions.

CMake 3.16 added support for the `COMMAND_EXPAND_LISTS` keyword, which has the same effect as the same-named option for the `add_custom_command()` and `add_custom_target()` commands. When this keyword is present, any list given as a command name or argument is expanded. This list expansion occurs after any generator expressions are evaluated. One of the primary motivations for this feature is to avoid passing an unwanted empty string as a command argument after a generator expression expands to nothing. For example:

```
add_test(NAME Expander
    COMMAND someCommand $<$<CONFIG:Debug>:-g>
    COMMAND_EXPAND_LISTS
)
```

If the above test is run for non-Debug configurations, `COMMAND_EXPAND_LISTS` ensures that after the generator expression expands to nothing, no empty argument is added to the command line.

A reduced form of the `add_test()` command is also supported for backward compatibility reasons:

```
add_test(testName command [args...])
```

This form should not be used in new projects, since it lacks some features of the full `NAME` and `COMMAND` form. The main differences are that generator expressions are not supported, and if `command` is the name of a target, CMake will not automatically substitute the location of its binary.

To run the tests, the `ctest` command line tool is used. It would normally be run from the top of the build directory, although with CMake 3.20 or later, a `--test-dir` command-line option can be given to specify the directory for which tests should be run. By default, `ctest` will execute all defined tests one at a time, logging a status message as each test is started and completed, but hiding all test output. An overall summary of the tests will

be printed at the end. Typical output would look something like this:

```
Test project /path/to/build/dir
  Start 1: FooWithBar
  1/2 Test #1: FooWithBar..... Passed  0.00 sec
  Start 2: FooWithoutBar
  2/2 Test #2: FooWithoutBar..... Passed  0.00 sec

  100% tests passed, 0 tests failed out of 2

  Total Test time (real) =  0.02 sec
```

If using a multi-configuration generator like Xcode, Visual Studio or Ninja Multi-Config, `ctest` needs to be told which configuration to test. This is done by including the `-C configType` option, where `configType` is one of the supported build types (Debug, Release, etc.). The longer form `--build-config` is an alternative to the shorter `-C`. For single-configuration generators, the `-C` option is not mandatory. Since a single-configuration build can only produce one configuration, there is no ambiguity for where to find the binaries to execute. Nevertheless, it can still be useful to specify a configuration. This avoids the unintuitive behavior of excluding tests that are defined to only run under certain configurations, and where the empty string is not among those listed.

`ctest` can be instructed to show all test output and various other details about the run with the `-V` option. `-VV` shows an increased level of verbosity, but this is typically only needed by

developers working on `ctest` itself. Even the `-V` level of verbosity is usually more detail than users want to see. It is more likely that only the output of failed tests needs to be shown. This can be achieved by passing the `--output-on-failure` option. Alternatively, developers can set the `CTEST_OUTPUT_ON_FAILURE` environment variable (the value isn't used, `ctest` merely checks if `CTEST_OUTPUT_ON_FAILURE` has been set). With CMake 3.18 or later, the `--stop-on-failure` option can also be given to end the test run immediately at the first error encountered.

As a convenience primarily for IDE applications, when testing has been enabled, CMake defines a custom build target that invokes `ctest` with a default set of arguments. For the Xcode and Visual Studio generators, this target will be called `RUN_TESTS`, and it will pass the currently selected build type as the configuration to `ctest`. For other generators, the target is simply called `test`, and if it is a single-configuration generator, that target does not specify any configuration when invoking `ctest`.

With CMake 3.16 or earlier, there is no facility to specify which tests will be executed or any other custom options to pass to `ctest` when using the `RUN_TESTS` or `test` build target. CMake 3.17 introduced the `CMAKE_CTEST_ARGUMENTS` variable, which can be used to prepend arbitrary options to the `ctest` command line for that build target.

27.2. Test Environment

By default, each test will be run with the same environment as the `ctest` command. If a test requires changes to its environment, this can be done through the `ENVIRONMENT` test property. This property is expected to be a list of `NAME=VALUE` items that define environment variables to be set before running the test. Changes are local to that test only, so they do not affect other tests.

```
set_tests_properties(SomeTest PROPERTIES
    ENVIRONMENT "FOO=bar;HAVE_BAZ=1"
)
```

A major weakness of the `ENVIRONMENT` test property is that list-valued variables are problematic. The test properties are written to another file that `ctest` later reads. `ctest` will interpret the semicolons in list values as separators between different environment variables to be set, not as part of the value. To prevent that splitting, one has to add an extra level of escaping. Note the backslash when defining the value for `FOO` in the following example:

```
set_tests_properties(SomeTest PROPERTIES
    ENVIRONMENT "FOO=one\;two;HAVE_BAZ=1"
)
```

If building up the environment string in one or more variables before passing it to `set_tests_properties()`, further escaping may be needed. CMake's rules for escaping are complicated,

which makes handling these cases very fragile and easy to get wrong. Therefore, avoid using ENVIRONMENT for variables with list values, if possible.

With CMake 3.22 or later, the ENVIRONMENT_MODIFICATION test property offers a more robust way of modifying environment variables. Instead of replacing an environment variable with a value determined at configure time, ENVIRONMENT_MODIFICATION can be used to apply a list of changes to one or more environment variables based on the variable's value when ctest runs. A change is specified in the form varName=operation:value. A variety of operations are supported, but some of the more useful ones include string_append, string_prepend, path_list_append, path_listprepend, cmake_list_append and cmake_listprepend. The string... operations have the expected behavior of appending and prepending to the variable's existing value. The cmake_list... operations do likewise, except they also add a semicolon separator between the new value and the existing value. The path_list... operations do the same, except the separator will be the one the host platform uses for PATH-like environment variables (a semicolon on Windows, a colon everywhere else).

```
# In this example, Algo is assumed to be a shared library
# defined elsewhere in the project and whose binary will
# be in a different directory to test_Algo
add_executable(test_Algo ...)
target_link_libraries(test_Algo PRIVATE Algo)
```

```

add_test(NAME CheckAlgo COMMAND test_Algo)

set_property(TEST CheckAlgo PROPERTY
    ENVIRONMENT_MODIFICATION
        SOME_VAR=string_append:ExtraPart
        QT_LOGGING_RULES=cmake_list_append:*.debug=true
)

if(WIN32)
    # Ensure the required DLLs can be found at runtime
    set(algoDir "<${SHELL_PATH}:<${TARGET_FILE_DIR}:Algo>>")
    set(otherDllDir "C:\\path\\to\\another\\dll")
    set_property(TEST CheckAlgo APPEND PROPERTY
        ENVIRONMENT_MODIFICATION
            PATH=path_list_prepend:${algoDir}
            PATH=path_list_prepend:${otherDllDir}
    )
endif()

```

The same fragility with passing through values containing semicolons applies to ENVIRONMENT_MODIFICATION. However, semicolons can often be avoided by incrementally applying value changes one at a time, as shown for the PATH in the WIN32 block in the above example.

With CMake 3.21 or earlier, situations where an environment variable needs to modify rather than replace an existing value are less straightforward. If the environment should be based on the one in which CMake is run rather than the ctest command, then the form \${ENV{SOMEVAR}} can be used to obtain existing values. Once again, extra care is needed for environment variable values that may contain semicolons. For example:

```

if(WIN32)
    set(algoDir  "$<SHELL_PATH:$<TARGET_FILE_DIR:Algo>>")
    set(execPath "PATH=${algoDir};$ENV{PATH}")

    # Add one level of escaping for any semicolons to
    # prevent ctest from treating them as separators
    # between environment variable names instead of as
    # part of the PATH value.
    string(REPLACE ";" "\\;" execPath "${execPath}")

    set_tests_properties(CheckAlgo PROPERTIES
        ENVIRONMENT "${execPath}"
    )
endif()

```

Modifying the environment based on the actual environment being used to invoke `ctest` rather than CMake is even more involved. It can be achieved with a combination of `cmake -E env` invoking a script, with CMake-provided locations being passed as variables to the `cmake -E env` part. Then the script does the actual task of augmenting the run-time environment using those values and invoking the test executable. Such an arrangement is complex, can be fragile, and should be avoided unless there is a definite need to support such a use case for CMake 3.21 or earlier.

27.3. Pass / Fail Criteria And Other Result Types

Basing the result of a test purely on the exit code of the test command can be quite restrictive. Another supported

alternative is to specify regular expressions to match against the test output. The PASS_REGULAR_EXPRESSION test property can be used to specify a list of regular expressions, at least one of which the test output must match for the test to pass. These regular expressions frequently span across multiple lines. Similarly, the FAIL_REGULAR_EXPRESSION test property can be set to a list of regular expressions. If any of these match the test output, the test fails, even if the output also matches a PASS_REGULAR_EXPRESSION or the exit code is 0. A test can have both PASS_REGULAR_EXPRESSION and FAIL_REGULAR_EXPRESSION set, just one of the two, or neither. If PASS_REGULAR_EXPRESSION is set and is not empty, the exit code is not considered when determining whether the test passes or fails.

```
# Ignore exit code, check output to determine the
# pass/fail status
set_tests_properties(test_Foo PROPERTIES
    FAIL_REGULAR_EXPRESSION "warning|Warning|WARNING"
    PASS_REGULAR_EXPRESSION [[
        Checking some condition for test_Foo: passed
        +.*
        All checks passed]]
)
```

Sometimes a test may need to be skipped, perhaps for reasons that only the test itself can determine. The SKIP_RETURN_CODE test property can be set to a value the test can return to indicate that it was skipped rather than failed. A test that exits with the SKIP_RETURN_CODE will override any other pass or fail criteria.

CMakeLists.txt

```
add_executable(test_Foo test_Foo.cpp ...)  
add_test(NAME Foo COMMAND test_Foo)  
  
set_tests_properties(Foo PROPERTIES  
    SKIP_RETURN_CODE 2  
)
```

test_Foo.cpp

```
int main(int argc, char* argv[])  
{  
    if (shouldSkip())  
        return 2; // Skipped  
  
    if (runTest())  
        return 0; // Passed  
  
    return 1; // Failed  
}
```

Output from the above test may look similar to the following:

```
Test project /path/to/build/dir  
  Start 1: Foo  
1/1 Test #1: Foo .....***Skipped  0.00 sec  
  
100% tests passed, 0 tests failed out of 1  
  
Total Test time (real) =  0.01 sec  
  
The following tests did not run:  
  1 - Foo (Skipped)
```

From CMake 3.16, a SKIP_REGULAR_EXPRESSION can also be specified. Similar to PASS_REGULAR_EXPRESSION and FAIL_REGULAR_EXPRESSION, it causes the test to be skipped if the

output matches any of the skip expressions. A skip regular expression also takes precedence over any pass or fail criteria.

When at least one test fails or is not run for some reason, a summary of all such tests and their status is printed at the end. A test that indicates it should be skipped via its return code is still counted in the total number of tests. These skipped tests are not considered failures with CMake 3.9 or later, but they *are* considered failures with CMake 3.8 and earlier. Regardless of CMake version, a test may also be skipped for other reasons which could be deemed a failure, such as a test dependency failing to be met (see [Section 28.1, “Simple Test Dependencies”](#) and [Section 28.2, “Test Fixtures”](#)).

With CMake 3.9 or later, a DISABLED test property is also supported. This can be used to mark a test as temporarily disabled, which allows it to be defined but not executed or counted in the total number of tests. It will not be considered a test failure, but it will still be shown in the test results with an appropriate status message. Note that such tests should not normally remain disabled for extended periods. The feature is intended as a temporary way to disable a problematic or incomplete test until it can be fixed. The following example demonstrates the behavior:

```
add_test(NAME FooWithBar ...)
add_test(NAME FooWithoutBar ...)

set_tests_properties(FooWithoutBar PROPERTIES DISABLED YES)
```

The ctest output for the above may look something like this:

```
Test project /path/to/build/dir
  Start 1: FooWithBar
  1/2 Test #1: FooWithBar ..... Passed    0.00 sec
  Start 2: FooWithoutBar
  2/2 Test #2: FooWithoutBar ....***Not Run (Disabled)  0.00 sec

100% tests passed, 0 tests failed out of 1

Total Test time (real) =  0.01 sec

The following tests did not run:
  2 - FooWithoutBar (Disabled)
```

In some cases, a test may be expected to fail. Rather than disabling the test, it may be more appropriate to mark the test as expecting failure so that it continues to be executed. The `WILL_FAIL` test property can be set to true to indicate this, which will then invert the pass/fail result. This has the added advantage that if the test starts to pass unexpectedly, ctest will consider that a failure, and the developer is immediately aware of the change in behavior.

Another aspect of a test's pass/fail status is how long it takes to complete. The `TIMEOUT` test property, if set, specifies the number of seconds the test is allowed to run before it will be terminated and marked as failed. The ctest command line also accepts a `--timeout` option which has the same effect for any test without a `TIMEOUT` property set (i.e. it acts as a default timeout). Furthermore, a time limit can also be applied to the entire set of

tests as a whole by specifying the `--stop-time` option to `ctest`. The argument after `--stop-time` must be a real time of day rather than a number of seconds, with local time assumed if no timezone is given.

```
add_test(NAME t1 COMMAND ...)  
add_test(NAME t2 COMMAND ...)  
  
set_tests_properties(t2 PROPERTIES TIMEOUT 10)
```

```
ctest --timeout 30 --stop-time 13:00
```

In the above example, the default per-test timeout is set to 30 seconds on the `ctest` command line. Since `t1` has no `TIMEOUT` property set, it will have a 30-second timeout, whereas `t2` has its `TIMEOUT` property set to 10, which will override the default set on the `ctest` command line. The tests will be given until 1pm local time to complete.

In some circumstances, a test may need to wait for a particular condition before it starts the test proper. It may be desirable to apply a timeout to just the part of the run after that condition has been met and the real test begins. With CMake 3.6 or later, the `TIMEOUT_AFTER_MATCH` test property is available to support this behavior. It expects a list containing two items, the first being the number of seconds to use as a timeout after the condition is met, and the second is a regular expression to match against the test output. When the regular expression is found, the test's

timeout countdown and start time is reset, and the timeout value is set to the first list item.

For example, the following will apply an overall timeout of 30 seconds to the test, but once the string `Condition met` appears in the test output, the test will have 10 seconds to complete from that point, and the original 30-second timeout condition will no longer apply:

```
set_tests_properties(t2 PROPERTIES  
    TIMEOUT 30  
    TIMEOUT_AFTER_MATCH "10;Condition met"  
)
```

If the test took 25 seconds for the condition to be satisfied, the overall time of the test could be up to 35 seconds. But because the test's start time is also reset, `ctest` would report a time between 0 and 10 seconds (the time for the condition to be met is not counted). On the other hand, if the condition fails to be met within 30 seconds, the test will show an overall test time of about 30 seconds.

The reported times for the above can be confusing, so prefer to avoid using `TIMEOUT_AFTER_MATCH` in favor of other ways to handle preconditions. [Section 28.1, “Simple Test Dependencies”](#), [Section 28.2, “Test Fixtures”](#), and [Section 28.4, “Simple Resource Constraints”](#) discuss better alternatives.

For more advanced scenarios, CMake 3.27 and later allow the project to specify the POSIX signal sent to the process upon timeout. This is only supported on non-Windows platforms. The `TIMEOUT_SIGNAL_NAME` and `TIMEOUT_SIGNAL_GRACE_PERIOD` test properties control this advanced behavior. Projects should avoid using these if they don't have a strong need for them, as they are not supported on all platforms.

An example of where the `TIMEOUT_SIGNAL_...` test properties might be useful is when investigating a flaky test which occasionally hangs in continuous integration jobs. Since the hanging occurs in a situation where the developer doesn't typically have direct access, it can be a challenge to obtain details about why the test is hanging. To assist with investigations, a signal handler can be added to the test, which will dump the executable's internal state when it receives a `SIGUSR1` signal, then exit the application with a non-zero exit code. The test properties can then be set such that if the test takes too long and looks to be hanging, `ctest` will send a `SIGUSR1` signal. The output may then reveal what was going on at that time. This would not interfere with the test when it runs normally, dumping the internal state only when it appears to have hung.

```
add_test(NAME SomethingFlaky COMMAND doSomething)
set_tests_properties(SomethingFlaky PROPERTIES
    TIMEOUT 10
    TIMEOUT_SIGNAL_NAME SIGUSR1
```

```
    TIMEOUT_SIGNAL_GRACE_PERIOD 5  
)
```

27.4. Test Grouping And Selection

In larger projects, it is quite common to want to run only a subset of all defined tests. The developer may be focusing on a particular failing test and may not be interested in all the other tests while working on that problem. CMake offers a few different ways to narrow down the set of tests to execute.

27.4.1. Test Names

One way to execute only a specific subset of tests is by giving the `-R` and `-E` options to `ctest`. These options each specify a regular expression to be matched against test names. The `-R` option selects tests to be included in the test set, whereas `-E` excludes tests. Both options can be specified to combine their effects.

```
add_test(NAME FooOnly    COMMAND ...)  
add_test(NAME BarOnly    COMMAND ...)  
add_test(NAME FooWithBar COMMAND ...)  
add_test(NAME FooSpecial  COMMAND ...)  
add_test(NAME Other_Foo   COMMAND ...)
```

```
# Run just FooOnly and BarOnly  
ctest -R Only  
  
# Run all but FooWithBar  
ctest -E Bar
```

```
# Run all tests starting with Foo except FooSpecial  
ctest -R '^Foo' -E FooSpecial  
  
# Run only FooSpecial and Other_Foo  
ctest -R 'FooSpecial|Other_Foo'
```

Sometimes it isn't always easy to work out a regular expression to capture just the desired tests, or a developer may just want to see all the tests that have been defined without running them. The `-N` option instructs `ctest` to only print the tests rather than run them, which can be a useful way to check that the regular expressions yield the desired set of tests.

```
ctest -N  
  
Test project /path/to/build/dir  
Test #1: FooOnly  
Test #2: BarOnly  
Test #3: FooWithBar  
Test #4: FooSpecial  
Test #5: Other_Foo  
  
Total Tests: 5
```

```
ctest -N -R 'FooSpecial|Other_Foo'  
  
Test project /path/to/build/dir  
Test #4: FooSpecial  
Test #5: Other_Foo  
  
Total Tests: 2
```

Starting with CMake 3.29, `ctest` also supports the options `--tests-from-file` and `--exclude-from-file`. Either option requires

the name of a file to be given after it, and that file must exist. Each line of the file specifies the exact name of a test to be included or excluded from the test set respectively. These further reduce the list of tests, which may already be filtered by options such as -R or -E.

For example, consider a file `some_tests.txt` which contains the following lines:

```
FooOnly  
BarOnly
```

With the same set of five tests defined above, the following command would result in no tests being run:

```
ctest -R FooSpecial --tests-from-file some_tests.txt
```

This is because -R FooSpecial already filters the test list down to just the one test named FooSpecial. The only tests listed in `some_tests.txt` are FooOnly and BarOnly, neither of which is in the filtered list of tests, so the result is an empty test set. The order of the command line options is not important.

27.4.2. Test Numbers

As each test is added, it is given a test number. This number will remain the same between runs, unless another test is added or removed before it in the project. The ctest output shows this number beside the test.

When using the `-N` option, tests are listed in the order they have been defined by the project, but the tests might not necessarily be executed in that order. Tests to be run can be selected by test number rather than name using the `-I` option. This method is rather fragile, since the addition or removal of a single test can change the number assigned to any number of other tests. Even passing a different configuration via the `-C` option to `ctest` can result in the test numbers changing. In most cases, matching by name will be preferable.

One situation where test numbers can be useful is where two tests have been given exactly the same name. Except when defined in the same directory, both tests are accepted without any warnings being issued. While duplicate test names should generally be avoided, in hierarchical projects involving externally provided tests, this may not always be possible.

The `-I` option expects an argument which has a somewhat complicated form. The most direct form involves specifying test numbers on the command line, separated by commas with no spaces:

```
ctest -I [start[,end[,stride[,testNum[,testNum...]]]]]
```

To specify just individual test numbers, the start, end and stride can be left blank like so:

```
ctest -I ,,,3,2      # Selects tests 2 and 3 only
```

The same details can be read from a file instead of being specified on the command line by giving the name of the file to the -I option. This can be useful if regularly running the same complicated set of tests, and no tests are being added or removed:

testNumbers.txt

```
...,3,2
```

```
ctest -I testNumbers.txt
```

27.4.3. Labels

Selecting tests individually by name or number can become cumbersome if a large set of related tests needs to be executed. Tests can be assigned an arbitrary list of labels using the LABELS test property, and then tests can be selected by these labels. The -L and -LE options are analogous to the -R and -E options respectively, except they operate on test labels rather than test names. Continuing with the same tests defined in the earlier example:

```
set_tests_properties(FooOnly PROPERTIES
    LABELS "Foo"
)
set_tests_properties(BarOnly PROPERTIES
    LABELS "Bar"
)
set_tests_properties(FooWithBar PROPERTIES
    LABELS "Foo;Bar;Multi"
)
set_tests_properties(FooSpecial PROPERTIES
```

```
LABELS "Foo"
)
set_tests_properties(Other_Foo PROPERTIES
    LABELS "Foo"
)
```

```
ctest -L Bar

Test project /path/to/build/dir
  Start 2: BarOnly
  1/2 Test #2: BarOnly ..... Passed   1.52 sec
    Start 3: FooWithBar
  2/2 Test #3: FooWithBar ..... Passed   1.02 sec

100% tests passed, 0 tests failed out of 2

Label Time Summary:
Bar      =  2.53 sec*proc (2 tests)
Foo      =  1.02 sec*proc (1 test)
Multi    =  1.02 sec*proc (1 test)

Total Test time (real) =  2.54 sec
```

Labels not only enable convenient grouping for test execution, they also provide grouping for basic execution time statistics. As seen in the example output above, the `ctest` command prints a label summary when any test in the set of executed tests has its `LABELS` property set. This allows the developer to get an idea how each label group is contributing to the overall test time. The `proc` part of the `sec*proc` units refers to the number of processors allocated to tests (described in [Section 28.3, “Parallel Execution”](#)). A test that ran for 3 seconds and required 4 processors would report a value of 12. The label time summary can be suppressed with the `--no-label-summary` option.

With CMake 3.22 or later, labels can also be added dynamically to a test when the test runs. Dynamically added labels can't be used with `-L` or `-LE` options, they are typically only useful for dashboard reporting. See the discussion in [Section 31.4, “Test Measurements And Results”](#) for further details.

27.4.4. Repeating Tests

Another common need is to re-run only those tests that failed the last time `ctest` was run. This can be a convenient way to re-check only the relevant tests after making a small fix, or to re-run tests that failed due to some temporary environmental condition. The `ctest` command supports a `--rerun-failed` option which provides this behavior without needing any test names, numbers or labels to be given.

Sometimes a particular test or set of tests only fails intermittently, so the test(s) may need to be run many times to try to reproduce a failure. Rather than running `ctest` itself over and over, the `--repeat-until-fail` option can be given with the upper limit on the number of times each test can be repeated. If a test fails, it will not be re-run again for that `ctest` invocation.

```
ctest -L Bar --repeat-until-fail 3

Test project /path/to/build/dir
Start 2: BarOnly
Test #2: BarOnly ..... Passed    1.52 sec
Start 2: BarOnly
Test #2: BarOnly .....***Failed   0.00 sec
```

```
Start 3: FooWithBar
Test #3: FooWithBar ..... Passed 1.02 sec
Start 3: FooWithBar
Test #3: FooWithBar ..... Passed 1.02 sec
Start 3: FooWithBar
2/2 Test #3: FooWithBar ..... Passed 1.02 sec
```

50% tests passed, 1 tests failed out of 2

Label Time Summary:

```
Bar      = 1.02 sec*proc (2 tests)
Foo      = 1.02 sec*proc (1 test)
Multi    = 1.02 sec*proc (1 test)
```

Total Test time (real) = 4.59 sec

The following tests FAILED:

2 - BarOnly (Failed)

Errors while running CTest

The label summary doesn't accumulate the total time for the repeated tests, it only uses the time of a test's last execution. The total test time does, however, count all repeats.

CMake 3.17 expanded the repeat capabilities to re-run tests covering more situations. A new `ctest` option `--repeat mode:n` was added, where `n` is the maximum number of times a test will be run, and `mode` is one of the following:

`until-fail`

This corresponds to the `--repeat-until-fail` option and is provided for consistency.

`until-pass`

This mode re-runs a test until it passes. Ordinarily, tests should always pass, but occasionally this option may be useful during development, or to investigate a problem. It should not be relied upon for a more permanent arrangement.

after-timeout

Certain types of tests may experience an occasional failure due to external environmental factors. For example, a test case may need to perform a network operation, and it may sometimes take longer than expected or even block indefinitely. Tests that interact with websites across the internet are especially susceptible to such timeouts. This option can be used to allow such tests to be retried if they timeout. A low value for `n` should typically be used to avoid having repeated timeouts significantly extend the overall test time.

27.5. Cross-compiling, Emulators, And Launchers

When an executable target defined by the project is used as the command for `add_test()`, CMake automatically substitutes the location of the built executable. For a cross-compiling scenario, this won't typically work, since the host cannot usually run binaries built for a different platform directly.

To help with this, CMake provides a `CROSSCOMPILING_EMULATOR` target property which can be set to a script or executable to be used to launch the target. CMake will prepend this to the target binary when forming the command to run, so the real target binary becomes the first argument to the emulator script or executable. This enables tests to be run even when cross-compiling. With CMake 3.15 or later, `CROSSCOMPILING_EMULATOR` can be a list to allow arguments to be included in the items inserted before the target binary.

The `CROSSCOMPILING_EMULATOR` doesn't have to be an actual emulator, it just has to be a command that can be run on the host to launch the target executable. While a dedicated emulator for the target platform is the obvious use case, one could also set it to a script that copies the executable to a target machine and runs it remotely (e.g. over a SSH connection). Whichever method is used, developers should be aware that the startup time for an emulator or for preparing to run the binary could be non-trivial, which may have an impact on the test timing measurements. This can, in turn, mean that test timeout settings may need to be revised.

The default value for the `CROSSCOMPILING_EMULATOR` target property is taken from the `CMAKE_CROSSCOMPILING_EMULATOR` variable. This is the usual way the emulator details would be specified, rather than setting each target's property individually. The variable would typically be set in the

toolchain file, since it affects things like `try_run()` commands in a similar way to how it affects tests and custom commands, as described above. See the discussion in [Section 24.5, “Compiler Checks”](#) for more on this aspect of the variable’s effects.

Even when not cross-compiling, CMake might still honor a non-empty `CROSSCOMPILING_EMULATOR` target property and prepend it to the command line for tests and custom commands executing that target. Policy `CMP0158`, introduced in CMake 3.29, controls this behavior. When the policy is set to `NEW`, `CROSSCOMPILING_EMULATOR` is only used if `CMAKE_CROSSCOMPILING` is set to true. When the policy is `OLD` or unset (or equivalently, if using CMake 3.28 or older), `CROSSCOMPILING_EMULATOR` is always used regardless of `CMAKE_CROSSCOMPILING`.

Using `CROSSCOMPILING_EMULATOR` even when not cross-compiling can be useful. It can effectively act like a launch script to assist with things like debugging or data-gathering. It is not recommended to use this technique as a permanent feature of a project’s build, but it may be useful in certain development situations. CMake 3.29 added a new `TEST_LAUNCHER` target property and an associated `CMAKE_TEST_LAUNCHER` variable which provide a much better way to handle such use cases. These work the same way as the `CMP0158` policy’s `OLD` behavior of `CROSSCOMPILING_EMULATOR` and `CMAKE_CROSSCOMPILING_EMULATOR`, but they more clearly communicate the intention instead of abusing a facility meant only for cross-compiling scenarios.

27.6. JUnit Output

The output from `ctest` is informative for humans, but it is not suitable for parsing by other tools. Such workflows need a more structured format. CMake 3.21 and later can write the test results in the widely supported JUnit XML format. JUnit XML files can often be directly imported by CI tools and test-reporting software.

A JUnit XML results file can be generated by adding an option to the `ctest` command line, specifying the file name to write the results to:

```
ctest --output-junit /path/to/resultFile.xml ...
```

By default, `ctest` only logs a brief summary of each test case to the standard output, whereas the JUnit XML results file contains the actual test output. However, tests can sometimes produce a lot of output. Therefore, `ctest` will truncate the output written to a JUnit results file once output gets beyond a configurable limit. By default, the output from any passing test will be truncated at 1024 bytes. For failing tests, the output will be truncated at 307,200 bytes (300kB). These limits can be overridden with the `--test-output-size-passed` and `--test-output-size-failed` command-line options respectively.

With CMake 3.24 or later, the type of output truncation can also be controlled using the `--test-output-truncation` command-line

option. The option must be followed by one of the following values:

tail

Retain the start of the output, cutting off the end. This is usually the most appropriate setting and is also the default behavior.

head

Retain the end of the output, skipping the start. This can be useful if the end of test output is more likely to hold interesting information. Beware that quite often the first error is the most important, with later errors often being spurious, or a consequence of earlier errors. Using head truncation can increase the chance of missing the first error and leading the user to focus on a later error that might not be the actual cause of the problem.

middle

The start and end of the output are retained, with the middle of the output omitted. This is less likely to be useful, but may be appropriate if important details are typically logged first and errors are likely to be captured at the end.

```
ctest --output-junit some-file.xml \
    --test-output-size-passed 10000 \
    --test-output-size-failed 40000 \
    --test-output-truncation middle
```

Individual tests can override the output limits by logging the special string `CTEST_FULL_OUTPUT` somewhere in their output. The entire output from that test will then be included in the test results, regardless of any output limit. Use this feature sparingly, as it has the potential to significantly increase the amount of data reported and therefore the size of the JUnit XML file.

None of the above output limits affect the results logged to standard output. They only affect the JUnit XML file's contents.

27.7. Recommended Practices

Aim to make each test name short, but sufficiently specific to the nature of the test. This makes it easy to narrow down a test set using regular expressions with the `-R` and `-E` options given to `ctest`. Avoid including `test` in the name, since it adds extra content to the test output with no benefit.

Assume that the project may one day be incorporated into a much larger hierarchy of projects which may have many other tests. Aim to use test names that are specific enough to reduce the chances of name clashes. More importantly, prefer to give parent projects control over whether to add the tests at all. Define the default behavior to only add tests if there is no parent project. Use a non-cache variable to implement the control so that a parent project can choose whether to expose it in the cache or not. A suitable variable name would be `TEST_XXX`.

where XXX is the uppercase project name. The following demonstrates such an arrangement for a top level project called FooBar:

```
if(TEST_FOOBAR OR
    CMAKE_SOURCE_DIR STREQUAL FooBar_SOURCE_DIR)
    add_test(...)
endif()
```

To further improve integration with parent projects, consider using the LABELS test property to include a project-specific label for each test. These per-project labels should allow tests to be easily included or excluded by regular expressions given to ctest via -L and -LE options. Tests can have multiple labels, so this places no restriction on how else labels can be used, but it may be difficult to ensure that the project-specific label is rigorously set on all of a project's tests.

Another good use of labels is to identify tests that are expected to take a long time to run. Developers and continuous integration systems may want to run these less frequently, so being able to exclude them based on test labels can be very convenient. Consider adding a label to tests that run for a non-trivial amount of time, and that don't need to run as often. In the absence of any other existing convention, a label of LongRunning is a good choice.

As well as using regular expression matching against test names and labels, it is also possible to narrow the set of tests

down to a particular directory and below. Instead of running `ctest` from the top of the build tree, it can be run from subdirectories below it. Only those tests defined from that directory's associated source directory and below will be known to `ctest`. To be able to take full advantage of this, tests should not all be collected together in one place and defined with no directory structure. It may be useful to keep tests close to the source code they are testing so that the natural directory structure of the source code can be re-used to also give structure to the tests. If the source code is ever moved around, this approach also makes it easier to move the associated tests with it.

It can be tempting to write tests that turn on a lot of logging and then use pass/fail regular expressions to determine success. This can be a fairly fragile approach, as developers frequently change logged output under the assumption that it is just for informational purposes. Adding timestamps into the logged output further complicates that approach. Rather than relying on matching logged output, prefer to make the test code itself determine the success or failure status by explicitly testing the expected pre- and post-conditions, intermediate values, etc.

If a test's environment variables need to be modified, prefer to use the `ENVIRONMENT_MODIFICATION` test property. It is more flexible and more robust than the older `ENVIRONMENT` property. Avoid passing list values to either test property so that fragile

escaping of semicolons won't be required. For more complicated cases, CMake 3.29 and later provide the `TEST_LAUNCHER` target property and its associated `CMAKE_TEST_LAUNCHER` CMake variable. These can be used to launch tests via a script, which can modify the environment in arbitrary ways, or perform other tasks before starting the test executable. Note that test fixtures may be a more flexible and more robust way to implement setup and cleanup tasks (see [Section 28.2, “Test Fixtures”](#)).

For projects where cross-compiling for a different target platform is a possibility, consider whether tests can be written to run under an emulator or be copied and executed on a remote system via a script or an equivalent mechanism. CMake's `CMAKE_CROSSCOMPILING_EMULATOR` variable and the associated `CROSSCOMPILING_EMULATOR` target property can be used to implement either of these strategies. Ideally, `CMAKE_CROSSCOMPILING_EMULATOR` would be set in the toolchain file used for the cross-compilation. Prefer to use the `CMAKE_TEST_LAUNCHER` variable instead for cases that do not involve cross-compilation.

With CMake 3.18 or later, the `ctest --stop-on-failure` option can be used to end a test run immediately upon the first error encountered. This can be a time-saving measure during development where any failure is likely to be related to the area the developer is working on at the time. It can also be used to

quickly end a continuous integration run so that the failure can be reported as early as possible. This comes at the expense of only providing feedback about one of possibly many errors, so it should normally only be considered when the time to run all tests is high.

28. TEST RESOURCES AND CONSTRAINTS

For larger, more complex projects, relationships often exist between test cases. Some tests may need other tests to have passed first before they can safely be executed. Other tests may need certain setup or cleanup actions performed before and after they run. The number of tests might also be sufficiently high that running them all one at a time would be prohibitively slow. Running tests in parallel may be desirable, but then they may compete for resources on the test machine. `ctest` provides a range of methods for handling these various aspects of test execution.

28.1. Simple Test Dependencies

Tests can be used to do more than verify a particular condition, they can also be used to enforce them. For example, one test may need a server to connect to so that it can verify a client implementation. Rather than relying on the developer to ensure such a server is available, another test case can be created which ensures a server is running. The client test then needs to

have some kind of dependency on the server test to make sure they are run in the correct order.

The DEPENDS test property allows a form of this constraint to be expressed by holding a list of other tests that must complete before that test can run. The above client/server example could loosely be expressed as follows:

```
set_tests_properties(ClientTest1 ClientTest2
    PROPERTIES DEPENDS StartServer
)
set_tests_properties(StopServer
    PROPERTIES DEPENDS "ClientTest1;ClientTest2"
)
```

A weakness with the DEPENDS test property is that while it defines a test order, it does not consider whether the prerequisite tests pass or fail. In the above example, if the StartServer test case fails, the ClientTest1, ClientTest2 and StopServer tests will still run. These tests will then likely fail, and the test output will show all four tests as failed. But in reality, only the StartServer test failed, and the others should have been skipped. Because of this limitation, the DEPENDS test property has limited usefulness. The next section discusses a better solution which is more robust and generally a better alternative.

28.2. Test Fixtures

CMake 3.7 added support for test fixtures, a concept which allows dependencies between tests to be expressed much more rigorously. A test can indicate it requires a particular fixture by listing that fixture name in its `FIXTURES_REQUIRED` test property. Any other test with that same fixture name in its `FIXTURES_SETUP` test property must complete successfully before the dependent test will be started. If any of the setup tests for a fixture fail, all tests that require that fixture will be marked as skipped. Similarly, a test can list a fixture in its `FIXTURES_CLEANUP` test property to indicate that it must be run after any other test with that same fixture listed in its `FIXTURES_SETUP` or `FIXTURES_REQUIRED` property. These cleanup tests do not require the setup or fixture-requiring tests to pass, since cleanup may be needed even if the earlier tests fail.

All three fixture-related test properties accept a list of fixture names. These names do not have to relate to the test names, the resources they use, or any other property, but they often align with values used for `RESOURCE_LOCK` properties (discussed further below in [Section 28.4, “Simple Resource Constraints”](#)). The fixture names should make clear to developers what they represent.

Consider the client/server example of the previous section. This can be expressed rigorously using fixtures with the following properties:

```
set_tests_properties(StartServer
    PROPERTIES FIXTURES_SETUP Server
)
set_tests_properties(ClientTest1 ClientTest2
    PROPERTIES FIXTURES_REQUIRED Server
)
set_tests_properties(StopServer
    PROPERTIES FIXTURES_CLEANUP Server
)
```

In the above, `Server` is the name of the fixture. `ClientTest1` and `ClientTest2` will only run if `StartServer` passes. `StopServer` will run last regardless of the results for the other three tests. If parallel execution is enabled (discussed further below in [Section 28.3, “Parallel Execution”](#)), `StartServer` will run first, the two client tests will run simultaneously, and `StopServer` will only run after both client tests have been completed or skipped.

Another benefit of fixtures can be seen when the developer is running only a subset of tests. Consider the scenario where the developer is working on `ClientTest2` and is not interested in running `ClientTest1`. If dependencies between tests are expressed using `DEPENDS`, the developer is responsible for ensuring they also include required tests in the test set. This means they would need to understand all the relevant dependencies. The `ctest` command line would then look something like this:

```
ctest -R "StartServer|ClientTest2|StopServer"
```

When fixtures are used, `ctest` automatically adds any setup or cleanup tests to the set of tests to be executed in order to satisfy fixture requirements. This means the developer need only specify the test they want to focus on and leave the dependencies to `ctest`:

```
ctest -R ClientTest2
```

When using the `--rerun-failed` option, this same mechanism ensures that setup and cleanup tests are automatically added to the test set to satisfy fixture dependencies of the previously failed tests.

A fixture may have zero or more setup tests and zero or more cleanup tests. Fixtures may define setup tests with no cleanup tests, and vice versa. While not particularly useful, a fixture can have no setup or cleanup tests at all, in which case the fixture does not affect test scheduling. Similarly, a fixture can have setup or cleanup tests associated with it, but no tests that require it. These situations can arise during development when tests are being defined or temporarily disabled. For the case of a fixture having no tests that require it, a bug in CMake 3.7 allowed that fixture's cleanup tests to run before the setup tests, but that bug was fixed in the 3.8.0 release.

A more involved example demonstrates how fixtures can be used to express more complex test dependencies. Expanding the previous example, suppose one client test requires just a

server, whereas another requires both a server and a database to be available. This is succinctly expressed by defining two fixtures: Server and Database. For the latter, it is acceptable to check whether there is a database available and fail if not, so the Database fixture requires no cleanup test. The Server and Database fixtures are not related, so they need no dependencies between them. These constraints can be expressed like so:

```
# Setup/cleanup
set_tests_properties(StartServer
    PROPERTIES FIXTURES_SETUP Server
)
set_tests_properties(StopServer
    PROPERTIES FIXTURES_CLEANUP Server
)
set_tests_properties(EnsureDbAvailable
    PROPERTIES FIXTURES_SETUP Database
)

# Client tests
set_tests_properties(ClientNoDb
    PROPERTIES FIXTURES_REQUIRED Server
)
set_tests_properties(ClientWithDb
    PROPERTIES FIXTURES_REQUIRED "Server;Database"
)
```

While having `ctest` automatically add fixture dependencies into the test execution set is a useful feature, there are also times when this can be undesirable. Continuing with the above example, the developer may want to leave the server running and keep executing just one client test multiple times. They may be making changes, recompiling the code, and checking

whether the client test passes with each change. To support this level of control, CMake 3.9 introduced the `-FS`, `-FC` and `-FA` options to `ctest`. Each requires a regular expression that will be matched against fixture names. The `-FS` option disables adding fixture setup dependencies for those fixtures that match the regular expression provided. `-FC` does the same for cleanup tests, while `-FA` combines both, disabling both setup and cleanup tests that match. A common situation is to disable adding any setup or cleanup dependencies at all, which can be done by giving a regular expression of a single period (.). The following demonstrates various examples of the fixture control options and their effects:

Command line	Tests in execution set
<code>ctest -FS Server -R ClientNoDb</code>	<code>ClientNoDb, StopServer</code>
<code>ctest -FC Server -R ClientNoDb</code>	<code>ClientNoDb, StartServer</code>
<code>ctest -FA Server -R ClientNoDb</code>	<code>ClientNoDb</code>
<code>ctest -FS . -R Client</code>	<code>ClientNoDb, ClientWithDb, StopServer</code>
<code>ctest -FA . -R Client</code>	<code>ClientNoDb, ClientWithDb</code>

28.3. Parallel Execution

Maximizing test throughput can be important for large projects, or where tests take a long time to run. Running tests in parallel,

a key feature of `ctest`, is enabled using command line options that are very similar to the standard `make` tool. The `-j` option (or equivalently `--parallel`) specifies an upper limit on how many tests can be run simultaneously. With CMake 3.28 and earlier, a positive value must be supplied after `-j` or the option will have no effect. CMake 3.29 and later allows a value of 0, or no value at all. If a value of 0 is provided, `ctest` will automatically determine an appropriate limit based on the number of CPUs. With no value provided, there will be no limit on the number of parallel tasks. Using an unbounded limit like this should only be done if `ctest` is running under the control of a `make` job server, which `ctest` will coordinate with when using CMake 3.29 or later.

The effect of enabling parallel execution can be seen in the following examples, which use the same set of tests as defined earlier (test summaries have been omitted for brevity).

```
ctest -j 5

Test project /path/to/build/dir
  Start 5: Other_Foo
  Start 2: BarOnly
  Start 3: FooWithBar
  Start 1: FooOnly
  Start 4: FooSpecial
  1/5 Test #4: FooSpecial ..... Passed   0.12 sec
  2/5 Test #1: FooOnly ..... Passed   0.52 sec
  3/5 Test #3: FooWithBar ..... Passed   1.01 sec
  4/5 Test #2: BarOnly ..... Passed   1.52 sec
  5/5 Test #5: Other_Foo ..... Passed   2.02 sec
```

Five tests were defined and the job limit was given on the command line as 5, so `ctest` was able to start all tests immediately. The result of each test was recorded as it was completed, not in the order they were started. If the job limit is reduced to 2, the output may be more like the following:

```
ctest -j 2

Test project /path/to/build/dir
  Start 5: Other_Foo
  Start 2: BarOnly
1/5 Test #2: BarOnly ..... Passed    1.52 sec
  Start 3: FooWithBar
2/5 Test #5: Other_Foo ..... Passed    2.01 sec
  Start 1: FooOnly
3/5 Test #1: FooOnly ..... Passed    0.52 sec
  Start 4: FooSpecial
4/5 Test #3: FooWithBar ..... Passed    1.02 sec
5/5 Test #4: FooSpecial ..... Passed    0.12 sec
```

As an alternative, the `CTEST_PARALLEL_LEVEL` environment variable can be used to specify the number of jobs. This is particularly useful for continuous integration builds, where `CTEST_PARALLEL_LEVEL` can be set to the number of CPU cores on each machine. This frees every project from having to compute the optimal number of jobs themselves when using CMake 3.28 or older. The `-j` command-line option takes precedence over `CTEST_PARALLEL_LEVEL`, so projects can still override the environment variable if required. With CMake 3.29 or later, `CTEST_PARALLEL_LEVEL` can have a value of 0, or be defined with an empty value. Both of these cases are handled with the same

meaning as for the `-j` option. On Windows, note the limitation that environment variables with empty values are treated as unset, so at least some whitespace must be included instead of `CTEST_PARALLEL_LEVEL` being completely empty.

A related option `--test-load` specifies a desired upper limit on the CPU load. This takes the whole system load into account, unlike `-j` or `CTEST_PARALLEL_LEVEL` which only consider the number of tests running simultaneously. Specifying a load limit can be useful on shared systems where other processes may be competing with the tests for CPU resources.

The intention of the `--test-load` option is to tell `ctest` that it should wait until the system load drops below the specified limit before starting a new test. But in practice, the system load sometimes lags behind after starting a new test or system process. `ctest` can start multiple tests before the measured system load increases, resulting in the system load rising above the specified limit, potentially by quite a lot. To prevent the load lag from allowing too much CPU over-commitment, the `-j` option should be specified, and the number of parallel jobs should be capped at no more than the load limit. Typically, the same limit should be specified for both `--test-load` and `-j`.

By default, `ctest` will assume each test consumes one CPU. For test cases that use more than one CPU, their `PROCESSORS` test property can be set to indicate how many CPUs they are

expected to use. `ctest` will then use that value when determining whether enough CPU resources are free before starting the test. If `PROCESSORS` is set to a value higher than the job limit, `ctest` will behave as though it was set to the job limit when determining whether the test can be started.

With a large number of tests and a high job limit, the logging of each test start and completion can be difficult to follow. The overall test summary at the end of the run then becomes much more important, with each test that didn't pass listed along with its result. The `--progress` option to `ctest`, which was added in CMake 3.13, can also help reduce the output and focus on the important details. It collapses the start and completion progress messages down to a single line, similar to the output of the Ninja build tool.

28.4. Simple Resource Constraints

Tests sometimes need to ensure that no other test is running in parallel with them. They may be performing an action that is sensitive to other activities on the machine, or they may create conditions that would interfere with other tests. To enforce this constraint, the test's `RUN_SERIAL` property can be set to true.

`RUN_SERIAL` is a brutal constraint which can have a strong impact on test throughput. The `RESOURCE_LOCK` test property is often a better alternative. It provides a list of resources the test needs exclusive access to. These resources are arbitrary strings

which ctest does not interpret in any way, except to ensure that no other test with any of those resources listed in its own RESOURCE_LOCK property will run at the same time. This is a great way to serialize tests that need exclusive access to something (e.g. a database, shared memory) without blocking tests that do not use that resource.

```
set_tests_properties(FooOnly FooSpecial Other_Foo
    PROPERTIES RESOURCE_LOCK Foo
)
set_tests_properties(BarOnly
    PROPERTIES RESOURCE_LOCK Bar
)
set_tests_properties(FooWithBar
    PROPERTIES RESOURCE_LOCK "Foo;Bar"
)
```

The following sample output (again with the test summary omitted) shows that even though the job limit of 5 would allow all tests to be executed simultaneously, ctest delays starting some tests until the resources they need are available.

```
ctest -j 5

Test project /path/to/build/dir
  Start 5: Other_Foo
  Start 2: BarOnly
  1/5 Test #2: BarOnly ..... Passed    1.52 sec
  2/5 Test #5: Other_Foo ..... Passed    2.02 sec
  Start 3: FooWithBar
  3/5 Test #3: FooWithBar ..... Passed    1.01 sec
  Start 1: FooOnly
```

```
4/5 Test #1: FooOnly ..... Passed 0.52 sec
Start 4: FooSpecial
5/5 Test #4: FooSpecial ..... Passed 0.12 sec
```

28.5. Resource Groups

The RESOURCE_LOCK test property is a good fit when a test needs exclusive access to something, but when more fine-grained control over test resources is needed, the RESOURCE_GROUPS test property available with CMake 3.16 or later may be more appropriate. Resource groups enable projects to define not just *what* resources a test needs, but also *how much* of each resource is required. This controlled sharing of resources can be useful for a variety of interesting scenarios:

- Tests that require non-trivial amounts of memory can specify how much memory they need. The ctest scheduler will keep track of the memory resources it has allocated to all currently running tests. It will ensure that the available memory resources are not exceeded, delaying test execution until that test's memory requirements can be met.
- Multiple tests may need access to a GPU, but they could potentially share a GPU with other jobs as long as there are only a few of them sharing a given GPU. The end user's machine might also have one GPU, or it might have multiple GPUs installed. The project only needs to define how many slots of a GPU each test needs. The ctest scheduler will take

care of distributing the tests across the GPUs available to it at run time.

- There could be many tests all needing to communicate with a particular service. In order to prevent flooding that service, the number of tests communicating with it can be capped. For each such test, the project specifies that the test requires a resource representing that service. The user running the test suite controls the upper limit on how many tests are allowed to communicate with the service at the same time.

Compared to RESOURCE_LOCK, setting up resource groups is considerably more involved, requiring a number of separate steps:

- Define the resources a test must have in order to run. This must be done by the project.
- Define the resources available on the system. This can be done by the user running the tests, or by the script used to invoke a CDash run (discussed in [Chapter 31, CDash Integration](#)). With CMake 3.28 or later, it can also be generated dynamically by the project at test time.
- Write tests to make use of resource details passed to it by ctest via environment variables.

28.5.1. Defining Test Resource Requirements

A test defines its required resources as a list of resource *groups*. Each group consists of one or more name:value pairs, with multiple pairs separated by commas. The name part is referred to as the *resource type*.

In the following example, the group requires 16 units of mem_gb and 4 cpus:

```
mem_gb:16,cpus:4
```

A group can also be preceded by a count of how many of that whole group are needed. It is given as an integer followed by a comma, then the group definition as described above. When this count value is omitted, as in the above example, it is assumed to be 1.

The following demonstrates how to specify that the test requires 3 sets of resources where each set needs 2 gpus and 4 workers:

```
3,gpus:2,workers:4
```

A group can also list a particular resource type more than once. Consider the following example:

```
gpus:2,gpus:4
```

The above group needs a total of 6 gpus, but they can be split across two separate instances of the gpus resource type

(instances are discussed in the next section). It is permitted for 2 gpus to come from one instance and 4 from the other. They could also be satisfied with 6 gpus all on the one instance if it has the slots available.

A test may need multiple sets of resource groups where the groups are not all the same. The RESOURCE_GROUPS property accepts a list for exactly this purpose. For example:

```
set_property(TEST ParallelCoordinator PROPERTY
    RESOURCE_GROUPS
        producers:1,consumers:1
        producers:1,consumers:4
        producers:4,consumers:1
        4,producers:1,consumers:1
    )
```

The above specification results in the ParallelCoordinator test requiring a total of seven resource groups. The test won't be executed unless enough resources are available to satisfy all seven groups at once.

Being able to split the total resource requirements across multiple groups is essential for supporting certain system resource configurations. The next section discusses scenarios that take advantage of this capability.

28.5.2. Specifying Available System Resources

In order for `ctest` to allocate resources to tests, it needs to be told what resources are available on the system. The system resources are specified in a JSON file, which is passed to `ctest` in one of the following ways (listed in order of precedence):

- Using the `RESOURCE_SPEC_FILE` keyword in a call to `ctest_test()` within a CDash script (see [Chapter 31, *CDash Integration*](#)).
- Setting the `CTEST_RESOURCE_SPEC_FILE` variable, either in a CDash script, or as a `ctest -D` command line option when running a CDash script. This variable acts as a default value for the `RESOURCE_SPEC_FILE` keyword in calls to `ctest_test()`, but it is only supported with CMake 3.18 or later.
- Providing the `--resource-spec-file` command line option to `ctest`.
- Setting `CTEST_RESOURCE_SPEC_FILE` as a CMake variable (only supported with CMake 3.18 or later). To ensure the user always has control, this variable should only be set using a `cmake -D` command line option rather than hard-coding it directly in the project.

If using CMake 3.28 or later, the file can also be generated dynamically at test time by setting the `GENERATED_RESOURCE_SPEC_FILE` property on one test. The property specifies the name of a spec file that test case will generate. The `FIXTURES_SETUP` property must also be set to

exactly one value, and all other tests that have RESOURCE_GROUPS set must also have their FIXTURES_REQUIRED test property set to that value. If these properties are all set, none of the other above methods can be used, which takes control away from the developer. The project should provide a way to disable setting the GENERATED_RESOURCE_SPEC_FILE in case the developer wants to override the resource specification.

The format of this JSON file can be thought of as follows (a more formal description can be found in the CMake documentation of the `ctest` command):

```
{
  "version": { "major": 1, "minor": 0 },
  "local": [
    {
      "resource1": [ ... ],
      "resource2": [ ... ],
      ...
    }
  ]
}
```

The `version` object must exist at the top level, and it must contain both a `major` and a `minor` element. The first release of the resource allocation feature in CMake 3.16 requires `major` to be 1 and `minor` to be 0. Future releases may support other version combinations.

The other top level JSON element must be named `local`, and it must be an array with exactly one element (future CMake

releases may allow more). That array element is a JSON object that defines each of the resource types provided by the system on which the tests will run. The name of each resource type must be all lowercase, may contain numbers and underscores, and must not start with a number. Each resource type is specified as an array of items with the following format:

```
{  
  "id": "name",  
  "slots": numericValue  
}
```

The `id` is the name used to identify this particular instance of the resource. This name must be unique across all instances for this resource type, and it must only contain lowercase letters, numbers or underscores. The name is not required to start with a letter or underscore, and it can contain just a number if desired. The `slots` specifies the amount of the resource that this instance provides, and it must be given as an integer.

Example resource spec file

```
{  
  "version": { "major": 1, "minor": 0 },  
  "local": [  
    {  
      "mem_gb": [  
        { "id": "pool_0", "slots": 64 }  
      ],  
      "gpus": [  
        { "id": "0", "slots": 2 },  
        { "id": "1", "slots": 2 }  
      ],  
      "workers": [  
        { "id": "0", "slots": 2 }  
      ]  
    }  
  ]  
}
```

```
        { "id": "0", "slots": 8 },
        { "id": "1", "slots": 4 }
    ]
}
]
}
```

The above example demonstrates that values for the id only need to be unique within the same resource type. Both gpus and workers have ids of 0 and 1, but that is okay because they are different resource types.

Because units cannot be specified with the value given to slots, it may be advisable to include units in the label for the resource type where the value's meaning requires some sort of unit. In the example above, the mem_gb resource type's name makes it clear that the slots are to be interpreted as gigabytes. In the case of gpus and workers, no units are needed, since it is already clear that the slots value is a count of those resources. For resource type names that don't require units, the convention is that names should generally be in plural form.

When ctest tries to satisfy the resource requirements of a test from the available pool of resources, it does not merge all the test's resource groups together. Rather, it iterates over the resource groups one by one and tries to satisfy each group individually. For each group, each name:value pair is assessed. ctest will look up the system allocations for the resource type and try to find an item in that resource type's array that has

enough slots unallocated to satisfy that resource requirement. Importantly, ctest will not combine slots from multiple array elements to try to meet one name:value pair's resource requirements.

An example helps demonstrate the allocation logic. Consider the resource spec file given above and a resource group defined as gpus:4. The system has a combined total of 4 slots of the gpus resource type, but they are split across two separate items with ids 0 and 1. Because ctest is only allowed to satisfy a name:value resource requirement from a single element of a resource type's array, this requirement cannot be satisfied and the test will fail to run. Conversely, if a test had a resource group definition of 4,gpus:1, it requires 4 separate groups, where each group needs one gpus slot. This *can* be satisfied, and two groups can even share one array item. For example, two groups can share the resource with id 0, and the other two groups can share resource id 1. A group defined as gpus:1,gpus:1 could be satisfied three different ways. It could receive both slots from id 0, both slots from id 1, or one slot from each.

28.5.3. Using Resources Allocated To A Test

The test receives information about the resources allocated to it through a number of environment variables. The most basic of these is CTEST_RESOURCE_GROUP_COUNT, which will hold the total number of resource groups the test specified. If this

environment variable is not defined, it means that no resource spec file was provided when ctest was invoked. It is up to the test to then decide what to do in such cases. If the test cannot run without resource allocations being provided, the test should either fail or indicate that it has been skipped (for example, by a return code that matches the SKIP_RETURN_CODE test property, or by output that matches a SKIP_REGULAR_EXPRESSION).

For each resource group, there will be a set of environment variables with the pattern CTEST_RESOURCE_GROUP_<num> containing a list of resource types allocated for that group. Another set of environment variables of the form CTEST_RESOURCE_GROUP_<num>_<resourceType> specifies exactly which resources of a given resource type were allocated. The <resourceType> will be the uppercase name of the resource type. The contents of these variables will be a list containing one or more items of the form id:X,slots:Y, which can be read as "Y slots from id X".

To illustrate, one example in the previous section specified a set of resource groups as 4,gpus:1. This might lead to the test receiving a set of environment variables like the following:

```
CTEST_RESOURCE_GROUP_COUNT=4
CTEST_RESOURCE_GROUP_0=gpus
CTEST_RESOURCE_GROUP_1=gpus
CTEST_RESOURCE_GROUP_2=gpus
CTEST_RESOURCE_GROUP_3=gpus
```

```
CTEST_RESOURCE_GROUP_0_GPUS=id:0,slots:1  
CTEST_RESOURCE_GROUP_1_GPUS=id:0,slots:1  
CTEST_RESOURCE_GROUP_2_GPUS=id:1,slots:1  
CTEST_RESOURCE_GROUP_3_GPUS=id:1,slots:1
```

For another example, consider a test that has one resource group, where that group is defined as gpus:2,gpus:2,workers:4. A possible set of environment variables it could receive would be:

```
CTEST_RESOURCE_GROUP_COUNT=1  
CTEST_RESOURCE_GROUP_0=gpus,workers  
CTEST_RESOURCE_GROUP_0_GPUS=id:0,slots:2;id:1,slots:2  
CTEST_RESOURCE_GROUP_0_WORKERS=id:0,slots:4
```

Note how two list items are returned for CTEST_RESOURCE_GROUP_0_GPUS because the resource group listed gpus:2 twice.

It is up to the test how it uses the information provided through the environment variables. At the very least, it should always confirm whether CTEST_RESOURCE_GROUP_COUNT is defined.

28.6. Recommended Practices

If the minimum CMake version can be set to 3.7 or later, prefer to use test fixtures to define dependencies between tests. Define test cases to set up and clean up resources required by other tests, to start and stop services, and so on. When running with a reduced test set as a result of regular expression matching or

options like `--rerun-failed`, `ctest` automatically adds the required fixture tests to the test set. Fixtures also ensure that tests whose dependencies fail are skipped, unlike the `DEPENDS` test property which merely controls test order without enforcing a success requirement. Also prefer to use fixtures over the `TIMEOUT_AFTER_MATCH` test property due to the clearer dependency relationship and timing control.

To gain fine-grained control over which tests will be automatically added to the test set to satisfy fixture dependencies, use CMake 3.9 or later for the `ctest` options `-FS`, `-FC` and `-FA`. Projects can still require only CMake 3.7 as a minimum version, but developers are free to use a later version for their own convenience.

Make the most of the support for parallel test execution in `ctest`. Where tests are known to use more than one CPU, set those tests' `PROCESSORS` property to provide better guidance to `ctest` for how to schedule them. If tests need exclusive access to a shared resource, use the `RESOURCE_LOCK` property to control access to that resource. Avoid using the `RUN_SERIAL` test property unless there is no other alternative. `RUN_SERIAL` can have a big negative impact on parallel test performance and is rarely justified apart from quick, temporary developer experiments, or where a test case is wrapping another test system which also supports parallel execution.

If the machine on which ctest is being run may have other processes contributing to the CPU load, consider using the --test-load option to help limit the CPU over-commit. This can be especially useful on developer machines where developers may be building and running tests for multiple projects simultaneously.

29. BUILD AND TEST MODE

ctest can do more than simply execute a set of tests. It can drive an entire configure, build and test pipeline. There are two main methods for doing this; a more basic, standalone way (the focus of this chapter), and a more powerful approach closely associated with a dashboard reporting tool (see [Chapter 31, CDash Integration](#)).

29.1. Using Build And Test Mode

Build-and-test mode is provided by the ctest tool. It is initiated by passing `--build-and-test` as the first command-line argument, with the following general form:

```
ctest --build-and-test sourceDir buildDir
      --build-generator generator
      [options...]
      [--test-command testCommand [args...]]
```

Without any options, the above will run CMake with the specified `sourceDir` and `binaryDir` and use the specified generator. All three of these must be specified. If the CMake run was successful, ctest will then build the `clean` target, and lastly

it will build the default `all` target. To run tests as well after the build step, the last option on the command line must be `--test-command` with its associated `testCommand` and optionally some arguments. This can be another invocation of `ctest` to run all tests, as demonstrated in the following example.

```
ctest --build-and-test sourceDir buildDir \
      --build-generator Ninja           \
      --test-command ctest -j 4
```

The above carries out a full configure-clean-build-test pipeline. Various options are provided, which can be used to modify which parts of the pipeline are run and how they are run. Some of the more notable options include:

- `--build-nocmake` and `--build-noclean` disable the configure and clean steps respectively.
- The `--build-two-config` option will invoke CMake twice. This handles certain special cases where a second CMake pass is needed to fully configure a project.
- When using a generator like Visual Studio, it may be necessary to specify extra generator details with `--build-generator-platform` and `--build-generator-toolset`. These will be passed through as the `-A` and `-T` options respectively to `cmake` for the configure step.
- Some generators like Xcode may require the project name to be given so that the project file generated by the configure

stage can be found. This can be done with the `--build-project` option.

- The target to build in the build step can be set using the `--build-target` option.
- The build tool can be overridden by passing `--build-makeprogram` with the alternative tool.

As can be seen in the above, all options related to the `--build-and-test` mode begin with `--build`. While most options have intuitive names, the common `--build` prefix can lead to some unfortunate confusing anomalies. An option with the name `--build-options` exists which may initially seem to be related to the build step, but it is actually used to pass command line options to the `cmake` command. It also has the additional constraint that it must be last on the command line, unless `--test-command` is also given, in which case `--build-options` must precede `--test-command`.

The following example should clarify these constraints. It adds two cache variable definitions to the `cmake` invocation, and it runs the full test suite after the build step.

```
ctest --build-and-test sourceDir buildDir      \
      --build-generator Ninja      \
      --build-options -DCMAKE_BUILD_TYPE=Debug \
                      -DBUILD_SHARED_LIBS=ON \
      --test-command ctest -j 4
```

There are a few other `--build-`... options, but the above covers the most useful ones. The other remaining option that should be mentioned is `--test-timeout`. It places a time limit (in seconds) on how long the test command is allowed to run before it is forced to terminate.

29.2. Use Cases

One situation where build and test mode is particularly convenient is where a project needs to perform a complete configure-build-test cycle off to the side, separate from the main build. Since the whole cycle can be controlled by a single `ctest` invocation, it can be used as the `COMMAND` part of a call to `add_test()`. This makes the process of adding a basic CMake project to the main project's test suite relatively straightforward. CMake itself uses the `ctest` build and test mode extensively in its own test suite in exactly this manner.

The following example demonstrates testing an API of a library built by the main project:

```
add_library(Decoder foo.c bar.c)

add_test(NAME Decoder.api
        COMMAND ${CMAKE_CTEST_COMMAND}
        --build-and-test  ${CMAKE_CURRENT_LIST_DIR}/test_api
                          ${CMAKE_CURRENT_BINARY_DIR}/test_api
        --build-generator ${CMAKE_GENERATOR}
        --build-options   -DDECODER_LIB=<TARGET_FILE:Decoder>
        --test-command    ${CMAKE_CTEST_COMMAND}
)
```

The `test_api` source directory would contain its own `CMakeLists.txt` file whose sole purpose is to configure a build that links against the `Decoder` library. The absolute path to that library is set in the `DECODER_LIB` variable (this is just one of a few ways to pass the library location to the test project).

An interesting thing about this sort of test is that it can also be used to verify that a particular test project does *not* build, or to verify that configuring fails with a particular fatal error, such as a missing symbol. Such expected fatal build errors cannot be tested in the main project, since it would cause the main project's build to fail. Separating the test build off to the side means it can fail without affecting the main build, and the test can verify the failure with an appropriate `FAIL_REGULAR_EXPRESSION` or a non-zero return code.

Another scenario where such tests can be helpful is to test the output of a code generator created by the main project. Test fixtures can be used to set up a pair of tests: one to generate the code, and the other to perform a test build with it. This is particularly helpful if the code generator creates files that `cmake` would normally read, such as `CMakeLists.txt` files. For example:

```
add_executable(CodeGen generator.cpp)

add_test(NAME GenerateCode COMMAND CodeGen)
add_test(NAME BuildGeneratedCode
    COMMAND ${CMAKE_CTEST_COMMAND}
    --build-and-test ${CMAKE_CURRENT_LIST_DIR}/test_gen
    ${CMAKE_CURRENT_BINARY_DIR}/test_gen
```

```

--build-generator ${CMAKE_GENERATOR}
--test-command    ${CMAKE_CTEST_COMMAND}
)

set_tests_properties(GenerateCode
PROPERTIES FIXTURES_SETUP Generator
)
set_tests_properties(BuildGeneratedCode
PROPERTIES FIXTURES_REQUIRED Generator
)

```

Build-and-test mode could also be used to verify CMake utility scripts by including them in a small test project and invoking its functionality as appropriate. In effect, this provides a fairly convenient way to implement unit testing of CMake scripts that avoids having to put such tests into the configure stage of the main project.

29.3. Alternatives

It is situation-dependent whether controlling the whole pipeline using a single `ctest` command is better or worse than invoking each of the tools needed for each stage explicitly. The last example of the previous section could just as easily be done with the following equivalent sequence of commands on Unix:

```

cmake -G Ninja          \
-B buildDir            \
-DCMAKE_BUILD_TYPE=Debug \
-DBUILD_SHARED_LIBS=ON
cd buildDir

```

```
cmake --build . --target clean  
cmake --build .  
ctest -j 4
```

Invoking each tool individually allows them to be run with the full set of options, whereas the `ctest --build-and-test` approach has only a very limited ability to control the build stage. [Chapter 31, *CDash Integration*](#) introduces an alternative way of invoking `ctest` which offers more powerful handling of the entire pipeline, including some useful additional reporting capabilities. That may be overkill for the typical use cases where build-and-test mode may be considered though.

If using CMake 3.25 or later, workflow presets may provide a simpler, more flexible alternative (see [Section 42.6, “Workflow Presets”](#)). They allow an almost arbitrary set of steps to be defined, so they can support scenarios that build-and-test mode cannot. For example:

- Multiple build or test steps can be invoked, in any order.
- Packaging can be included as part of the test. Multiple types of packaging can also be performed in the one run.
- If a multi-config generator is used, different configurations can be built, tested and packaged.

Build-and-test mode does have a couple of options that can't be implemented using workflow presets (notably running the `cmake configure` step twice or skipping it altogether). In practice,

the need for such options is rare. They usually indicate a structural problem in the test subproject, or in the main project's tests.

29.4. Recommended Practices

The `ctest` build and test mode can be a useful way of incorporating small test builds off to the side as test cases in the main project's test suite. These can be especially effective when some of those test builds need to verify that certain situations lead to configure or build errors. Since test cases can be defined as expected to fail, they can verify such conditions without making the main project's build fail. Consider using the `ctest` build and test mode as the `COMMAND` part of a call to `add_test()` to define such test cases.

On some platforms, running `cmake` configuration can take a long time. This may be due to the high cost of starting a new process (Windows), or non-trivial execution time of certain tools used during the toolchain checking performed on the first configuration (Xcode). With this in mind, use build-and-test mode judiciously. Avoid defining many separate build-and-test mode tests where each one has to configure its own build directory. Limit the number of such cases to only those that can't be implemented another way.

Consider whether workflow presets may be a better alternative to build-and-test mode (see [Section 42.6, “Workflow Presets”](#)).

They provide greater flexibility for the steps to be performed. Workflow presets may also be easier to run directly when the developer is working on code related to the test case.

30. TEST FRAMEWORKS

CMake and ctest provide support for building, executing and determining the pass or fail status of tests. The project is responsible for providing the test code itself, and this is where testing frameworks can be useful. Such frameworks complement the features provided by CMake and ctest to facilitate the writing of clear, well-structured test cases that integrate well into the way CMake and ctest work. Testing frameworks make writing and maintaining tests considerably easier. For most projects, using some kind of test framework is strongly recommended. Which framework is less important than using *some* suitable framework.

30.1. GoogleTest

CMake has supported GoogleTest via a `FindGTest` module for a very long time. The module searches for a pre-built GoogleTest location and creates variables that projects can use to incorporate GoogleTest into their build. From CMake 3.5, imported targets `GTest::GTest` and `GTest::Main` are also provided, which should be strongly preferred over the use of variables. Using imported targets results in much more robust

handling of usage requirements and properties. Unfortunately, these target names do not match those defined by the upstream GoogleTest project, which defines slightly different imported target names `GTest::gtest` and `GTest::gtest_main`. CMake 3.20 therefore added these new imported target names to the `FindGTest` module and deprecated the old names. It is therefore recommended that projects use at least CMake 3.20 as their minimum version and use these newer imported targets.

The following is a simple example of how to use the module with CMake 3.20 or later:

```
add_executable(MyGTestCases ...)

find_package(GTest REQUIRED)
target_link_libraries(MyGTestCases PRIVATE GTest::gtest)

add_test(NAME MyGTestCases COMMAND MyGTestCases)
```

The imported target takes care of ensuring the relevant header search path is used when building `MyGTestCases`, and things like the appropriate threading library are linked in, if needed. The above works on all platforms, hiding a fair amount of complexity associated with different names, runtimes, flags, etc. that are used on the different platforms and compilers. If using the variables defined by the module instead of the imported targets, these things mostly have to be handled manually, which is a fairly fragile task.

An even more robust approach is to incorporate GoogleTest's sources directly into the build, rather than relying on having pre-built binaries available. This ensures that GoogleTest is built with exactly the same compiler and linker settings as the rest of the project, which avoids many of the subtle issues that can arise when using pre-built GoogleTest binaries. Projects can do this in a number of ways, each with their advantages and drawbacks. Embedding a copy of the sources and headers in the project is the simplest, but it disconnects the project from improvements that may be made to GoogleTest in the future. The GoogleTest git repository can be added to the project as a git submodule, but that too comes with its own robustness issues. A third option of downloading the GoogleTest sources as part of the configure step is discussed in detail in [Chapter 39, *FetchContent*](#), which doesn't have the drawbacks of the other methods.

A test executable that uses GoogleTest typically defines more than one test case. The usual pattern of running the executable once and assuming it is a single test case isn't really appropriate. Ideally, each GoogleTest test case should be visible to `ctest` so that each one can be run and assessed individually. The `FindGTest` module provides a `gtest_add_test()` function which scans the source code looking for uses of the relevant GoogleTest macros and extracts out each test case as its own `ctest` test. The form of this command has traditionally been the following:

```
gtest_add_tests(executable "extraArgs" sourceFiles..)
```

From CMake 3.1, the list of `sourceFiles` to scan can be replaced by the keyword `AUTO`. The sources are then obtained by assuming `executable` is a CMake target and using its `SOURCES` target property.

In CMake 3.9, it was recognized that projects may want to use the `gtest_add_tests()` function with GoogleTest built by the project itself. This meant the project didn't need a Find module, so the function was moved out to a new GoogleTest module, and `FindGTest` then included it to maintain backward compatibility. An improved form of the function with keyword arguments was also added as part of that work:

```
gtest_add_tests(  
    TARGET target  
    [SOURCES src1...]  
    [EXTRA_ARGS arg1...]  
    [WORKING_DIRECTORY dir]  
    [TEST_PREFIX prefix]  
    [TEST_SUFFIX suffix]  
    [SKIP_DEPENDENCY]  
    [TEST_LIST outVar]  
)
```

The old form is still supported, but projects should prefer to use the new form instead where possible, since it is more flexible and more robust. For example, the same target can be given to multiple calls to `gtest_add_tests()` with different arguments, with each call having a different `TEST_PREFIX` and/or `TEST_SUFFIX`.

to differentiate the sets of tests generated. The new form also provides the set of tests found when the TEST_LIST option is given. With the test names available, the project is able to modify the tests' properties as needed. The following example demonstrates these various capabilities:

```
# Assume GoogleTest is already part of the build, so we
# don't need FindGTest and can reference the GTest::gtest
# target directly
include(GoogleTest)

add_executable(TestDriver ...)
target_link_libraries(TestDriver PRIVATE GTest::gtest)

# Run the TestDriver twice with two different arguments

gtest_add_tests(
    TARGET      TestDriver
    EXTRA_ARGS --algo=fast
    TEST_SUFFIX .Fast
    TEST_LIST   fastTests
)
gtest_add_tests(
    TARGET      TestDriver
    EXTRA_ARGS --algo=accurate
    TEST_SUFFIX .Accurate
    TEST_LIST   accurateTests
)
set_tests_properties(${fastTests} PROPERTIES
    TIMEOUT 3
)
set_tests_properties(${accurateTests} PROPERTIES
    TIMEOUT 20
)

set(betaTests ${fastTests} ${accurateTests})
list(FILTER betaTests INCLUDE REGEX Beta)
set_tests_properties(${betaTests} PROPERTIES
```

```
LABELS Beta  
)
```

The above example creates two sets of tests and applies different timeout limits to them. The test names will have different suffixes in each group. Without the TEST_SUFFIX options, the second call to `gtest_add_tests()` would fail because it would try to create tests with the same name as the first call. The example also sets a Beta label to some tests, regardless of which test set they belong to.

`gtest_add_tests()` works well for simple cases, but it doesn't handle parameterized tests or tests defined through custom macros. It also forces CMake to re-run on the next build to rescan the source files whenever the test sources change. This can be frustrating if the CMake step is slow. The SKIP_DEPENDENCY option prevents that behavior, relying instead on the developer manually re-running CMake to update the set of tests. This is a temporary workaround for when working on a test, not something that should be left in the project permanently.

CMake 3.10 added a new function to address the shortcomings of `gtest_add_tests()`. It queries the executable for its list of tests during the build or when running `ctest`, rather than scanning the source code during the configure stage. CMake does not need to be re-run whenever the test source is changed, parameterized tests are supported, and there is no restriction

on the formatting or the way tests are defined. A trade-off is the list of tests is not available during the CMake run.

```
ctest_discover_tests(target
    [EXTRA_ARGS arg1...]
    [WORKING_DIRECTORY dir]
    [TEST_PREFIX prefix]
    [TEST_SUFFIX suffix]
    [NO_PRETTY_TYPES]
    [NO_PRETTY_VALUES]
    [PROPERTIES name1 value1...]
    [TEST_LIST var]
    [TEST_FILTER filter]          # CMake 3.22 or later
    [DISCOVERY_TIMEOUT seconds]   # See notes below
    [DISCOVERY_MODE mode]         # CMake 3.18 or later
    [DISCOVERY_EXTRA_ARGS args...] # CMake 3.31 or later
    [XML_OUTPUT_DIR dir]          # CMake 3.18 or later
)

```

With CMake 3.22 or later, the set of tests reported by the executable can be constrained using the TEST_FILTER option. When the executable is asked to list its tests with --gtest_list_tests, the specified filter is also passed as --gtest_filter=filter. This allows a subset of the available tests to be selected.

By default, when generating the names of parameterized tests, the function will attempt to use type or value names rather than a numerical index. This will generally result in much more readable and useful names. For those cases where this is undesirable, the NO_PRETTY_TYPES and NO_PRETTY_VALUES options can be used to suppress the substitution and just use the index

values. Note that if TEST_FILTER is used, the filter is matched against the original test names with indexes, as reported by --gtest_list_tests, not the pretty test names used by ctest.

The DISCOVERY_TIMEOUT option refers to the time taken to run the executable to obtain the list of tests. The default of 5 seconds should be sufficient for all but those executables with a huge number of tests, or some other behavior that causes it to take a long time to return the test list. This option was originally added in CMake 3.10.1 with the keyword name TIMEOUT, but it was found to cause name clashes with the TIMEOUT test property in a way that led to unexpected but legal behavior. The keyword was changed to DISCOVERY_TIMEOUT in CMake 3.10.3 to prevent those scenarios.

Since the list of tests is not returned to the caller, it is not possible to call set_tests_properties() or set_property() to modify properties of the discovered tests. Instead, gtest_discover_tests() allows properties and their values to be specified as part of the call. These are then written into the ctest input file, to be applied when ctest is run. While not providing all the flexibility of being able to iterate through the set of discovered tests in CMake and processing them individually, the ability to set properties of the discovered tests as a whole is often all that is needed. The main exceptions to this are that it is not possible to set test properties that have names which correspond to keywords in the

`gtest_discover_tests()` command, or where properties require values that are lists. A custom `ctest` script must be used to handle such cases, an example of which is given below.

The `TEST_LIST` option works differently for `gtest_discover_tests()` than for `gtest_add_tests()`. In this case, the variable name given with this option is used in the `ctest` input file written out by CMake, rather than being available to CMake directly. The `TEST_LIST` option would only be needed if the project adds some of its own custom logic to the generated `ctest` input file and wants to refer to the list of generated tests. Even then, this would only be necessary if the same target is being used in multiple calls to `gtest_discover_tests()`. A default variable name of `<target>_TESTS` is used if not set by a `TEST_LIST` option.

Custom code can be added by appending file names to the list of files held in the `TEST_INCLUDE_FILES` directory property. Projects must not overwrite this directory property. They should only append to it, since `gtest_discover_tests()` uses the property to build up the set of files to be read by `ctest`.

The following example shows how to use a custom file to manipulate properties on discovered tests. It implements the same equivalent logic as the earlier example for `gtest_add_tests()`. It also includes a workaround for the `TIMEOUT` name clash corner case.

```

gtest_discover_tests(
    TestDriver
    EXTRA_ARGS --algo=fast
    TEST_SUFFIX .Fast
    TEST_LIST fastTests
)
gtest_discover_tests(
    TestDriver
    EXTRA_ARGS --algo=accurate
    TEST_SUFFIX .Accurate
    TEST_LIST accurateTests
)

set_property(DIRECTORY APPEND PROPERTY
    TEST_INCLUDE_FILES
    ${CMAKE_CURRENT_LIST_DIR}/customTestManip.cmake
)

```

customTestManip.cmake

```

# Set here to work around the TIMEOUT keyword clash for the
# gtest_discover_tests() call, works for all CMake versions
set_tests_properties(${fastTests} PROPERTIES
    TIMEOUT 3
)
set_tests_properties(${accurateTests} PROPERTIES
    TIMEOUT 20
)

set(betaTests ${fastTests} ${accurateTests})
list(FILTER betaTests INCLUDE REGEX Beta)
set_tests_properties(${betaTests} PROPERTIES
    LABELS Beta
)

```

Using a custom ctest script adds a little more complexity to the project, but it allows full control over test properties. There is

no concern about name clashes with `gtest_discover_tests()`, and properties with list values can be handled safely.

With CMake 3.17 and earlier, the executable is queried for the list of tests as a `POST_BUILD` step during the build. With CMake 3.18 or later, it is possible to defer querying the list of tests until `ctest` is run. This has at least the following advantages:

- It might not always be possible to run the test executable during the build stage. On the other hand, the test executable *must* be runnable at test time, either natively or via an emulator.
- Because the query happens during the test stage rather than the build, the cost of performing the query is only paid during testing. This improves turnaround time when the developer is focused on getting the test code to compile. In the cross-compilation case where emulator start-up time may be non-trivial, the potential benefits of this deferral can be significant.
- On Windows, querying the test list during the build requires the `PATH` environment variable to be set such that all the test executable's DLLs can be found. This is not just inconvenient, it also has the potential to change the way things are built. Deferring the query to the test stage means executables don't have to be runnable at build time, thereby avoiding such problems.

- Starting with Xcode 15, at the point where CMake runs a POST_BUILD step, the executable binary won't be code signed, not even with an ad hoc signature. This typically prevents the executable from running, which means it cannot be queried for the list of tests during a POST_BUILD step.

The DISCOVERY_MODE option controls when the test list query is performed. It gets its default value from the CMAKE_GTEST_DISCOVER_TESTS_DISCOVERY_MODE variable. If that variable is not set, the mode defaults to POST_BUILD to preserve backward compatibility. Instead of using POST_BUILD, the mode can be set to PRE_TEST, which delays the query until the test stage. In practice, the PRE_TEST mode should always be preferable. It will generally be more convenient to set the discovery mode project-wide via the variable instead of explicitly setting it in every call to gtest_discover_tests().

Another feature added in CMake 3.18 is the XML_OUTPUT_DIR keyword. When this keyword is present, the tests will save their output to an XML file in the directory given after the keyword. The file name will be based on the test name, including its prefix and suffix, if set. This ensures that every test will have its own unique output file, so tests can safely run in parallel without fear of any output file corruption. These XML output files can be processed by some continuous integration systems and test reporting tools, making them a potentially convenient

way of providing results in merge requests and other similar use cases.

30.2. Catch2

GoogleTest is the only actively maintained test framework with direct support in CMake. However, other popular test frameworks also have similar features for CMake integration, typically provided as part of the framework itself. Catch2 is one such test framework, and its usage has many similarities to GoogleTest.

The Catch2 documentation has clear instructions for the different ways Catch2 can be used with CMake projects. The following example gives a taste of how that integration works and the parallels with GoogleTest.

```
cmake_minimum_required(VERSION 3.5...3.27)
project(Catch2Example LANGUAGES CXX)
enable_testing()

find_package(Catch2 REQUIRED)

add_executable(tests test.cpp)
target_link_libraries(tests PRIVATE Catch2::Catch2WithMain)

# Very similar to gtest_discover_test()
include(Catch)
set(CMAKE_CATCH_DISCOVER_TESTS_DISCOVERY_MODE PRE_TEST)
catch_discover_tests(tests)
```

The `catch_discover_tests()` command supports many of the same options as `gtest_discover_tests()`, plus a couple of its own. Much of the discussion for `gtest_discover_tests()` also applies here too. In particular, the `DISCOVERY_MODE` should generally be set to `PRE_TEST`. Catch2 provides an analogous `CMAKE_CATCH_DISCOVER_TESTS_DISCOVERY_MODE` CMake variable to specify the default behavior.

The above example uses `find_package(Catch2)` to make Catch2 available. If relying on a package manager to provide project dependencies, this would generally be the recommended approach. Just as for GoogleTest though, other strategies like `FetchContent` or `git submodule`s can be used just as effectively.

30.3. doctest

Another popular test framework is doctest, which is derived from Catch2. Given the shared origins, it is no surprise that doctest also provides a similar `doctest_discover_tests()` command, again supporting many of the same options. Unlike GoogleTest or Catch2 though, there is no support for a `PRE_TEST` test discovery mode. Direct inclusion using `FetchContent` or `git submodule`s is also not quite as smooth (`CMAKE_MODULE_PATH` isn't set, so the `include(doctest)` call needs assistance to find the doctest module). Apart from those differences, the project setup is very similar:

```
cmake_minimum_required(VERSION 3.5...3.27)
project(doctestExample LANGUAGES CXX)
enable_testing()

find_package(doctest REQUIRED)

add_executable(tests test.cpp)
target_link_libraries(tests PRIVATE doctest::doctest)

include(doctest)
doctest_discover_tests(tests)
```

30.4. Recommended Practices

If using the GoogleTest framework, consider using the `gtest_add_tests()` and `gtest_discover_tests()` functions provided by the GoogleTest module. If the test code is simple enough for `gtest_add_tests()` to find all tests, it offers the simplest and most flexible way of manipulating individual test properties, but it can be less convenient while working on the test code itself, since it can require re-running CMake frequently.

If the project can require CMake 3.10.3 or later as a minimum version, `gtest_discover_tests()` may be more suitable. The main drawback to this function is that setting test properties to values that are lists requires more work. This is particularly relevant if following the advice in [Chapter 27, Testing Fundamentals](#) regarding the use of test labels.

If supporting CMake versions before 3.9 is required, only `gtest_add_tests()` can be used, and only the simpler form of the command. The project will also need to use the `FindGTest` module rather than the `GoogleTest` module, which adds further complexity if `GoogleTest` is being built as part of the project itself. Projects are therefore strongly advised to move to CMake 3.9 or later if using `GoogleTest`, ideally 3.10.3 or later.

Prefer to set the `CMAKE_GTEST_DISCOVER_TESTS_DISCOVERY_MODE` variable to `PRE_TEST`. This gives more robust and more convenient behavior for `gtest_discover_tests()` when using CMake 3.18 or later. If using Catch2 rather than GoogleTest, set the equivalent `CMAKE_CATCH_DISCOVER_TESTS_DISCOVERY_MODE` variable instead.

When deciding on a test framework for a project, consider the maintenance aspects of the test framework itself. Factors to weigh up include:

- Is it still being actively maintained?
- Is the CMake integration for the test framework actively supported by the framework maintainers, or does it rely mostly on community contributions? If the latter, how readily are contributions accepted?
- Is there a reasonable pool of contributors to the framework's development, or is it primarily only one or two people who support it?

- Is the framework closely tied to an organization? If so, how well do the goals of that organization for the framework align with the needs of the project?

No test framework is likely to be a perfect fit. Asking questions like the above can help steer a project toward a choice that minimizes longer term risks. Since CMake is a very actively developed project, it is important that the test framework also has active support and will be maintained to keep up with improvements in CMake over time.

31. CDASH INTEGRATION

ctest has a long history and close relationship with another product called CDash, which is also developed by the same company behind CMake and ctest. CDash is a web-based dashboard that collects results from a software build and test pipeline driven by ctest. It collects warnings and errors from each stage of the pipeline, and shows per-stage summaries with the ability to click through to each warning or error. A history of past pipelines allows trends to be observed over time and to compare runs.

CMake itself has its own fairly extensive dashboard which tracks nightly builds, builds associated with merge requests, and so on. A few minutes spent exploring a sample dashboard will be helpful in understanding the material covered in this chapter:

<https://open.cdash.org/index.php?project=CMake>

31.1. Key CDash Concepts

Three important concepts tie together how `ctest` and CDash execute pipelines and report results: *steps* (sometimes also referred to as *actions*), *models* (also sometimes called *modes*), and *groups* (previously called *tracks* with CMake 3.15 and earlier). Steps are the sequence of actions that a pipeline performs. The main set of defined actions in the order they would normally be invoked is:

- Start
- Update
- Configure
- Build
- Test
- Coverage
- MemCheck
- Submit

Not all actions have to be executed, some may not be supported or do not need to be run. Loosely speaking, each row in the CDash dashboard corresponds to a single pipeline, and will typically show a summary of each action taken (a commit hash, a total of warnings, errors, failures, etc.).

Each pipeline must be associated with a model, which is used to define certain behaviors, such as whether to continue with later steps after a particular step fails. The model also provides a

default set of actions when no specific action is requested. The supported models are:

Nightly

Intended to be invoked once per day, usually by an automated job during a time when the executing machine is less busy. The default set of actions includes all the steps listed above, except *MemCheck*. If the *Update* step fails, the rest of the steps will still be executed.

Continuous

Very similar to *Nightly*, except that it is intended to be run multiple times a day as needed, usually in response to a change being committed. It defines the same set of default actions as *Nightly*, but if the *Update* step fails, the later steps will not be executed.

Experimental

As the name suggests, this model is intended for ad hoc experiments executed by developers as needed. Its default set of actions includes all steps except *Update* and *MemCheck*. If a model other than one of the three defined models is specified, or if no model is specified at all, it will be treated as *Experimental*.

The *group* controls which group the pipeline results will be shown under in the dashboard results. Group names can be anything the project or developer wishes to use, but if no group

is specified, it will be set to the same as the model. This has led to a common misunderstanding that the model controls the grouping in the dashboard, but it is the group that does this. The *Coverage* and *MemCheck* actions are a special case. They effectively ignore the group, and their dashboard results are shown in their own dedicated groups (*Coverage* and *Dynamic Analysis* respectively). With CMake 3.22 or later, in addition to populating the dedicated *Dynamic Analysis* group, the *MemCheck* action will also submit test results in the same way as the *Test* action, for which the nominated group *will* be used.

31.2. Executing Pipelines And Actions

For a project with the necessary configuration files in place (covered in the next section), entire pipelines or individual steps can be invoked using the following form of the `ctest` command:

```
ctest [-M Model] [-T Action] [--group Group] ...
```

If using CMake 3.16 or earlier, `--track` `Track` must be used rather than `--group` `Group`.

At least one or both of the *Model* and *Action* must be specified. As a convenience, the `-M` and `-T` options can be combined into a single `-D` option like so:

```
ctest -D Model[Action] [--group Group] ...
```

Arguments to -D can omit the action or append it to the *Model*. Examples of valid arguments include *Continuous*, *NightlyConfigure*, *ExperimentalBuild*, and so on. The -T and -D options can be specified multiple times to list multiple steps in the one ctest invocation.



Note that -D is also used to define ctest variables, and the ctest command will treat any *Model* or *ModelAction* it doesn't recognize as setting a variable instead. It is advisable to use the -M and -T options rather than -D to minimize opportunities for a mistyped command line option to be misinterpreted.

A nightly run using the default set of steps and reporting its results under the default group *Nightly* is trivially invoked as:

```
ctest -M Nightly
```

For the same thing, but with results reported under a group called *Nightly Main*:

```
ctest -M Nightly --group "Nightly Main"
```

Consider a custom *Experimental* pipeline consisting of just *Configure*, *Build* and *Test* steps, with results grouped under *Simple Tests*. This requires the set of steps to be explicitly specified, since it differs from the default set of actions defined for an *Experimental* model (no *Coverage* step is being executed).

This can be done as either a sequence of ctest invocations with one step per invocation, or they could all be listed together using multiple -T options on the one command line. Both forms are shown for comparison:

Separate commands

```
ctest -T Start -M Experimental --group "Simple Tests"  
ctest -T Configure  
ctest -T Build  
ctest -T Test  
ctest -T Submit
```

One command

```
ctest -M Experimental --group "Simple Tests" \  
-T Start -T Configure -T Build -T Test -T Submit
```

The first step should be a *Start* action, which is used to initialize the pipeline details, and to record the model and group names that later steps will use. These details do not need to be repeated for any of the later steps if splitting each action out to its own separate ctest invocation. The last step would be a *Submit* action, assuming the goal is to submit the final set of results to a dashboard.

All output from the above is collected under a Testing subdirectory below the directory in which ctest is invoked. The *Start* action writes out a file named TAG, which contains at least two lines. The first line is a date-time for the start of the run in the form YYYYMMDD-hhmm. The second line is the group name.

CMake 3.12 and later adds a third line containing the model name.

As each step after the *Start* action is executed, it will create its own output file at Testing/YYYYMMDD-hhmm/<Action>.xml and a log file at Testing/Temporary/Last<Action>_YYYYMMDD-hhmm.log. In the case of the *MemCheck* step, the <Action> part will be DynamicAnalysis rather than MemCheck in these file names (with CMake 3.22 or later, a second Testing/YYYYMMDD-hhmm/DynamicAnalysis-Test.xml file will also be created). The *Submit* action collects the XML output files and some of the log files, and submits them to the nominated dashboard.

To attach a build note to the whole pipeline, use the -A or --add-notes option with the *Submit* step to specify the file names to upload. If multiple files are being added, separate the file names with a semicolon. This can be a useful way to record extra details about that particular pipeline, such as information from a continuous integration system that initiated the run.

```
ctest -T Submit --add-note JobNote.txt
```

An --extra-submit option is also supported, but it is intended more for internal use by ctest. It is not a general file upload mechanism, but is often mistakenly assumed to serve that purpose. It should not be used by developers or projects directly.

While the above functionality is intended primarily for integration with CDash, it can also be used for other scenarios too. For example, the Jenkins CI system has a plugin that allows it to read the Test action's `Test.xml` output file and record test results in a similar way to CDash. Instead of running `ctest` in the ordinary way, it can be invoked as a dashboard run with just the *Test* action. The Jenkins plugin then only needs to be told where to find the `Test.xml` file and it can read the test results. When used this way, even the *Start* action can be omitted. `ctest` will silently perform the equivalent of a *Start* action with an *Experimental* model if one of the other steps is executed without any prior *Start* action.

When passing the XML output file of an action to a tool other than CDash, it may be necessary to instruct `ctest` to not compress the output it captures. By default, the action's output is compressed and written to the XML file in an ASCII-encoded form, but this can be prevented by passing the `--no-compress-output` option to `ctest`. Only use this option if it is necessary, since it will result in larger output files.

Another situation where dashboard steps can be useful without CDash is to take advantage of the support for code coverage or memory checking (Valgrind, Purify, various sanitizers, etc.). These dashboard actions can make invoking the relevant tool and collecting results easier. See the next section for details on how to set up and use these tools.

31.3. CTest Configuration

Preparing a project for CDash integration is mostly handled by a CTest module provided by CMake. It should be included soon after the `project()` command in the top level `CMakeLists.txt` file. This is important because the module writes various files into the current build directory at the point it is included, and developers typically expect to be able to run `ctest` from the top level build directory.

```
cmake_minimum_required(VERSION 3.0)
project(CDashExample)

# ... set any variables to customize CTest behavior

include(CTest)

# ... Define targets and tests as usual
```

The CTest module defines a `BUILD_TESTING` cache variable which defaults to true. It is used to decide whether the module calls `enable_testing()` or not, so the project does not have to make its own explicit call to `enable_testing()`. The project can also use this cache variable to perform certain processing only if testing is enabled. If the project has many tests that take a long time to build, this can be a useful way to avoid adding them to the build when they are not needed.

```
cmake_minimum_required(VERSION 3.0)
project(CDashExample)

include(CTest)
```

```
# ... define regular targets

if(BUILD_TESTING)
    # ... define test targets and add tests
endif()
```

The CTest module defines build targets for each *Model* and for each *ModelAction* combination. These targets execute `ctest` with the `-D` option set to the target name and are intended as a convenient way to execute the whole pipeline, or just one dashboard action from within an IDE application. The targets don't offer any real advantage over invoking `ctest` directly if working from the command line.

The more important task performed by the CTest module is to write out a configuration file called `DartConfiguration.tcl` in the build directory. The name of this file is historical, with Dart being the original name of the CDash project. This file records basic details like the source and build directory locations, information about the machine on which the build is being performed, the toolchain used, the location of various tools, and other defaults. It will also contain the details of the CDash server, but in order for it to do so, the project needs to provide a `CTestConfig.cmake` file at the top of the source tree with the relevant contents. A suitable `CTestConfig.cmake` file can be obtained from CDash itself (requires administrator privileges), but it is usually not difficult to create one manually. A minimal

example which works for all CMake versions would look something like this:

```
# Name used by CDash to refer to the project
set(CTEST_PROJECT_NAME "MyProject")

# Time to use for the start of each day. Used by CDash to
# group results by day, usually set to midnight in the
# local timezone of the CDash server.
set(CTEST_NIGHTLY_START_TIME "01:00:00 UTC")

# Details of the CDash server to submit to
set(CTEST_DROP_METHOD      "https")
set(CTEST_DROP_SITE        "my.cdash.org")
set(CTEST_DROP_LOCATION    "/submit.php?project=${CTEST_PROJECT_NAME}")
)
set(CTEST_DROP_SITE_CDASH YES)

# Optional, but recommended so that command lines can be
# seen in the CDash logs
set(CTEST_USE_LAUNCHERS YES)
```

From CMake 3.14, the various CTEST_DROP_... options can be replaced by a single CTEST_SUBMIT_URL option. This is much simpler and more readable, so if the minimum CMake version of the project is at least 3.14, this should be preferred. The equivalent for the above example would be:

```
set(CTEST_SUBMIT_URL
  "https://my.cdash.org/submit.php?project=${CTEST_PROJECT_NAME}"
)
```

The `DartConfiguration.tcl` file written out by the CTest module contains options for dashboard actions. Most are set to

appropriate values by default, but the *Coverage* and *MemCheck* steps have options that may be of interest. These are controlled by CMake variables, which the developer can manipulate in the CMake cache or in the `CMakeLists.txt` file before the `CTest` module is included.

The *Coverage* step is assumed to be invoking `gcov` (see [Section 33.2.1, “`gcov-based Coverage`”](#)), and the `CTest` module will search for a command by that name. The `COVERAGE_COMMAND` cache variable holds the result of that search, but it can be modified by the developer if needed. A second cache variable `COVERAGE_EXTRA_FLAGS` is used to hold the options that should immediately follow the `COVERAGE_COMMAND`, so the developer has the ability to control both the command used and the options passed to it.

The *MemCheck* step is more interesting. A number of different memory checkers are supported, including Valgrind, Purify, BoundsChecker, Dr Memory (with CMake 3.17 or later), Cuda Sanitizer (with CMake 3.19 or later), and various other sanitizers. For the first five, they can be selected by setting `MEMORYCHECK_COMMAND` to the location of the relevant executable. `ctest` will then identify the checker from the executable name. For Valgrind, the `VALGRIND_COMMAND_OPTIONS` variable can also be set to override the options given to `valgrind` itself. Dr Memory has a similar capability with the `DRMEMORY_COMMAND_OPTIONS` variable. To use one of the sanitizers, set `MEMORYCHECK_TYPE` to

one of the following strings (`MEMORYCHECK_COMMAND` will then be ignored):

- AddressSanitizer
- LeakSanitizer
- MemorySanitizer
- ThreadSanitizer
- UndefinedBehaviorSanitizer

`ctest` will then launch test executables as normal, but with the relevant environment variables set to enable the requested sanitizer. Note that sanitizers require building with the relevant compiler and linker flags (see [Section 33.1, “Sanitizers”](#) for further discussion).

The above details are enough to be able to perform various dashboard actions and submit results to a CDash server, but there is a chicken-and-egg problem. The *Update* and *Configure* steps need to have already been performed to obtain the `DartConfiguration.tcl` file. Therefore, details of those two steps cannot be captured. In the case of the *Configure* step, the output from the first `cmake` run are lost, and one can only get the output from re-running CMake in an already-configured build directory. Nevertheless, all the other steps will have their output captured, and that may be enough in some situations.

For example, when using a continuous integration system like Gitlab CI or Jenkins, the initial clone or update of the source tree can be handled by the CI system itself. An initial `cmake` run can be performed, and then the rest of the steps can be run as dashboard actions. The final results can be submitted to a CDash server, read directly by the CI system, or possibly both.

To capture a complete pipeline, including the initial clone or update of a source tree and first configure step, one has to write a custom `ctest` script to define the required setup details and call the relevant `ctest` functions. This can be an involved process, and isn't typically necessary if already using another CI system. If the clone and update steps don't need to be captured, the complexity of the custom script is reduced. When used this way, `ctest` is invoked with the `-S` option and the name of the script to execute.

The following demonstrates a fairly straightforward example:

```
ctest -S MyCustomCTestJob.cmake
```

MyCustomCTestJob.cmake

```
# Re-use CDash server details we already have
include(${CTEST_SCRIPT_DIRECTORY}/CTestConfig.cmake)

# Basic information every run should set, values here are
# just examples
site_name(CTEST_SITE)
set(CTEST_BUILD_NAME ${CMAKE_HOST_SYSTEM_NAME})
set(CTEST_SOURCE_DIRECTORY
    "${CTEST_SCRIPT_DIRECTORY}"
```

```

)
set(CTEST_BINARY_DIRECTORY
    "${CTEST_SCRIPT_DIRECTORY}/build"
)
set(CTEST_CMAKE_GENERATOR      Ninja)
set(CTEST_CONFIGURATION_TYPE RelWithDebInfo)

# Dashboard actions to execute, always clearing the
# build directory first
ctest_empty_binary_directory(${CTEST_BINARY_DIRECTORY})
ctest_start(Experimental)
ctest_configure()
ctest_build()
ctest_test()
ctest_submit()

```

The following more interesting example shows how custom scripts allow more flexible pipeline behavior to be defined:

```

include(${CTEST_SCRIPT_DIRECTORY}/CTestConfig.cmake)

site_name(CTEST_SITE)
set(CTEST_BUILD_NAME
    "${CMAKE_HOST_SYSTEM_NAME}-ASan"
)
set(CTEST_SOURCE_DIRECTORY
    "${CTEST_SCRIPT_DIRECTORY}"
)
set(CTEST_BINARY_DIRECTORY
    "${CTEST_SCRIPT_DIRECTORY}/build"
)
set(CTEST_CMAKE_GENERATOR      Ninja)
set(CTEST_CONFIGURATION_TYPE RelWithDebInfo)
set(CTEST_MEMORYCHECK_TYPE    AddressSanitizer)

set(flags "-fsanitize=address -fno-omit-frame-pointer")
set(configureOpts
    "-DCMAKE_CXX_FLAGS_INIT=${flags}"
    "-DCMAKE_EXE_LINKER_FLAGS_INIT=${flags}"

```

```

)
ctest_empty_binary_directory(${CTEST_BINARY_DIRECTORY})
ctest_start(Experimental GROUP Sanitizers)
ctest_configure(OPTIONS "${configureOpts}")
ctest_submit(PARTS Start Configure)

ctest_build()
ctest_submit(PARTS Build)

ctest_memcheck()
ctest_submit(PARTS MemCheck)

ctest_upload(FILES
    ${CTEST_BINARY_DIRECTORY}/mytest.log
    ${CTEST_BINARY_DIRECTORY}/anotherFile.txt
)
ctest_submit(PARTS Upload Submit)

if(NOT CMAKE_VERSION VERSION_LESS "3.14")
    ctest_submit(PARTS Done)
endif()

```

In this more production-quality example, rather than waiting to the very end of the run before submitting results to the dashboard, results are submitted progressively after each step. This can be useful if some steps take a long time. The executables are built with address sanitizer support, and the address sanitizer check is run instead of regular testing. Some extra files are also uploaded at the end.

The *Done* part was only added in CMake 3.14. It is used to tell CDash that the job is complete. Recent versions of CDash then report a more reliable total duration for the job. Earlier CDash versions will simply ignore it. When not submitting by parts,

the *Done* part is handled automatically as part of the *Submit* action or a call to `ctest_submit()` with no parts specified.

Each of the various `ctest_...` commands is detailed in the CMake documentation, along with CTest and CMake variables that can be used to customize each step or affect the processing in various ways. The above should be a good base script that can be used to experiment with the different parameters and variables.

Creating a script that also handles cloning and updating the project adds more complexity. Projects often have their own special ways of doing this, and they typically need to decide how things like *Nightly* and *Continuous* builds should be scheduled. Supporting things like automated builds for merge requests will depend heavily on the capabilities of the repository hosting the project. For those interested in exploring this path, a recommended way to get started is to find a project using a similar repository hosting arrangement and use it as a guide. Some projects include the custom script in their repository for ease of access (many projects from Kitware do this, and the scripts have been documented reasonably well).

31.4. Test Measurements And Results

The above example briefly showed how file uploads can be incorporated into a custom `ctest` script. The `ctest_upload()` command provides a basic mechanism for recording files to

upload with the build results. The upload is executed as part of a subsequent call to `ctest_submit()`. Sometimes, however, file uploads should be associated with a particular test rather than the whole scripted run. The `ATTACHED_FILES` and `ATTACHED_FILES_ON_FAIL` test properties are provided for this purpose. Both hold a list of files to be uploaded and associated with that particular test. The only difference between the two properties is that the latter contains files that are only uploaded if the test fails. This is a very useful way to record additional information about the failure to allow further investigation.

```
add_executable(CodeGen ...)  
add_test(NAME GenerateFile COMMAND CodeGen)  
  
set_tests_properties(GenerateFile PROPERTIES  
    ATTACHED_FILES_ON_FAIL  
    ${CMAKE_CURRENT_BINARY_DIR}/generated.c  
    ${CMAKE_CURRENT_BINARY_DIR}/generated.h  
)
```

Tests can also record a single measurement value which will be recorded and tracked in CDash. A measurement generally has the form `key=value`, although the `=value` part can be omitted to use an assumed default value of 1. The measurement is recorded as a test property like so:

```
set_tests_properties(PerfRun PROPERTIES  
    MEASUREMENT mySpeed=${someValue}  
)
```

Because the measurement value has to be defined before the test is even run, this has limited usefulness. Much more useful is a feature which has long been supported, but has only been documented since CMake 3.21, where measurements can be embedded in the test output in a form similar to HTML tags. `ctest` scans the test output for these measurements, extracts the relevant data, and uploads it to CDash as part of the test results. These measurements are then displayed in a result table near the top of the test details page. The simplest type of measurement is defined by the following form:

```
<DartMeasurement name="key" type="someType">value</DartMeasurement>
```

The `name` attribute will be used as the label for the measurement in the results table. The `type` attribute will typically be something like `text/string`, `text/link` (for URLs) or `numeric/double`. The `value` is whatever text or numerical content makes sense for the measurement. For numerical values, CDash provides a facility to plot the history of each measurement across recent test runs, which is very useful for spotting changes in behavior over time.

Another form can be used to embed a file rather than a specific value:

```
<DartMeasurementFile name="key" type="someType">filePath</DartMeasurementFile>
```

This second form is most useful for uploading images, where the type attribute would be something like image/png or image/jpeg. The filePath should be the absolute path to the file to be uploaded.

CDash recognizes a few special measurement names when it comes to images. These can be used to help compare expected and actual images. CDash even provides a useful interactive UI element for overlapped comparisons. The recognized name attributes and their meanings include:

TestImage

This is interpreted as the image generated by the test. It can be thought of as the test output, and will be shown both on its own and also as part of the interactive comparison image.

ValidImage

This is equivalent to the expected image for the test. It should generally be of the same dimensions as the TestImage, but is not necessarily required to be of the same image format. It will be included in the interactive image only. BaselineImage can also be used as the name, and it means the same thing as ValidImage.

DifferenceImage2

Various tools can be employed to generate an image that represents the difference between two other images. Where the test provides such an image file, it can use this name to

include it in the test output measurements uploaded to CDash. It will be incorporated into the interactive comparison image.

Names other than the above and types other than images can be uploaded, but bugs in CMake 3.20 and earlier may make that unreliable. For best results, use 3.21 or later if possible. CMake 3.21 also provides better handling for non-image files when the type is set to file. The file will then be uploaded as an attachment, just like the ATTACHED_FILES test property would. With any other type, it will be treated as a named measurement instead, and may not display as appropriately in CDash.

CMake 3.21 also added the ability for the test output to override the test's details field in CDash. The default contents normally state whether the test completed and what the test result was, but the test can use this facility to provide more specific information. It should still be relatively short though, ideally no more than one line.

```
<CTestDetails>Replacement test details go here</CTestDetails>
```

Starting with CMake 3.22, a test can also dynamically add labels at runtime by including the relevant tags in its output like so:

```
<CTestLabel>Some dynamic label</CTestLabel>
<CTestLabel>Another label</CTestLabel>
```

These labels are uploaded to CDash along with the test results, just like regular labels assigned to the test at configure time with the LABELS test property (see [Section 27.4.3, “Labels”](#)). These dynamic labels are also included in the results summary at the end of the ctest run.

Because dynamic labels are only assigned when the test is executed, they cannot be used to include or exclude tests to be run. If the user specifies ctest options like -L or -LE to control which tests to execute, only the statically assigned labels set through the LABELS test property are considered. If a test adds a label dynamically to its output, and that same label is set statically on another test, users may be confused if they then try to filter the test set based on that label. Tests they thought they had filtered out might still show up in the output, or those they thought were included might be missing. Consider using non-overlapping sets of labels for static and dynamic cases to avoid setting up this situation.

31.5. Output Control

The type and form of results reported by a dashboard run is fairly powerful. Nevertheless, it can still be useful to generate results in a format more widely supported by other tools. [Section 27.6, “JUnit Output”](#) discussed how to generate results in JUnit XML format for non-dashboard runs. With CMake 3.21 or later, dashboard runs can also be instructed to generate a JUnit

XML results file by passing the OUTPUT_JUNIT option to `ctest_test()`:

```
ctest_test(OUTPUT_JUNIT /path/to/resultFile.xml)
```

The JUnit output does not support features like named measurements or file attachments, so it isn't a complete replacement for what can be accomplished with the native CDash results output. But if the project does not need those CDash-specific features, the reduced feature set of the JUnit output may still be good enough.

Dashboard runs offer the same output controls as the non-CDash JUnit output. These controls apply to both the native CDash results and any JUnit results file it creates. The same defaults apply, with the output from any passing test truncated to 1024 bytes, and failing tests truncated to 307,200 bytes (300kB). These limits can be overridden by setting variables in the `dashboard` script.

`CTEST_CUSTOM_MAXIMUM_PASSED_TEST_OUTPUT_SIZE` and `CTEST_CUSTOM_MAXIMUM_FAILED_TEST_OUTPUT_SIZE` can be used to specify the number of bytes to truncate at instead of the default values. These variables have long been supported by CMake, but have only been officially documented since CMake 3.4.

With CMake 3.24 or later, the type of output truncation can also be controlled using the `CTEST_CUSTOM_TEST_OUTPUT_TRUNCATION`

variable. The variable supports the same values as for the JUnit output: `tail`, `head`, and `middle`.

```
# Save more output, keeping the start and end
set(CTEST_CUSTOM_MAXIMUM_PASSED_TEST_OUTPUT_SIZE 10000)
set(CTEST_CUSTOM_MAXIMUM_FAILED_TEST_OUTPUT_SIZE 40000)
set(CTEST_CUSTOM_TEST_OUTPUT_TRUNCATION middle)

ctest_test()
```

As for the non-CDash JUnit output, individual tests can override the output limits by logging the special string `CTEST_FULL_OUTPUT` somewhere in their output. The entire output from that test will then be included in the test results, regardless of any output limit. For native CDash output, `CTEST_FULL_OUTPUT` has long been supported. For JUnit output, it is only supported with CMake 3.21 or later.

31.6. Recommended Practices

For running the complete configure, build and test pipeline of the main project, consider the functionality offered by the CDash integration features rather than using the `ctest` build and test mode. The CDash integration does a better job of capturing output from the whole pipeline and providing mechanisms for customizing each step's behavior. It also has additional features that facilitate using code coverage and dynamic analysis tools, such as memory checkers, sanitizers, etc. These features can be used whether submitting results to a

CDash server or not. In fact, the custom `ctest` scripting functionality that drives the whole CDash pipeline can be used without CDash, making it a potentially convenient platform-independent way of scripting the whole build and test pipeline for other continuous integration systems as well. The JUnit output support available with CMake 3.21 or later can be especially useful in that scenario. A CDash server can also be used in conjunction with other CI systems to provide a richer set of features for recording and comparing build histories, test failure trends, and so on.

On the other hand, workflow presets may be a better alternative to dashboard scripts when there is no dashboard to report results to. Workflow presets are simpler, and they are more closely aligned with the steps developers would perform in their everyday development. This makes them typically more familiar and easier to maintain. See [Section 42.6, “Workflow Presets”](#) for discussion of that functionality.

The `STOP_ON_FAILURE` option to the `ctest_test()` command has a similar effect as the `ctest --stop-on-failure` option. It can be used to end a test run immediately upon the first error encountered. Hard-coding this behavior into a dashboard script reduces flexibility, since there is no way to override it when running the dashboard script locally. Therefore, use of that option is generally not recommended.

32. STATIC CODE ANALYSIS

Software projects these days have a wide range of tools at their disposal for code checking, verification, and analysis. This is especially true for C and C++ code, but the tools are not always easy to set up, and good material on how to do so can be hard to find.

Static analysis is one form of code analysis. It doesn't require running any binaries built by the project, which means it can typically be used even when cross-compiling. A number of static analysis tools have direct support in CMake, which runs the tools as part of the build step using a *co-compilation* approach. When a source file is compiled, the static analysis tools are run first on the source file before the compiler is executed. This direct support can be helpful in shortening the path to the adoption of static analysis, but the approach does have some weaknesses (see [Section 32.5, “Potential Problems With Co-compilation”](#)). These static code analysis tools are the main focus of this chapter. Verifying that headers are well-formed is another form of static code analysis, which CMake supports through file sets. This is also discussed toward the end of the chapter.

In contrast, dynamic analysis (discussed in the next chapter, [Chapter 33, Dynamic Code Analysis](#)) requires running the built executables. This normally occurs as part of running `ctest`. Results are then collected and processed at the end in a separate step.

The two types of code analysis are complementary. They each have their strengths and weaknesses, but the most effective result can be obtained by using both.

32.1. clang-tidy

Of all the static code analysis tools for C and C++ projects, clang-tidy is one of the most widely used. It offers an extensive range of checks, it has flexible configuration settings, and it supports source code annotations for locally disabling checks where needed. Most popular IDEs these days also have direct support for running clang-tidy to provide interactive feedback in their code editor.

32.1.1. Basic Setup

CMake has direct support for running clang-tidy as part of the build when using one of the Makefiles or Ninja generators. It is enabled by setting the `<LANG>_CLANG_TIDY` target property to the path of the `clang-tidy` executable, where `<LANG>` is the language to enable the checks for. Supported languages are C, CXX, OBJC, and OBJCXX. The property can also hold a list, where the first

item is the path to the clang-tidy executable, and the rest are command-line arguments for that tool.

In general, projects would not set the `<LANG>_CLANG_TIDY` property directly. Instead, the developer would set the `CMAKE_<LANG>_CLANG_TIDY` variable on the `cmake` command line, in a toolchain file, or in a CMake preset (see [Chapter 42, Presets](#)). The `<LANG>_CLANG_TIDY` target property is initialized from the `CMAKE_<LANG>_CLANG_TIDY` variable when a target is created. This allows a developer to enable clang-tidy globally in a project without having to modify the project at all.

```
cmake -G Ninja -S . -B build \
  -DCMAKE_CXX_CLANG_TIDY:STRING=/path/to/clang-tidy \
  -DCMAKE_C_CLANG_TIDY:STRING=/path/to/clang-tidy
```

In practice, the above is not ideal. The clang-tidy tool will use its own heuristics to find the toolchain headers, but in certain cases, it may find the wrong ones. These can be the result of user error, a poorly configured environment, or an unsupported toolchain directory layout, but importantly, the underlying cause of such errors can be hard to trace. For best results, CMake should be told to generate a *compilation database*, and clang-tidy should be given the information needed to find it. A compilation database is a `compile_commands.json` file, which is expected to be at the top of the build directory. This file contains the compiler command line for each source file of a target. CMake can be told to create

a `compile_commands.json` file by setting the `CMAKE_EXPORT_COMPILE_COMMANDS` variable to true. With CMake 3.20 or later, it is possible to set the `EXPORT_COMPILE_COMMANDS` property on each target individually, but the `CMAKE_EXPORT_COMPILE_COMMANDS` variable is far more convenient and almost always the preferred method. Generation of the compilation database takes negligible time and can be used by a range of clang-based tools, so it is common for projects to always enable its generation.

The `clang-tidy` tool is made aware of the `compile_commands.json` file by passing the `-p` option, followed by the path to the build directory. A toolchain file is therefore a more convenient place to specify the `clang-tidy` details, since the `CMAKE_BINARY_DIR` variable is available. The toolchain file can even search for the `clang-tidy` executable and find it on the `PATH` using `find_program()` (see [Section 34.2, “Finding Programs”](#)). A toolchain file may contain code similar to the following:

```
set(CMAKE_EXPORT_COMPILE_COMMANDS TRUE)

find_program(CLANG_TIDY_EXECUTABLE clang-tidy REQUIRED)

set(CMAKE_CXX_CLANG_TIDY
    ${CLANG_TIDY_EXECUTABLE} -p ${CMAKE_BINARY_DIR}
)
set(CMAKE_C_CLANG_TIDY
    ${CLANG_TIDY_EXECUTABLE} -p ${CMAKE_BINARY_DIR}
)
```

When using CMake 3.25 or later, the presence of the `-p` option changes how CMake constructs the full `clang-tidy` command line. It avoids the problem where `clang-tidy` may find and use the wrong toolchain headers in some cases. Therefore, it is highly recommended to use CMake 3.25 or later, and to pass the `-p` option as shown above.

32.1.2. Settings

The `clang-tidy` tool supports a number of useful settings. These can be specified directly on the command line, in a `.clang-tidy` configuration file (which is in YAML format), or both. The `clang-tidy` executable will search in the current directory and progressively up its parent directories until it finds a `.clang-tidy` file. It reads that file, applies any settings contained therein, and then applies any settings specified on the command line.

The `.clang-tidy` file is much more convenient than trying to specify settings directly on the command line. The settings can get quite complicated, and long command lines are both difficult to work with and may potentially run into command length limits on some platforms. An added advantage of using a `.clang-tidy` file is that many IDEs support them and are able to provide tailored feedback directly in the source file editor.

In practice, most projects will want to place a `.clang-tidy` file at the top of their source tree. This file will then be used for all

sources in the project. The `.clang-tidy` file usually specifies at least the set of checks to be enabled, which is done with the `Checks` setting. For example:

```
---
```

```
Checks: >
  -*,
  bugprone-*/,
  cppcoreguidelines-*/,
  -cppcoreguidelines-macro-usage,
  clang-analyzer-core.*,
  clang-analyzer-cplusplus.*
```

```
...
```

The value of the `Checks` option has the same form as the `--checks` command-line option. The checks are specified as a comma-separated string. In YAML files, this can be split across multiple lines with the `>` marker after the `Checks:` key. This allows specifying one value per line, which makes things like git diffs much more readable as the file contents are modified over time.

Each item in the list of checks is a globbing pattern. If a pattern starts with a `-`, then checks matching that pattern are excluded. The list of enabled checks is built up by applying each pattern in turn, so later patterns can effectively override or modify earlier ones. The above example takes advantage of this by first disabling all checks, then only enabling the checks the project wants to use. This is far more efficient than starting with all checks enabled and disabling checks selectively. There is a lot of

overlap between the many tests clang-tidy can perform, and some checks are expensive. On large projects, having all checks enabled can be prohibitively time-consuming. Therefore, it is generally much more efficient to only enable the specific checks the project actually wants. A good compromise is to identify a group of checks that align well with the project's goals, then disable checks selectively within that group if needed. In the above example, the C++ Core Guidelines checks are first enabled as a group (`cppcoreguidelines-*`), then a specific check within that group is disabled (`-cppcoreguidelines-macro-usage`).

In some cases, there may be a part of the source directory where the set of checks needs to be different to the default set applied to the whole project. This may be the case for test code where certain code patterns need to be used, but where such patterns wouldn't be appropriate for the main code. Another example might be source files that are very large, and for which clang-tidy takes too long to run with the full set of checks normally applied to the rest of the project. Rather than disabling clang-tidy altogether, a custom `.clang-tidy` file can be placed in that particular subdirectory. The custom `.clang-tidy` file should contain `InheritParentConfig: true`, which instructs the tool to apply the settings as overrides on top of the settings from the parent directory. The custom `.clang-tidy` then only has to specify the things that need to change, not repeat most of the list of checks.

```
---  
InheritParentConfig: true  
Checks: -clang-analyzer-*  
...
```

The above example keeps all the checks enabled by the parent, except the `clang-analyzer-*` checks. Everything else stays the same. [Section 32.7, “Disabling Checks For Some Files”](#) discusses further choices for dealing with particularly problematic files when even a custom `.clang-tidy` file isn’t enough.

For CMake projects, the location of the build directory is an added consideration. If the project contains generated sources, those files would normally be created in the build directory. Unless steps are taken to exclude these files from analysis, they will also be processed by clang-tidy. If the build directory is a subdirectory below the source directory, the generated sources will inherit the settings from the `.clang-tidy` file at the top of the source tree. But if the build directory is outside the source directory, then the generated source file won’t have any `.clang-tidy` file providing settings.

To account for the above situation, projects may want to copy the `.clang-tidy` file from the top of their source tree to the top of the build tree as part of regular CMake execution. However, care must be taken to also account for scenarios where the project is being absorbed into a parent project directly (see [Chapter 39, *FetchContent*](#), which discusses this pattern in detail).

An appropriate way to safely do this would be to add the following line to the project's top level `CMakeLists.txt` file:

```
configure_file(.clang-tidy .clang-tidy COPYONLY)
```

This will do the right thing, regardless of whether the project is being built standalone or as part of some larger parent project.

Another important consideration for CMake projects is whether clang-tidy warnings should be treated as errors. [Section 16.8.1, “Warnings As Errors”](#) discussed an abstraction CMake offers for compilation of sources, but that abstraction does not extend to its invocation of clang-tidy. If turning clang-tidy warnings into errors is desired, that needs to be enforced by the clang-tidy settings. It is therefore common to see something like the following line in a project's top level `.clang-tidy` file:

```
WarningsAsErrors: '*'
```

32.1.3. Other Considerations

The clang-tidy tool supports many different checks. Some of those checks can be very expensive, taking longer than the normal compilation of the file. Therefore, perform some basic benchmarking to ensure that the set of enabled checks are not taking an unreasonable amount of time to complete.

If enabling clang-tidy in continuous integration jobs, consider having a dedicated job which stops after the build step. Skip

any tests or packaging steps, and instead let that CI job have code analysis as its main focus. This will allow the job to complete earlier, thereby providing more timely feedback. It will also reduce the likelihood of it becoming the longest running job, which would put it on the critical path for overall turnaround time for changes made by developers.

Another more subtle point to be aware of is that the build won't automatically create a dependency on any `.clang-tidy` files. When the developer makes changes to a `.clang-tidy` file, they are generally responsible for clearing any previous compiled objects before re-running the build. This is related to the way CMake implements its support for clang-tidy, which is discussed in [Section 32.5, “Potential Problems With Co-compilation”](#).

CMake's direct support for running clang-tidy isn't the only way to incorporate the tool into the build. Projects are free to use other methods which may better fit their needs. More recent clang-tidy releases include the `run-clang-tidy` tool, which can be a convenient and efficient way to run clang-tidy on a whole project. Projects may want to wrap that into a custom build target for convenience. A block similar to the following could be added to the top `CMakeLists.txt` of the project to achieve this:

```
if(PROJECT_IS_TOP_LEVEL)
    set(CMAKE_EXPORT_COMPILE_COMMANDS TRUE)

    find_program(CLANG_TIDY_EXECUTABLE
        clang-tidy REQUIRED
```

```
)  
find_program(RUN_CLANG_TIDY_EXECUTABLE  
    run-clang-tidy REQUIRED  
)  
  
add_custom_target(run-clang-tidy  
    COMMAND ${RUN_CLANG_TIDY_EXECUTABLE}  
        -clang-tidy-binary ${CLANG_TIDY_EXECUTABLE}  
        -p ${CMAKE_BINARY_DIR}  
)  
endif()
```

32.2. cppcheck

An alternative to clang-tidy is the cppcheck tool. It is perhaps less widely used, but may have advantages in some situations. For example, the commercial version offers checks that may be relevant for embedded projects with certification or security requirements, like MISRA, AUTOSAR, and others.

CMake has direct support for cppcheck, implemented in the same way as for clang-tidy. This is again only available with Makefiles or Ninja generators. The `<LANG>_CPPCHECK` target property specifies the path to the cppcheck executable. It can also be a list, where the first list item is the path to cppcheck, and the remaining items are passed as command-line arguments. Again, rather than setting this property on every target, it is more customary to set the `CMAKE_<LANG>_CPPCHECK` variable, which is then used to provide the initial value for the property when each target is created.

The simplest way to enable cppcheck for a project is to set the relevant cache variables on the `cmake` command line:

```
cmake -G Ninja -S . -B build \
-DCMAKE_CXX_CPPCHECK:STRING=/path/to/cppcheck
```

CMake attempts to pass relevant compiler flags along to `cppcheck`, such as for compiler definitions and header search paths. But CMake doesn't pass things like the C++ standard, which can cause problems. Depending on compiler defaults, `cppcheck` may fail to analyze files correctly, or possibly fail to analyze them at all.

A potentially more reliable alternative is to take advantage of `cppcheck`'s support for using a compilation database, just like can be done for `clang-tidy`. The `cppcheck` tool will then extract all relevant command-line options from the compilation database instead of CMake having to pass them along. This mode is enabled by passing the `--project=/path/to/compile_commands.json` option to `cppcheck`. On its own, that option will result in every file in the compilation database being analyzed. Instead of using the `CMAKE_<LANG>_CPPCHECK` method, a project may choose to invoke `cppcheck` with the `--project` option once for the whole build. This can be implemented as a custom target using a very similar approach as that shown earlier for `clang-tidy`:

```
if(PROJECT_IS_TOP_LEVEL)
set(CMAKE_EXPORT_COMPILE_COMMANDS TRUE)
```

```
find_program(CPPCHECK_EXECUTABLE cppcheck REQUIRED)

add_custom_target(run-cppcheck
    COMMAND ${CPPCHECK_EXECUTABLE}
        --project=${CMAKE_BINARY_DIR}/compile_commands.json
)
endif()
```

There are some drawbacks to the above:

- The checks run on each source file one at a time. The -j option could be used to enable it to run in parallel, but that would involve determining a suitable number of parallel jobs and specifying that with the -j option. The build rule would then compete with other build tasks unless measures were taken to ensure the cppcheck task ran on its own.
- There's no direct way for the developer to check only a subset of the project's source files. That hinders its use when a developer is working on a specific file. It can also be a problem if the project uses things like code generators, and the generated code is not expected to conform to the project's code standard.

A better way is to adapt CMake's direct cppcheck support to use the compilation database. More recent versions of the cppcheck tool support a --file-filter=... command-line option. This can be used in conjunction with --project=... to limit the analysis to just one file instead of the whole compilation database. Unfortunately, the way CMake passes the arguments from the

`CMAKE_<LANG>_CPPCHECK` variable on the `cppcheck` command line prevents the `--file-filter=...` option from being specified there. Instead, the project (or toolchain file) needs to create a script which invokes `cppcheck` with the necessary options. The source file will be the last argument passed by CMake, and the script needs to extract that file name and include it with the `--file-filter=...` argument. The following shows how this could be done on a Unix system:

cppcheck.in

```
#!/usr/bin/env bash

"@CPPCHECK_EXECUTABLE" \
"--project=@CMAKE_BINARY_DIR@/compile_commands.json" \
"--file-filter=${@: -1}"
```

CMakeLists.txt

```
if(PROJECT_IS_TOP_LEVEL)
    set(CMAKE_EXPORT_COMPILE_COMMANDS TRUE)
    find_program(CPPCHECK_EXECUTABLE cppcheck REQUIRED)
    configure_file(cppcheck.in cppcheck @ONLY)
    set(CMAKE_CXX_CPPCHECK
        ${CMAKE_CURRENT_BINARY_DIR}/cppcheck
    )
endif()
```

The `configure_file()` call is used to copy the `cppcheck.in` file to the build directory, substituting the value of `CMAKE_BINARY_DIR` and the `CPPCHECK_EXECUTABLE` variables along the way. The `${@: -1}` part extracts the last argument passed to the shell script, which will be the file to be analyzed.

Projects may also want to consider adding the `--cppcheck-build-dir=...` option to the script. This option is required for certain checks to be activated, and it can speed up analysis for files that have been analyzed before and that haven't changed. If problems identified by `cppcheck` should be treated as errors and fail the build, also add the `--error-exitcode=2` option (any value in the range 2—255 can safely be used).

The compilation database support in `cppcheck` is not without its problems. A bug in `cppcheck` can result in it interpreting paths as compiler flags. On macOS, for example, absolute paths to files under the user's home directory will typically start with `/Users/....` The `/U` will be seen by `cppcheck` as the same as a `-U` option, which means to undefine a compiler symbol. As it happens, this specific case will typically be harmless, since the rest of the path is highly unlikely to match any symbol. Other paths which start with a different letter may not be so fortunate. But in most cases, the compilation database approach is still likely to be more robust than CMake's more basic flag-passing.

32.3. cpplint

The `cpplint` tool checks for compliance with Google's style guide. It won't be appropriate for all projects, but for those seeking to follow Google's style, it may be helpful.

CMake supports cpplint with a similar mechanism as for clang-tidy and cppcheck. This is again only available with Makefiles or Ninja generators. The `<LANG>_CPPLINT` target property is initialized from the `CMAKE_<LANG>_CPPLINT` variable. The contents of these specify the path to the cpplint executable, or a list containing the path to cpplint followed by any command-line arguments. Enabling cpplint can be done directly from the `cmake` command line in the expected way:

```
cmake -G Ninja -S . -B build \
-DCMAKE_CXX_CPPLINT:STRING=/path/to/cpplint
```

Like for clang-tidy, command-line options are supported, but configuration files are a better choice for projects. These allow IDEs with support for cpplint to automatically pick up the same settings when providing in-editor feedback. A settings file is named `CPPLINT.cfg`, and separate settings files can be provided for each directory. Inheritance from parent directories is enabled by default, which is the opposite behavior to clang-tidy's settings files. The `CPPLINT.cfg` file in the top level source directory should contain `set noparent` to prevent the tool from searching any higher for settings files. The checks to be performed can be tailored with a `filter=...` line in the settings file. See the `cpplint --help` output for available settings and examples.

Unlike clang-tidy and cppcheck, there is no support for using a compilation database with cpplint. However, the purpose of the tool is for linting rather than deep code analysis, so a compilation database isn't required.

Also note that if cpplint finds any issues, it will log a message, but it won't be treated as a build error. This means it has limited usefulness, especially in CI builds where the build output often won't be seen unless something else causes the build to fail.

32.4. Include What You Use

The include-what-you-use tool (often referred to as IWYU) focuses on the header files included by sources and headers. In general, a source or header file should `#include` headers for all symbols the file uses directly. This has a number of benefits, but the main two are:

- It makes the dependencies of a source or header file explicit, which in turn makes dependencies between CMake targets clearer. When IWYU is first introduced into an existing project, it often reveals direct dependencies between targets that developers may not have previously been aware of.
- It prevents a build from breaking when dependencies change the headers they include from one version to another. Relying on a dependency to pull in a header for a symbol is fragile,

since the dependency might not need that header in the future and may remove it from its own public headers.

The IWYU tool also identifies where an `#include` statement isn't needed, and where a forward declaration of a symbol is sufficient. This can greatly reduce the number of headers a file pulls in. Again, there are a number of benefits, including:

- Less work for the compiler front end (the part that parses files, and typically handles C++ template instantiations). This can speed up compilation of individual files.
- When the developer changes a header, fewer other files are affected. Therefore, less of the project may need to be recompiled.
- Changes to headers cause fewer cache misses when a compiler cache is used (see [Section 26.5, “Compiler Caches”](#)).

CMake has direct support for IWYU, and it uses the same approach as the other tools discussed in this chapter. Again, this support is only available with Makefiles or Ninja generators. The `<LANG>_INCLUDE_WHAT_YOU_USE` target property is initialized from the `CMAKE_<LANG>_INCLUDE_WHAT_YOU_USE` CMake variable. These specify the path to the `include-what-you-use` executable, or a list containing the path to `include-what-you-use` followed by any command-line arguments.

Command-line arguments for include-what-you-use need a little extra care compared to the other tools. The tool has its own options, but it also accepts flags for the clang compiler. In order to differentiate between the two, each include-what-you-use option must be prefixed by a -Xiwyu option. Options not prefixed by -Xiwyu will be treated as clang options.

While it is possible to set CMAKE_<LANG>_INCLUDE_WHAT_YOU_USE variables on the cmake command line, this will often not be convenient (for reasons discussed further below). Therefore, the project may want to provide a cache option for enabling IWYU support, and add the necessary details when that cache option is true.

```
if(PROJECT_IS_TOP_LEVEL)
    option(ENABLE_IWYU "Enable include-what-you-use" ON)
    if(ENABLE_IWYU)
        set(CMAKE_EXPORT_COMPILE_COMMANDS TRUE) ①

        find_program(INCLUDE_WHAT_YOU_USE_EXECUTABLE
            include-what-you-use
            REQUIRED
        )
        set(CMAKE_CXX_INCLUDE_WHAT_YOU_USE
            ${INCLUDE_WHAT_YOU_USE_EXECUTABLE}
            -Xiwyu --mapping_file=...
            -Xiwyu --error
            CACHE STRING "Include-what-you-use command"
        )
    endif()
endif()
```

① A compilation database isn't strictly needed for this example, but see the discussion at the end of this section for why it might still be useful.

The IWYU tool isn't perfect. Sometimes it identifies the wrong header to include for a particular symbol. For such cases, the tool provides a way to override wrong choices using a mapping file. The location of that file is specified with the `--mapping_file=...` option. The mapping file format is beyond the scope of this book, but it is described in the IWYU documentation. CMake's own source code contains a mapping file which may serve as a starting point for projects. It can be found in CMake's source repository at `Utilities/IWYU/mapping.imp`.

A project will often want to provide its own mapping file. Leaving every developer to work out what symbols the IWYU tool will misidentify would be tedious. Storing the mapping file as part of the project means that effort only needs to be spent once and can be re-used by all developers. In the above example, the project sets everything up for the developer, but the developer still has control due to the `ENABLE_IWYU` option, and also because `CMAKE_CXX_INCLUDE_WHAT_YOU_USE` is defined as a cache variable rather than a regular variable. The same approach could be used for the other tools discussed earlier in the chapter, but it is especially beneficial for IWYU.

Earlier versions of CMake and IWYU were unable to cause IWYU warnings to be treated as errors. The exit code of the IWYU tool did not follow normal conventions, so CMake didn't treat non-zero exit codes as errors. When using CMake 3.27 or

later with IWYU 0.18 or later, the `--error` IWYU option is properly respected, and warnings will be treated as errors. Note that the IWYU version is tied directly to a specific version of LLVM. The IWYU version should be determined by the clang version when a clang toolchain is being used by the build. See the IWYU documentation which details what IWYU version to use for each LLVM version.

The `include-what-you-use` command does not use a compilation database. CMake passes the compiler flags directly on the `include-what-you-use` command line. However, a compilation database may be useful if the developer wants to run the IWYU tool over the whole project without compiling the sources. An `iwyu_tool.py` script is provided alongside `include-what-you-use` for this purpose. The `iwyu_tool.py` script is a wrapper around `include-what-you-use`, offering some basic options to control things like which files to process, how many tasks to run in parallel, and so on. It uses the compilation database to work out the appropriate command line for the `include-what-you-use` tool. The output from `iwyu_tool.py` may be too noisy for everyday use, but it may be suitable for some continuous integration or occasional use scenarios. The output from `iwyu_tool.py --help` provides the necessary details for using the tool.

32.5. Potential Problems With Co-compilation

As mentioned at the start of the chapter, the CMake support for each of the `CMAKE_<LANG>_<TOOL>` static analysis tools is implemented using a *co-compilation* approach. Instead of the build tool invoking the compiler directly to compile a source file, it invokes `cmake` with some special options. That `cmake` invocation will first run each of the enabled checkers, one by one. Only after they all succeed will the file then be compiled.

The assumption made by the co-compilation model is that running the checkers is relatively fast compared to the time taken to compile the file. If this assumption holds true, then any problems identified by the checkers will be exposed quickly. But if any of the checkers are more expensive than compilation, it may take longer to get feedback about problems than if the file had simply been compiled without any checkers. A common situation where this occurs is where too many checks are enabled for `clang-tidy`. Therefore, be careful about the configuration settings used for each tool. Ensure that the analyses performed are providing value for the computational cost they incur. Try to avoid duplicating checks, or enabling too many very similar checks.

Another consequence of the co-compilation model is that the developer cannot ask the build to run just the compilation without the checkers. The developer would have to first re-run CMake and disable the checkers by clearing the relevant `CMAKE_<LANG>_<TOOL>` variables, or maintain two separate build

directories with the analysis tools enabled and disabled. Similarly, the developer cannot ask the build to run just one or more of the checkers and skip source compilation. If this degree of separation is needed, alternative methods like the `run-clang-tidy` tool mentioned in [Section 32.1.3, “Other Considerations”](#) may be more suitable.

Some static code analysis tools will give different results depending on the level of optimization specified by the compiler command-line options. Some internal data structures may only be built when certain optimizations are enabled, so any checks that rely on those data structures won’t be enabled at low optimization levels. It may be tempting therefore to enable optimizations for builds configured with code analysis, but that has a couple of potential problems. Firstly, it will increase compilation time, and if the code analysis is the main thing of interest rather than compilation, the overall build will take longer. Secondly, some checks will only identify problems when optimizations are *not* enabled. The optimizer might optimize away code that would normally trigger a warning. Therefore, in the ideal scenario, some checkers should be run with different optimization settings in order to provide better overall code analysis. Typically, this would be Debug and Release, which should cover most checks of interest.

32.6. File Sets Header Verification

When a target provides headers for other targets to use, those headers should not rely on any other headers having been included first. It should always be possible to include a header as the first and potentially only header that a source file brings in with an `#include` statement. The header should itself include any other headers it relies on. One can verify this by creating a source file that includes just that header and trying to compile it.

Manually creating a source file for each header would be tedious for large projects. With CMake 3.24 or later, INTERFACE and PUBLIC file sets of type HEADERS can be verified automatically at build time by setting the `CMAKE_VERIFY_INTERFACE_HEADER_SETS` variable to true. This variable is intended to be set by the developer, not the project. The developer should be in control of whether to enable header verification or not. File sets belonging to STATIC, SHARED, OBJECT, and INTERFACE libraries will be verified, as will those belonging to executable targets whose `ENABLE_EXPORTS` property is set to true (a rarely needed arrangement).

When verification is enabled, CMake will define a `<targetName>_verify_interface_header_sets` target for each eligible target that has at least one non-private HEADERS file set. These extra verification targets are object libraries, each one consisting of generated sources that include just one header from the file set(s) being verified. The generated `#include`

statement within a source file will use the path to the header relative to the file set's base directory under which the header is located, not just the bare header file name.

Building one of these extra verification targets confirms that all the headers being verified for that target do not rely on some other header having been included first. `<targetName>_verify_interface_header_sets` is also linked to `<targetName>`, so the usage requirements from `<targetName>` are applied to the verification target. CMake will also define an `all_verify_interface_header_sets` target which depends on all the other `<targetName>_verify_interface_header_sets` targets. The developer needs to explicitly build the individual or catch-all verification targets, none of them are part of the default `all` target. Building `all_verify_interface_header_sets` will typically be the most convenient.

```
add_library(Colors colors.cpp color_mixers.cpp)
target_sources(Colors
PUBLIC
    FILE_SET installed
    TYPE HEADERS
    BASE_DIRS include
    FILES
        include/colors.h
        include/algo/color_mixers.h
PRIVATE
    FILE_SET internal
    TYPE HEADERS
    BASE_DIRS private
    FILES
```

```
    private/colors_impl.h  
)
```

```
cmake -DCMAKE_VERIFY_INTERFACE_HEADER_SETS=TRUE ...  
cmake --build ... \  
--target all_verify_interface_header_sets
```

In the above example, CMake would generate a target called `Colors_verify_interface_header_sets`. That target would have two C++ source files generated, one including only `colors.h` and the other including only `algo/color_mixers.h`. No source file would be generated for the `colors_impl.h` header because it is only in a PRIVATE file set.

By default, all PUBLIC and INTERFACE header sets for a target are eligible for verification. If some header sets are not suitable, the project can set the `INTERFACE_HEADER_SETS_TO_VERIFY` target property to a list of file set names to be verified instead. If none of a target's header file sets are suitable for verification, the project can disable it for the target by setting the `VERIFY_INTERFACE_HEADER_SETS` target property to false. Thus, the project is responsible for what is *eligible* for verification, while the developer controls whether to enable verification globally. It should also be noted that `FetchContent_MakeAvailable()` sets `CMAKE_VERIFY_INTERFACE_HEADER_SETS` to false for any dependencies it brings in (see [Chapter 39, *FetchContent*](#)). This disables verification of any headers owned by those dependencies.

32.7. Disabling Checks For Some Files

CMake 3.27 added the `SKIP_LINTING` source file property for more fine-grained control over which files the `CMAKE_<LANG>_<TOOL>` tools and the file set header verifications operate on. When `SKIP_LINTING` is set to true on specific source files, those files will not be analyzed by the analysis tools. The property applies to all the tools, there are no per-tool properties to disable analysis only for specific tools. The `SKIP_LINTING` property can also be set on headers. If the property is set to true on files that are part of a `HEADERS` file set, file set verification will not be performed on those files.

Setting `SKIP_LINTING` to true is often appropriate for source files or headers created by code generators, since they won't typically be files the developer can change. As an example of this, CMake automatically sets the `SKIP_LINTING` property to true for files generated as part of the Qt Autogen features (see [Section 45.5, “Autogen”](#)).

Another case where source files may need `SKIP_LINTING` set to true is for huge files. Analysis of such files may be prohibitively expensive, or they might trigger failures of the tool itself. Rather than disabling the tool for a whole target, `SKIP_LINTING` can be set to true on only the problematic files. This allows analysis to still be performed on the target's other sources and headers.

32.8. Recommended Practices

In most cases, static code analysis tools should only be used on source code the developer has the opportunity to modify. If a tool generates a warning or error in code from one of its dependencies, the developer wouldn't normally be able to change that code to address the warning or error. This implies that the main project should avoid enabling analysis tools for dependency code it builds directly (see [Chapter 39, *FetchContent*](#) for a detailed discussion of such a structural pattern). A project may also want to check whether it is the top level project and only enable its static analysis tools if it is the top level. These two steps will focus code analysis on the main project, which is usually all the developer is really interested in.

Where a code analysis tool supports a configuration file for specifying the checks to perform, it is generally preferable to use that facility instead of loading up the command line with various options. These configuration files tend to allow simpler per-directory customization of the analysis checks, and they can often be used by IDEs to provide the same static analysis checks interactively in the code editor. This makes earlier detection of problems more likely. For clang-tidy, prefer to use `.clang-tidy` files over command line options. Use `InheritParentConfig: true` to make subdirectories modify rather than completely replace settings defined higher up in the parent directories. For cpplint,

use `CPPLINT.cfg` files, which inherit and modify their parent settings by default.

Most static code analysis tools can take advantage of a compilation database, and in some cases, doing so will give more robust behavior. CMake will generate a `compile_commands.json` file at the top of the build directory if the `CMAKE_EXPORT_COMPILE_COMMANDS` cache variable is set to true. This generation takes very little time, so it is generally recommended that all projects set this to true. For clang-tidy, use the `-p` option to direct the tool to use the compiler command lines from the compilation database instead of details appended to the tool's command line. This avoids a clang-tidy bug which can result in the wrong headers being used during the analysis.

Turning code analysis warnings into errors is generally advisable, especially for continuous integration builds. Otherwise, the warnings may go unnoticed if nobody is checking the build logs. For clang-tidy, consider putting `WarningsAsErrors: *` in the `.clang-tidy` file. For include-what-you-use, ensure the IWYU tool version is at least 0.18, and the CMake version is at least 3.27. The `--error` option is then respected by the build. For cppcheck, add `--error-exitcode=2` to the command-line options to treat warnings as errors (any value in the range 2—255 can be used).

With CMake 3.24 or later, the developer can enable header file set verification by setting the `CMAKE_VERIFY_INTERFACE_HEADER_SETS` cache variable to true. The project should not set this variable, it is a developer control. Continuous integration builds are a good place to enable this, which would require adding a step to explicitly build the `all_verify_interface_header_sets` target. Employing a compiler cache should help reduce the cost of the added compilations involved, assuming most headers don't change frequently (see [Section 26.5, “Compiler Caches”](#)).

It can be easy to go overboard with the static code analysis in a project. If too many checks are enabled, the code analysis can take considerably longer than regular compilation of the sources. This is especially the case with clang-tidy, as some of its checks can be very expensive. Select a reasonable set of checks that avoid too much overlap. Do some benchmarking with different settings to determine which checks cost a lot of time for questionable benefit.

33. DYNAMIC CODE ANALYSIS

The previous chapter discussed various tools that perform code analysis at build time. Those are excellent for catching logic problems, especially locally within a small region of code. However, some problems can only be detected by running the code, and for this, dynamic code analysis is needed.

CMake has only limited direct support for dynamic analysis, restricted mostly to some CDash dashboard settings mentioned briefly in [Section 31.3, “CTest Configuration”](#). But projects and developers can still readily set up and use a number of dynamic analysis tools and incorporate them into their regular workflow. Two popular and widely used forms of dynamic analysis are discussed in this chapter: sanitizers and code coverage.

Dynamic analysis typically requires the code to be instrumented, which means it needs to be built with specific flags. The built binaries are then executed, typically by running a test suite. Analysis tools like sanitizers check the code as it executes, or when the program ends. Code coverage tools record data during the run and write out results for later post-

processing and report generation. Some tools also support environment variables which modify the behavior of the analysis when the binaries are executed.

33.1. Sanitizers

An important class of dynamic code analysis is sanitizers. These are provided by the compiler, typically for C or C++, but also potentially other related languages like CUDA. The various types of sanitizers each detect specific classes of problems. They include things like use of invalid memory addresses or uninitialized values, memory allocation and deallocation errors, leaks, data races across threads, and other undefined behavior. The behavior at run time of each sanitizer can also be tailored through environment variables.

All three major compilers (clang, gcc and Visual Studio) have some degree of sanitizer support. Of the three, clang has the most extensive functionality. Recent gcc versions are not far behind, while Visual Studio is still fairly limited in what it supports. All three have a close relationship and shared origins, so it is common to see the same term refer to the same type of sanitizer across the different compilers.

33.1.1. Main Types Of Sanitizers

AddressSanitizer (ASan)

This is perhaps the most commonly used and certainly most widely supported of all the sanitizers. It is a relatively fast memory error detector, and it is supported by all three major compilers. It detects problems like buffer overflows, use of freed memory, use after return, use after going out of scope, and order-of-initialization bugs. On some platforms, it can also detect memory leaks by essentially enabling the LeakSanitizer as well.

LeakSanitizer (LSan)

This is a more specialized sanitizer with a much narrower focus. It reports memory leaks at the end of program execution, having very little run-time cost up until the application is ending. It may be enabled by default as part of the AddressSanitizer on platforms that support it. The LeakSanitizer is typically only useful as a standalone sanitizer when AddressSanitizer is too expensive, and where the only required checks are those for memory leaks. It relies on inserting its own `malloc()` and `free()` implementations that replace the standard ones normally provided by the system.

MemorySanitizer (MSan)

Perhaps the least widely supported, this sanitizer detects reads of uninitialized memory. Memory use will typically increase by a factor of 2x or 3x with this sanitizer enabled, depending on run-time options used.

ThreadSanitizer (TSan)

When used with multi-threaded applications, this sanitizer will detect data races. This is a very expensive checker, as it increases memory use by 3—9 times, and slows execution by a factor of about 5—15 times.

UndefinedBehaviorSanitizer (UBSan)

This is also a relatively fast checker with low run-time cost. It detects undefined behavior, specifically problems like out-of-bounds array accesses, dereferencing null pointers, certain numerical overflow cases, and more.

Clang, and to some extent gcc, offer a number of other sanitizers, but they are less widely used, less mature, or still considered experimental.

33.1.2. Toolchain Support

Both clang and gcc support all the main sanitizers described in the previous section, at least on some platforms. Visual Studio only supports the AddressSanitizer.

There are constraints around which sanitizers can be used together. In general, only one of AddressSanitizer, MemorySanitizer or ThreadSanitizer may be enabled at the same time. The LeakSanitizer can be enabled with AddressSanitizer, but not MemorySanitizer or ThreadSanitizer.

The UndefinedBehaviorSanitizer can be enabled with any of the other sanitizers.

In more recent versions of some toolchains (notably clang), a further constraint is that static linking cannot be used with some sanitizers (typically AddressSanitizer and MemorySanitizer). For the broadest compatibility across toolchains and toolchain versions, it is therefore generally advisable to avoid static linking for all sanitizer builds. Since dynamic linking is already the default for all toolchains, this should only be relevant for projects where static linking is specifically requested. Static linking is not discussed further in this book.

The following table shows the minimal flags needed to enable each sanitizer, where it is supported for the target platform. The flags for clang and gcc need to be specified when compiling and linking. The Visual Studio flag is only needed during compilation.

	Clang, GCC	Visual Studio
AddressSanitizer	<code>-fsanitize=address</code>	<code>/fsanitize=address</code>
LeakSanitizer	<code>-fsanitize=leak</code>	<i>not supported</i>
MemorySanitizer	<code>-fsanitize=memory</code>	<i>not supported</i>
ThreadSanitizer	<code>-fsanitize=thread</code>	<i>not supported</i>

Clang, GCC	Visual Studio
UndefinedBehaviorSanitizer -fsanitize=undefined	<i>not supported</i>

If using the Visual Studio toolchain, AddressSanitizer requires at least VS2019 16.9 and CMake 3.23. Earlier versions are either missing the necessary support, or do not work reliably. Some Visual Studio toolchain options and features are also incompatible with AddressSanitizer, such as edit-and-continue debugging, the /RTC... compiler flags, and incremental linking. Note that CMake adds /RTC1 by default for the Debug configuration, so the CMAKE_<LANG>_FLAGS_DEBUG cache variable will need to be modified.

[Section 33.1.4, “Sanitizer Implementation Strategies”](#) discusses the merits of different approaches for setting sanitizer flags, but for this example, consider using a toolchain file. For Visual Studio, a toolchain file might contain something like the following to enable the AddressSanitizer with a minimal set of flags:

```

set(CMAKE_C_FLAGS_INIT
    "/DWIN32 /D_WINDOWS /fsanitize=address"
)
set(CMAKE_C_FLAGS_DEBUG_INIT "/O0 /Od")

set(CMAKE_CXX_FLAGS_INIT
    "/DWIN32 /D_WINDOWS /EHsc /fsanitize=address"
)
set(CMAKE_CXX_FLAGS_DEBUG_INIT "/O0 /Od")

```

For clang and gcc, lines like the following would be a minimal set of flags for enabling both AddressSanitizer and UndefinedBehaviorSanitizer at the same time (but see further below for additional recommended flags):

```
set(CMAKE_C_FLAGS_INIT
    "-fsanitize=address -fsanitize=undefined"
)
set(CMAKE_CXX_FLAGS_INIT
    "-fsanitize=address -fsanitize=undefined"
)
set(CMAKE_EXE_LINKER_FLAGS_INIT
    "-fsanitize=address -fsanitize=undefined"
)
set(CMAKE_SHARED_LINKER_FLAGS_INIT
    "-fsanitize=address -fsanitize=undefined"
)
set(CMAKE_MODULE_LINKER_FLAGS_INIT
    "-fsanitize=address -fsanitize=undefined"
)
```

See [Section 24.3, “Tool Selection”](#) for discussion of why the ..._INIT variables are the correct ones to set in a toolchain file.

With the Visual Studio toolchain, it may also be desirable to add the /fsanitize-address-use-after-return option to the CMAKE_<LANG>_FLAGS_INIT variables. While this will result in significantly slower execution, it may also result in better detection of some problems. The equivalent option is already enabled by default with clang and gcc. All toolchains require this feature to also be enabled at runtime, the compiler flag alone is not enough (except for Linux where the runtime

default is also to enable it). This is covered in [Section 33.1.5, “Run-time Control”](#).

Clang and gcc both provide more granular control over individual checks with additional compiler flags. See their respective --help output or man pages for details, as the set of options is extensive. Note there are some subtle differences in behavior between the two compilers, so be sure to check the documentation for both rather than expecting them to always behave the same.

The Google documentation for the MemorySanitizer with clang recommends adding -fPIE -pie to the compiler and linker flags, but this is not necessary. That documentation is out-of-date, it relates to a restriction for clang 3.7 and older where MemorySanitizer didn't work for non-position-independent executables. Clang's own documentation provides the explanation, which should be considered authoritative.

When sanitizers find problems, they usually provide a stack trace in the output. With clang or gcc, the -fno-omit-frame-pointer compiler flag should be used to make that stack trace useful. It could be added to the `CMAKE_<LANG>_FLAGS_INIT` variable to apply it to all configurations, or it could be added selectively to only those configurations with debug information (`CMAKE_<LANG>_FLAGS_DEBUG_INIT` and `CMAKE_<LANG>_FLAGS_RELWITHDEBINFO_INIT`). The equivalent flag to

add for the Visual Studio toolchain is `/Oy-`, although it isn't needed for 64-bit builds, since the option isn't available in that case. The `UndefinedBehaviorSanitizer` requires a run-time option to enable printing a stack trace when it finds problems (see [Section 33.1.5, “Run-time Control”](#)). For all other sanitizers, stack traces would normally be printed by default.

When enabling sanitizers, it is also generally recommended to build with an optimization level that provides performance improvements without hurting the debugging experience. Typically, that means disabling inlining, and potentially selecting only basic optimizations. Stack traces for any detected problems will then be much easier to follow. With clang and gcc, `-O1` or `-Og` would be an appropriate setting, while `/Obo /O1` would be roughly equivalent for Visual Studio. If execution time isn't prohibitive, disabling all optimizations may still be desirable for the most unambiguous stack trace (`-O0` for clang and gcc, `/Od` for Visual Studio). Some problems are only detected at certain optimization levels though, so running sanitizers with different optimization settings can be helpful, even at higher settings where stack traces may be less clear.

33.1.3. Xcode Generator

If building with the Xcode generator, the flags for clang described in the previous section can still be used. However, Xcode has named options for `AddressSanitizer`, `ThreadSanitizer`, and `UndefinedBehaviorSanitizer`

(LeakSanitizer and MemorySanitizer are not supported). These options are part of the *schemes*, not the Xcode project settings. CMake 3.13 and later provides direct support for these sanitizer options with the following target properties:

- XCODE_SCHEME_ADDRESS_SANITIZER
- XCODE_SCHEME_THREAD_SANITIZER
- XCODE_SCHEME_UNDEFINED_BEHAVIOR_SANITIZER

The XCODE_GENERATE_SCHEME target property must also be set to true on the target for the above three properties to have any effect. All four of these properties are initialized by CMake variables of the same name, with CMAKE_ prepended. In most cases, a project would not modify the sanitizer properties directly. The developer would set the variables instead and apply them to the whole project. For example:

```
cmake -G Xcode ... \
-D CMAKE_XCODE_GENERATE_SCHEME=TRUE \
-D CMAKE_XCODE_SCHEME_ADDRESS_SANITIZER=TRUE \
-D CMAKE_XCODE_SCHEME_UNDEFINED_BEHAVIOR_SANITIZER=TRUE
```

Unfortunately, CMake does not apply the scheme settings to the default ALL_BUILD target. It only applies them to targets added by the project. Furthermore, cmake --build ... doesn't use the schemes at all, it invokes xcodebuild with a -target option rather than a -scheme option. The result of these behaviors is that building from the command line fails to enable the

sanitizers when using the Xcode generator and relying on the schemes, as described above. The developer can still force the sanitizers to be enabled at build time though. The `xcodebuild` command supports options for explicitly enabling the sanitizers. For example:

```
xcodebuild -enableAddressSanitizer YES \
            -enableUndefinedBehaviorSanitizer YES \
            ...
```

Or equivalently if using `cmake --build`:

```
cmake --build . . . -- \
      -enableAddressSanitizer YES \
      -enableUndefinedBehaviorSanitizer YES
```

Note the `--` at the end of the first line. Anything after `--` will be passed to the underlying build tool, which is `xcodebuild` in this case. If using build presets (see [Section 42.3, “Build Presets”](#)), the `nativeToolOptions` field can be used to pass through the same options.

33.1.4. Sanitizer Implementation Strategies

The sanitizer flags and project settings can be applied in a number of different ways. Which approach works best will depend on the situation. For toolchain flags that affect how a project is built, the logic would normally be implemented either in a toolchain file, or directly in the project. The logic might also be brought into the main project from a dependency, but

ultimately it will still effectively act like one of those two main approaches.

For the broadest generality, using a toolchain file is recommended. To get the most accurate results, it may be necessary to build dependencies with the same sanitizer settings as the main project. If package managers are being used, a toolchain file may be the only way to get the necessary changes to propagate to the dependencies too. The main drawback to putting the logic in a toolchain file is that some projects might not otherwise need a toolchain file, so developers may find it less convenient or less familiar. On the other hand, a toolchain file can often be re-used across many projects, so the one-time cost of their creation may quickly pay off.

[Section 33.1.2, “Toolchain Support”](#) provided toolchain file fragments showing a minimal set of flags for basic sanitizer use. The following toolchain contents build on those earlier examples, incorporating more of the recommended settings:

Visual Studio toolchain file fragment

```
set(CMAKE_C_FLAGS_INIT
    "/DWIN32 /D_WINDOWS /fsanitize=address /fsanitize-address-use-after-
return"
)
set(CMAKE_C_FLAGS_DEBUG_INIT "/Ob0 /O1")

set(CMAKE_CXX_FLAGS_INIT
    "/DWIN32 /D_WINDOWS /EHsc /fsanitize=address /fsanitize-address-use-after-
return"
```

```
)  
set(CMAKE_CXX_FLAGS_DEBUG_INIT "/O0 /O1")
```

clang and gcc toolchain file fragment

```
set(CMAKE_C_FLAGS_INIT  
    "-fsanitize=address -fsanitize=undefined -fno-omit-frame-pointer"  
)  
set(CMAKE_C_FLAGS_DEBUG_INIT "-g -Og")  
  
set(CMAKE_CXX_FLAGS_INIT  
    "-fsanitize=address -fsanitize=undefined -fno-omit-frame-pointer"  
)  
set(CMAKE_CXX_FLAGS_DEBUG_INIT "-g -Og")  
  
set(CMAKE_EXE_LINKER_FLAGS_INIT  
    "-fsanitize=address -fsanitize=undefined"  
)  
set(CMAKE_SHARED_LINKER_FLAGS_INIT  
    "-fsanitize=address -fsanitize=undefined"  
)  
set(CMAKE_MODULE_LINKER_FLAGS_INIT  
    "-fsanitize=address -fsanitize=undefined"  
)
```

If a project has no external dependencies, or if its dependencies are always built directly as part of the project (see [Chapter 39, *FetchContent*](#) for an example of the latter), other choices may be available. It may be more convenient for developers to rely on CMake presets to configure the sanitizers, potentially in conjunction with logic implemented directly in the project or brought in via one of its dependencies. Developers may find this simpler to use than a toolchain file, but it would not generally be appropriate if the project is consumed by something else as a dependency. Such logic should therefore

only try to enable sanitizers if it is the top level project. [Section 40.2, “Don’t Assume A Top Level Build”](#) discusses other cases where similar recommendations apply.

The following example demonstrates how such settings might be provided directly in a project. For simplicity, this example does not check that the set of enabled sanitizers is a valid combination, but a production project should implement such checks. See [Appendix B, Sanitizers Example](#) for a more complete version of this example.

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.23)
project(MyProj)
enable_testing()

if(PROJECT_IS_TOP_LEVEL)
    include(Sanitizers.cmake)
endif()

# Add dependencies here after flags are already set up...

# Add targets and tests...
```

Sanitizers.cmake

```
option(ENABLE_ASAN "Enable AddressSanitizer" YES)

if(MSVC)
    if(ENABLE_ASAN)
        string(REPLACE "/RTC1" ""
            CMAKE_C_FLAGS_DEBUG "${CMAKE_C_FLAGS_DEBUG}"
        )
        string(REPLACE "/RTC1" ""
            CMAKE_CXX_FLAGS_DEBUG "${CMAKE_CXX_FLAGS_DEBUG}"
        )
    
```

```

add_compile_options(
    /fsanitize=address
    /fsanitize-address-use-after-return
)
endif()
elseif(CMAKE_C_COMPILER_ID MATCHES "GNU|Clang")
option(ENABLE_ASAN "Enable AddressSanitizer" NO)
option(ENABLE_TSAN "Enable ThreadSanitizer" NO)
option(ENABLE_UBSAN "Enable UndefinedBehaviorSanitizer" YES)
if(NOT APPLE)
    option(ENABLE_MSAN "Enable MemorySanitizer" NO)
endif()

add_compile_options(
    -fno-omit-frame-pointer
    $<$<BOOL:${ENABLE_ASAN}>:-fsanitize=address>
    $<$<BOOL:${ENABLE_LSAN}>:-fsanitize=leak>
    $<$<BOOL:${ENABLE_MSAN}>:-fsanitize=memory>
    $<$<BOOL:${ENABLE_TSAN}>:-fsanitize=thread>
    $<$<BOOL:${ENABLE_UBSAN}>:-fsanitize=undefined>
)
add_link_options(
    $<$<BOOL:${ENABLE_ASAN}>:-fsanitize=address>
    $<$<BOOL:${ENABLE_LSAN}>:-fsanitize=leak>
    $<$<BOOL:${ENABLE_MSAN}>:-fsanitize=memory>
    $<$<BOOL:${ENABLE_TSAN}>:-fsanitize=thread>
    $<$<BOOL:${ENABLE_UBSAN}>:-fsanitize=undefined>
)
endif()

```

A third strategy sometimes employed is to define dedicated configuration types for each sanitizer. For example, instead of just Debug, Release, RelWithDebInfo, and MinSizeRel, additional configurations like ASan, TSan, and so on might be defined. A drawback to this approach is that it doesn't easily allow using more than one sanitizer at a time. Each combination has to be explicitly added as a new configuration

type. Another drawback is that it is less convenient to switch between different optimization levels for a given sanitizer. Again, each desired combination requires a new configuration type. This results in an increasingly complex set of configurations to build for. If using CMake presets, this can be especially inconvenient due to the large number of combinations to be accounted for. If using third party dependencies, a further complication is the need to map these new configuration types to the types the dependency project understands or produces binary packages for. In short, using custom configuration types for sanitizers is generally too inflexible, and it can be problematic when integrating with other projects.

33.1.5. Run-time Control

Each of the main sanitizers has a corresponding environment variable which can be used to tailor that sanitizer's behavior at run time. The names of these environment variables are based on the uppercase abbreviated name of the sanitizer: ASAN_OPTIONS, LSAN_OPTIONS, MSAN_OPTIONS, TSAN_OPTIONS, and UBSAN_OPTIONS. All major toolchains support this same set of environment variables. Multiple options are separated by a colon. These environment variables are not used when configuring or building the project, they are only used when the built code is executed.

The default options are generally a good starting point for most sanitizers, but some additional checks and features are only enabled on request. Set the relevant `xSAN_OPTIONS` environment variable to `help=1` and run the application to get a full listing of the available options for each sanitizer.

Most sanitizers except `UndefinedBehaviorSanitizer` will print a stack trace with each detected problem by default. To get a stack trace with `UndefinedBehaviorSanitizer`, it must be explicitly requested in the `UBSAN_OPTIONS` with `print_stacktrace=1`.

Stack traces are also normally symbolicated automatically if the `llvm-symbolizer` tool can be found on the PATH (this is for all toolchains, not just clang). This symbolification is usually desirable, since it makes the stack trace much more readable by providing function names rather than raw memory addresses. The location of `llvm-symbolizer` can be provided explicitly in the sanitizer-specific `xSAN_SYMBOLIZER_PATH` environment variable if it cannot be provided on the PATH.

Depending on the toolchain and platform, `AddressSanitizer` might or might not enable the stack-use-after-return check. Adding `detect_stack_use_after_return=true` to the `ASAN_OPTIONS` will enable it (Visual Studio requires building with the `/fsanitize-address-use-after-return` option as well). In

pathological cases, it may be necessary to enable this option for other problems to be detected.

The following example shows how one might enable some additional checks for AddressSanitizer, print stack traces for UndefinedBehaviorSanitizer issues, and use a custom location for the `llvm-symbolizer`.

```
cmake -E env \
    ASAN_OPTIONS=check_initialization_order=true:detect_stack_use_after_return=true \
    UBSAN_OPTIONS=print_stacktrace=1 \
    ASAN_SYMBOLIZER_PATH=/path/to/llvm-symbolizer \
    UBSAN_SYMBOLIZER_PATH=/path/to/llvm-symbolizer \
    path/to/executable
```

If using a CDash dashboard script, the `MemCheck` step has support for managing the sanitizer options. See [Section 31.3, “CTest Configuration”](#) for further details.

33.2. Code Coverage

It is useful to know what parts of the source code are covered by tests, or more importantly, which parts are not. In some scenarios, code coverage may even be a certification requirement, where coverage results must meet some specific criteria. While code coverage should not generally be seen as proof of correctness, it can still be a useful metric for catching

reduced test coverage over time, and hence increased risk of undetected problems.

Typically, code coverage is performed on builds that use the gcc or clang toolchains. While functionality exists for Visual Studio too, it is less accessible to most developers and is not discussed here.

The process for code coverage generally follows a basic pattern:

1. The project is built with additional compiler and linker flags. These instrument the binaries so that they automatically record details each time the binaries are executed.
2. Tests are run to exercise the code base. The results will reflect how much of the source code is covered by the tests.
3. One or more tools are run to collect and analyze the data recorded by the tests, then produce reports in one or more common formats.



Getting an end-to-end set of steps working for code coverage can be non-trivial. There are multiple tools available, each with their own advantages, challenges, and gaps in functionality. What works for one project might not be suitable for another. Scripts and CMake modules for automating code coverage can be found online, but their logic should be checked carefully before adopting them. They frequently contain errors, use outdated methods, or make assumptions and choices that might not be appropriate for all projects. They can also be overly complex as a result of trying to work for many different scenarios. Projects may be better off implementing a more concise set of steps that focus on the things that are directly relevant to itself.

33.2.1. gcov-based Coverage

The most mature form of code coverage is based on gcov. The gcc toolchain has long supported this, and clang supports most of the same options, but with some important differences. In both cases, optimizations should be disabled (-O0) so that accurate line coverage can be obtained. Debug information should also be enabled (-g). These are already the default flags supplied by CMake for the Debug configuration when using clang or gcc.

Compiler and linker flags need to be added so that coverage data is generated at run time. For gcc and clang, add --coverage to both the compiler flags and to the linker flags. For the compiler, this adds the -fprofile-coverage-dwarf and -fprofile-arcs flags. For the linker, it adds -lgcov. Using --coverage instead of

the flags it represents is recommended due to its simplicity. For gcc, it is highly recommended to also add `-fprofile-abs-path` to the compiler flags. This ensures the paths embedded in the coverage files are handled correctly (discussed further below).

When the appropriate flags discussed above are used, building the project will generate a set of `.gcno` files along with the usual build products. When the tests are run, a set of associated `.gcda` files will be generated. Together, these two sets of files can be processed to generate code coverage reports in various formats, depending on the tools used. The `.gcno` and `gcda` files will be created in the same directory as the object files with which they are associated. CMake treats these as internal implementation details, and there's usually not much need for the project or developer to interact with these files directly.

Unlike the situation discussed in [Section 33.1.4, “Sanitizer Implementation Strategies”](#), there is more flexibility in how code coverage flags can be added to the build. There is usually only one combination of flags needed for coverage, so defining a custom CMake configuration for it may be reasonable (see [Section 15.3, “Custom Build Types”](#)). This could be implemented in a toolchain file, directly in the project, or even by setting CMake cache variables directly in a CMake preset. Adding the necessary changes directly in the project tends to be the simplest, since the project is best placed to handle any project-specific aspects, such as directories to be included in or

excluded from the coverage analysis. The following example defines a custom Coverage build type in the project's top level `CMakeLists.txt` file:

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.21)
project(coverage_example LANGUAGES CXX)
enable_testing()

if(PROJECT_IS_TOP_LEVEL AND
CMAKE_CXX_COMPILER_ID MATCHES "GNU|Clang")
set(CMAKE_CXX_FLAGS_COVERAGE "-g -O0 --coverage")
if(CMAKE_CXX_COMPILER_ID STREQUAL "GNU")
string(APPEND
CMAKE_CXX_FLAGS_COVERAGE
"-fprofile-abs-path"
)
endif()
set(CMAKE_EXE_LINKER_FLAGS_COVERAGE "--coverage")
set(CMAKE_SHARED_LINKER_FLAGS_COVERAGE "--coverage")
set(CMAKE_MODULE_LINKER_FLAGS_COVERAGE "--coverage")
endif()

add_subdirectory(src)
```

One could then configure, build, and test the project to generate the coverage data. The custom configuration would be selected in the usual way. For example, the steps for a single-configuration generator would be similar to this:

```
cmake -G Ninja -DCMAKE_BUILD_TYPE=Coverage -S . -B build
cd build
cmake --build .
ctest
```

And for a multi-config generator:

```
cmake -G "Ninja Multi-Config" -S . -B build
cd build
cmake --build . --config Coverage
ctest -C Coverage
```

Also see [Section 42.6, “Workflow Presets”](#), which demonstrates how to assemble the steps for code coverage into a very convenient, easy-to-use form.

Processing Results With gcovr

Once coverage data has been generated, a separate tool must be run to collect the results and generate reports. Historically, lcov has often been used for this, but gcovr is another flexible and fairly widely available alternative. An advantage of gcovr is that it supports more output formats, and all the processing can be performed in a single command invocation. As will be seen in the next section, lcov requires stringing a few commands together to generate equivalent results, so it can be less convenient.

For CMake projects, once tests have been run to produce coverage data, gcovr should be executed from the top level of the build directory. The following shows some suitable options for the example at the end of the previous section. It demonstrates how multiple different formats can be generated in one pass.

```
cd build
gcovr --root .. \
    --cobertura coverage/cobertura.xml \
    --sonarqube coverage/sonarqube.xml \
    --html-details coverage/html \
    -j 10 \
    .
```

Internally, `gcovr` invokes a separate `gcov` tool, and that `gcov` tool must match the compiler used. When building with `gcc`, the default `gcov` found on the `PATH` will usually be appropriate, so `gcovr` won't need any assistance in finding it. However, for `clang`, the tool to use is `llvm-cov`, which must be called with `gcov` as its first command-line argument, or more reliably through a symlink named `gcov` which points to `llvm-cov` (some tools discussed in later sections further below can only handle the symlink approach). This can be communicated to `gcovr` with the `--gcov-executable` option:

```
gcovr --gcov-executable /path/to/gcov ...
```

Some systems may already have a symlink named `gcov` pointing at `llvm-cov`, in which case that can be used directly. The Xcode SDK is one such case. Otherwise, the project may create its own symlink in its build directory and use that instead.

The project may wish to capture all the commonly used options into a `gcovr` config file for convenience. The developer then

doesn't have to provide any options other than the location of that config file each time they run gcovr.

gcovr.cfg.in

```
root = @CMAKE_SOURCE_DIR@
cobertura = @CMAKE_BINARY_DIR@/coverage/cobertura.xml
sonarqube = @CMAKE_BINARY_DIR@/coverage/sonarqube.xml
html-details = @CMAKE_BINARY_DIR@/coverage/html
gcov-executable = @GCOV_EXECUTABLE@
gcov-parallel = yes
```

CMakeLists.txt

```
if(CMAKE_CXX_COMPILER_ID STREQUAL "AppleClang")
  execute_process(
    COMMAND xcrun --find gcov
    OUTPUT_VARIABLE GCOV_EXECUTABLE
    OUTPUT_STRIP_TRAILING_WHITESPACE
  )
elseif(CMAKE_CXX_COMPILER_ID MATCHES "Clang")
  find_program(LLVM_COV_EXECUTABLE llvm-cov REQUIRED)
  file(CREATE_LINK
    ${LLVM_COV_EXECUTABLE} ${CMAKE_BINARY_DIR}/gcov
    SYMBOLIC
  )
  set(GCOV_EXECUTABLE "${LLVM_COV_EXECUTABLE} gcov")
else() # Assuming gcc for this example
  find_program(GCOV_EXECUTABLE gcov REQUIRED)
endif()

configure_file(gcovr.cfg.in gcovr.cfg @ONLY)
```

Note the added advantage that the `gcovr.cfg` file can specify to run in parallel without having to specify the number of processors. The `gcovr` command will then determine an

appropriate number automatically. With the above, running `gcovr` is then straightforward:

```
cd build  
gcovr --config gcovr.cfg .
```

If desired, the project could even create a custom build target to process the coverage data. This would allow it to be used as part of a workflow preset (see [Section 42.6, “Workflow Presets”](#)).

```
add_custom_target(process_coverage  
  WORKING_DIRECTORY ${CMAKE_BINARY_DIR}  
  COMMENT "Running gcovr to process coverage results"  
  COMMAND ${GCOV_EXECUTABLE} --config gcovr.cfg .  
)
```

In practice, using gcov-based coverage data with clang can be challenging. Due to the way paths are written to the coverage files, and the way those paths are handled between `gcovr` and `llvm-cov`, the processing will often fail. When using gcc 8 or later, the `-fprofile-abs-path` flag prevents those problems, but clang does not support that flag or anything similar to it. As a result, it is generally easier to implement code coverage for the gcc toolchain.

Processing Results With lcov

In general, `gcovr` is likely to be a more convenient tool for processing gcov data than `lcov`. But due to its longer history, `lcov` is often still the tool encountered in mature projects. If

using clang, lcov might also be more tolerant of relative path issues and potentially be able to process the coverage data where gcovr cannot. Therefore, it is still useful to know how to use lcov and its associated tools.



When building with the toolchain provided by Xcode, the SDK lacks a consistent set of tools to make using lcov for processing gcov data feasible. Xcode uses a different, clang-specific method for generating code coverage information rather than gcov (see [Section 33.2.2, “clang Source-based Coverage”](#)).

The first step when using lcov is to collect the coverage data into a single trace file. A variety of options can be used to filter the results, but the following is a reasonable starting point:

```
cd build
lcov --capture \
    --directory . \
    --include '/path/to/source/*' \
    --demangle-cpp \
    --parallel \
    --output-file coverage.info
```

The --demangle-cpp and --parallel options are only supported on more recent versions of lcov. The --parallel option in particular is very desirable, since for larger, more complex projects, running lcov serially can be prohibitively slow.

The `--include` option may be necessary to filter out things like toolchain headers, or headers coming from dependencies outside the project. The argument after `--include` is a wildcard pattern. It may need to be surrounded in single quotes to prevent the shell from expanding it before passing it to the command.

Once a trace file has been generated (`coverage.info` in the above example), a HTML report can be created from it with the `genhtml` tool.

```
genhtml coverage.info \
    --demangle.cpp \
    --output-directory coverage
```

If `genhtml` encounters path-related problems when using the clang toolchain, adding `--ignore-errors` source may be enough to get past that. But be aware that the coverage results may then be incomplete.

If reports need to be generated in formats other than HTML, separate tools must be used. For example, a python script for generating a report in Cobertura format can be found at <https://github.com/eriwen/lcov-to-cobertura-xml> and used like so:

```
lcov_cobertura \
    coverage.info \
    --demangle \
```

```
--base-dir /path/to/source/directory \
--output cobertura.xml
```

As for gcovr, these steps can all be wrapped up into a custom target so that they can be easily invoked as part of a workflow preset (see [Section 42.6, “Workflow Presets”](#)).

Dashboard Script Support

As mentioned back in [Section 31.3, “CTest Configuration”](#), CDash dashboard scripts support a *Coverage* step. It assumes a gcov-based coverage implementation. Dashboard scripts can use the `ctest_coverage()` command to collect the results from the `.gcda` files and produce a CDash-specific `Coverage.xml` file. This is analogous to running `gcovr` or `lcov`, but the only supported output format is the native one used for CDash.

For projects that do not use dashboard scripts, the `ctest_coverage()` command is not really relevant. The methods discussed in the preceding sections are more appropriate in that case. Even if using a dashboard script, the lack of choice for the format of the coverage results means `ctest_coverage()` really only makes sense if the script is submitting results to a CDash server. If the script is merely coordinating steps for continuous integration, but something other than CDash is presenting the coverage results, then the methods discussed in the preceding sections will again be more suitable in most cases.

33.2.2. clang Source-based Coverage

Clang has its own native alternative to gcov, which it calls "source-based coverage". It uses different compiler and linker flags, and it uses its own tools for processing the coverage data and generating reports. It may be a more reliable way of implementing code coverage when using the clang toolchain, especially when using the Xcode SDK on Apple platforms.

As a starting point, optimizations should be disabled (-O0) and debug info enabled (-g), just as for gcov. The additional flags -fprofile-instr-generate and -fcov-coverage-mapping also need to be added for the clang compiler, and -fprofile-instr-generate for the linker. These perform a similar function to the --coverage flags discussed in [Section 33.2.1, “gcov-based Coverage”](#), but they enable clang's source-based coverage instead.



If using the Xcode generator, note that Xcode provides dedicated controls for enabling coverage in the scheme options. It is only available in the Test part of the scheme. CMake does not provide any support for these scheme options though, so they cannot be manipulated from the CMake project.

After building the project, tests should be run. For gcov-based coverage, .gcno files are created at compile time, and .gcda files are created at run time for each object file. For clang's source-based coverage, the data output method is different. Instead of

.gcno files, details are encoded directly into each binary (executable, shared library, object files). This creates some implementation difficulties for the project, which are discussed further below.

Next, each time the executable is run, it will add coverage data to a file determined by the LLVM_PROFILE_FILE environment variable rather than in .gcda files at well-known locations. That environment variable supports placeholder substitutions, which allow each run to write to its own file if the placeholders are used appropriately. This is important when tests are run in parallel, which will often be the case with ctest. Clang's documentation for source-based coverage describes the supported placeholders, but of most interest here is the %p placeholder. It is replaced by the process ID, which will be unique for each test run. Thus, setting the environment variable to a value like test.%p.profraw when invoking ctest will ensure tests don't overwrite each other's coverage data.

Once tests have been run, the raw coverage output files need to be *indexed*. LLVM provides a separate tool called llvm-profdata which can be used to do this:

```
llvm-profdata \
  merge \
  -sparse \
  --output=merged.profdata \
  *.profraw
```

Most of the options shown above should be fairly self-explanatory. The `-sparse` option is recommended, as it can significantly reduce the size of the output file.

Once the merged index file has been created, `llvm-cov` can be used to produce a basic HTML report.

```
llvm-cov \
    show \
    --instr-profile=merged.profdata \
    --format=html \
    --output-dir=coverage \
    <binaries>
```

A complication with the processing of the index file is that the list of executables, shared libraries or object files to report coverage for must be explicitly given on the command line (the `<binaries>` part in the example above). This is a consequence of the compile-time coverage information being embedded directly in the binary instead of in separate files. If the project has only one executable, it can be listed directly on the `llvm-cov` command line. But in many projects, there will be multiple test executables. When more than one needs to be given, each one has to be prefixed by `--object=`. For example:

```
llvm-cov \
    show \
    --instr-profile=merged.profdata \
    --format=html \
    --output-dir=coverage \
    --object=bin1 \
    --object=bin2
```

```
--object=src/app1/test_things \
--object=src/app2/test_more_bits \
--object=test/full_system_test
```

The HTML report produced by the above is not as rich as with the other tools discussed in previous sections. `llvm-cov` can be told to produce a `lcov` trace file instead of a HTML report by using the `export` operation instead of `show`. The trace file can then be processed by tools like `genhtml`, as described earlier in [Section 33.2.1.2, “Processing Results With lcov”](#). The HTML report from `genhtml` will typically have better navigation, and the trace file can also be used to generate reports in other formats, like Cobertura.

```
llvm-cov \
    export \
    --instr-profile=merged.profdata \
    --format=lcov \
    <binaries> \
    > coverage.info

genhtml coverage.info \
    --demangle.cpp \
    --output-directory coverage
```

So far, this section has shown the commands that need to be executed from a command line. CMake projects will likely want to collect the commands appropriate for the approach they want to use in a Unix shell script. That script can then either be run directly, or executed as a `COMMAND` in a custom build target added by `add_custom_target()`. For most non-trivial projects, the

main difficulty will be in obtaining the list of test executables to add to the `llvm-cov` command as `--object` arguments. There are no one-size-fits-all solutions to that aspect of the task, since different projects will have different needs. In some cases, all executables defined by the project might be safe to list. In other cases, only some executables should be mentioned. The project needs to implement the logic that builds up the required list of executable targets for its own situation.

33.3. Recommended Practices

Dynamic code analysis is a complement to static analysis. Both are useful and are aimed at identifying different types of problems. It is advisable for projects to incorporate both forms of analysis into their continuous integration systems as early as possible. The longer a project is developed without them, the more problems there will be to fix later before they can be enabled. Depending on the nature of those problems, they may be time-consuming to address, and they may build resistance in the project developers for accepting the analysis tools as part of their everyday workflow.

Give careful consideration to how dynamic analysis is incorporated into continuous integration workflows. When the analysis calls for the code to be built without any optimizations, running the tests may take a long time. Consider whether all tests need to be run in these cases, or whether a subset of the

tests is enough to sufficiently exercise the code paths. For example, unit tests might be appropriate for code coverage, but integration tests might not. On the other hand, integration tests may be appropriate for sanitizer tests, and potentially more valuable than unit tests. Test labels may be helpful in creating sets of tests to run for the different types of code analysis (see [Section 27.4.3, “Labels”](#)).

Consider adding continuous integration jobs with sanitizers. At the very least, the AddressSanitizer is worth setting up and is supported by all the major toolchains. Also take advantage of the fact that the UndefinedBehaviorSanitizer can be enabled at the same time as the other sanitizers. It doesn’t need its own separate build, and it will likely be a more efficient use of CI resources to enable it in conjunction with another sanitizer (typically that will be with AddressSanitizer).

Try to use a recent toolchain for sanitizer builds. Earlier versions of some toolchains can be harder to use due to the way they handle their associated run-time support library. It can be problematic to ensure the run-time support library is loaded early enough when running a test suite with `ctest`. Later versions largely avoid those complications, and they are also likely to detect more issues with the code. Also avoid static linking when enabling sanitizers, since more recent toolchain versions won’t typically support it with some sanitizers.

In projects that use third-party dependencies, some sanitizers will require the dependencies to be built with special compiler and linker flags too, not just the main project. Popular package managers like Conan and Vcpkg will require these flags to be provided as part of the toolchain file used to build the dependencies. Therefore, projects may want to implement their sanitizer logic in toolchain files rather than directly in the project itself. If a project builds all its dependencies from sources as part of the main build rather than using a package manager (such as when using techniques like those described in [Chapter 39, *FetchContent*](#)), in-project logic may be more convenient and more flexible than a toolchain file. This can work well in companies with tightly controlled build environments, but it is less suitable for open source projects which frequently need to support package managers. If using in-project logic, only enable sanitizers if the project is the top level of the build.

Related to the above, avoid defining custom CMake build types for each sanitizer. Such an approach limits the combinations available to the developer, and custom build types may not be understood by dependencies built directly as part of the project, such as described in [Chapter 39, *FetchContent*](#). Sanitizers can also be used with different optimization settings, so it is better to think of them as something that can be enabled or disabled for the existing set of build types, rather than their own separate build type.

If enabling code coverage, choose an implementation that best fits the needs of the project. The gcc toolchain is likely to give the simplest path, with gcov-based tooling being very mature, and the gcc toolchain itself providing options for robust path handling. Consider using `gcovr` for its rich choice of output formats. If clang must be used, consider using its native source-based coverage features. This can still be used to generate output readable by `lcov`, which may provide better HTML output with more flexible navigation than clang's own native HTML reports.

V: DEPLOYMENT AND DEPENDENCIES

For the lucky few, a project may be independent of anything else, having no reliance on any externally provided content. The more likely scenario is that, at some point, the project needs to move beyond its own isolated existence and interact with external entities. This occurs in two directions:

Dependencies

The project may depend on other externally provided files, libraries, executables, packages, and so on.

Consumers

Other projects or users may wish to consume the project in a variety of ways. Some may want to incorporate the project at the source level, others may expect a pre-built binary package to be available. Another possibility is the assumption that the project is installed somewhere on the system. End users might just be installing the project to run it, not to build with it.

The CMake suite of tools provides assistance with both areas. For dependencies, it provides commands that operate at both the package level and at a lower level for finding individual files, libraries, etc. CMake also provides features that give a higher level entry point for dependency management. To support consumers, installation and package creation features are available. Packages can be created in a range of common formats.

This part of the book provides chapters covering both of the above main areas. A common link between them is the way packages and lower level things are found by CMake projects. This is covered first in its own chapter before moving on to the separate areas of deployment and dependencies.

34. FINDING THINGS

A project of at least modest size will likely rely on things provided by something outside the project itself. For example, it may expect a particular library or tool to be available, or it may need to know the location of a specific configuration or header file for a library it uses. At a higher level, the project may want to find a complete package that potentially defines a range of things including targets, functions, variables and anything else a regular CMake project might define.

CMake provides a variety of features which enable projects to find things and to be found by or incorporated into other projects. Various `find_...()` commands provide the ability to search for specific files, libraries or programs, or indeed for an entire package. CMake modules also add the ability to use `pkg-config` to provide information about external packages, while other modules facilitate writing package files for other projects to consume. This chapter covers CMake's support for searching for something already available on the file system. The ability to download missing dependencies is covered in [Chapter 38, *ExternalProject*](#), [Chapter 39, *FetchContent*](#) and [Chapter 41](#),

[*Dependency Providers*](#), while preparing a project for being found by other projects is addressed in [*Section 35.9, “Writing A Config Package File”*](#) and [*Chapter 40, Making Projects Consumable.*](#)

The basic idea of searching for something is relatively straightforward, but the details of how the search is conducted can be quite involved. In many cases, the default behaviors are appropriate, but an understanding of the search locations and their ordering can allow projects to tailor the search to account for non-standard behaviors and unusual circumstances.

34.1. Finding Files And Paths

Conceptually, the most basic search task is to find a specific file. The most direct way to achieve this is with the `find_file()` command, which also serves as a good introduction to the whole family of `find_...()` commands, since they all share many of the same options and have similar behavior.

```
find_file(outVar
          name | NAMES name1 [name2...]
          [HINTS path1 [path2...] [ENV var]...]
          [PATHS path1 [path2...] [ENV var]...]
          [PATH_SUFFIXES suffix1 [suffix2 ...]]
          [REGISTRY_VIEW viewMode]      # CMake 3.24 or later
          [NO_DEFAULT_PATH]
          [NO_PACKAGE_ROOT_PATH]
          [NO_CMAKE_PATH]
          [NO_CMAKE_ENVIRONMENT_PATH]
          [NO_SYSTEM_ENVIRONMENT_PATH]
          [NO_CMAKE_SYSTEM_PATH]
```

```
[NO_CMAKE_INSTALL_PREFIX]      # CMake 3.24 or later
[CMAKE_FIND_ROOT_PATH_BOTH | 
 ONLY_CMAKE_FIND_ROOT_PATH | 
 NO_CMAKE_FIND_ROOT_PATH]
[DOC "description"]
[REQUIRED]                      # CMake 3.18 or later
[NO_CACHE]                       # CMake 3.21 or later
[VALIDATOR function]             # CMake 3.25 or later
)
```

The command can search for a single file name, or it can be given a list of names with the NAMES option. A list can be useful when the file being searched for may have a few variations on its name, such as different operating system distributions choosing different naming conventions, incorporating version numbers or not, accounting for a file changing names from one release to another, and so on. The names should be listed in preferred order, since the search will stop at the first one found (the complete set of search locations is checked for a particular name before moving on to the next name). When specifying names that contain some form of version numbering, the CMake documentation recommends listing the name(s) without version details ahead of those that do. Locally built files are then more likely to be found ahead of files provided by the operating system.

The search will be conducted over a set of locations checked according to a well-defined order. Most locations have an associated option which will cause that location to be skipped if

the option is present, thereby allowing the search to be tailored as needed. The following table summarizes the search order:

Location	Skip Option
Package root variables	NO_PACKAGE_ROOT_PATH
Cache variables (CMake-specific)	NO_CMAKE_PATH
Environment variables (CMake-specific)	NO_CMAKE_ENVIRONMENT_PATH
Paths specified via the HINTS option	
Environment variables (system-specific)	NO_SYSTEM_ENVIRONMENT_PATH
Cache variables (platform-specific)	NO_CMAKE_SYSTEM_PATH
Paths specified via the PATHS option	

Package root variables

The first location searched only applies when `find_file()` is invoked from a script invoked as part of a `find_package()` call (discussed later in this chapter). It was initially added as a search location in CMake 3.9.0, but was removed in 3.9.1 due to backward compatibility issues. It was then re-added again in CMake 3.12 with the problems addressed. Further discussion of this search location is deferred to [Section 34.4, “Finding Packages”](#) where its use is more relevant.

Cache variables (CMake-specific)

The CMake-specific cache variable locations are derived from the cache variables `CMAKE_PREFIX_PATH`, `CMAKE_INCLUDE_PATH` and `CMAKE_FRAMEWORK_PATH`. Of these, `CMAKE_PREFIX_PATH` is perhaps the most convenient, as setting it works not just for `find_file()`, but also for all the other `find_...()` commands. It represents a base point below which a typical directory structure of `bin`, `lib`, `include` and so on is expected and each `find_...()` command appends its own subdirectory to construct search paths. In the case of `find_file()`, for each entry in `CMAKE_PREFIX_PATH`, the directory `<prefix>/include` will be searched. If the `CMAKE_LIBRARY_ARCHITECTURE` variable is set, then the architecture-specific directory `<prefix>/include/${CMAKE_LIBRARY_ARCHITECTURE}` will be searched first to ensure architecture-specific locations take precedence over generic locations. The `CMAKE_LIBRARY_ARCHITECTURE` variable is normally set automatically by CMake and projects should not generally try to set it themselves.

For the cases where a more specific include or framework path needs to be searched, and it is not part of a standard directory layout or package, the `CMAKE_INCLUDE_PATH` and `CMAKE_FRAMEWORK_PATH` variables can be used. They each provide a list of directories to be searched, but unlike `CMAKE_PREFIX_PATH`, no `include` subdirectory is appended.

`CMAKE_INCLUDE_PATH` is supported by `find_file()` and `find_path()`, whereas `CMAKE_FRAMEWORK_PATH` is supported by those two commands and by `find_library()`. Other than that, these two sets of paths are handled in the same way. See [Section 34.1.1, “Apple-specific Behavior”](#) further below for additional details.

When using CMake 3.16 or later, the `CMAKE_FIND_USE_CMAKE_PATH` variable controls the default behavior of whether to consider CMake-specific cache variables in the search. The search will only consider the cache variables if `CMAKE_FIND_USE_CMAKE_PATH` is not defined, or it is set to true.

Environment variables (CMake-specific)

The CMake-specific environment variable locations are very similar to the cache variable locations. The three environment variables `CMAKE_PREFIX_PATH`, `CMAKE_INCLUDE_PATH`, and `CMAKE_FRAMEWORK_PATH` are treated in the same way as the same-named cache variables, except that on Unix platforms, each list item will be separated by a colon (`:`) instead of a semicolon (`;`). This is to allow the environment variables to use platform-specific path lists defined in the same style as other path lists for each platform.

When using CMake 3.16 or later, the `CMAKE_FIND_USE_CMAKE_ENVIRONMENT_PATH` variable can be used to control the default behavior in a similar way as for `CMAKE_FIND_USE_CMAKE_PATH`.

Environment variables (system-specific)

The system-specific environment variables are `INCLUDE` and `PATH`. Both may contain a list separated by the platform-specific path separator (colon on Unix, semicolon on Windows), with each item being added to the set of search locations (`INCLUDE` is added before `PATH`).

On Windows only (including Cygwin), the `PATH` entries will be further processed in a more complex manner, but only for CMake versions 3.3 through to 3.27. For each item in the `PATH` environment variable, a base path will be computed by dropping any trailing `bin` or `sbin` subdirectory from the end.

If `CMAKE_LIBRARY_ARCHITECTURE` is defined, `<base>/include/${CMAKE_LIBRARY_ARCHITECTURE}` is added. After that, the `<base>/include` path is added to the set of search paths regardless of whether `CMAKE_LIBRARY_ARCHITECTURE` is defined. In the search path ordering, these paths are placed immediately before the unmodified `PATH` item itself. For example, if `CMAKE_LIBRARY_ARCHITECTURE` was set to `somearch` and the `PATH` environment variable contained `C:\foo\bin;D:\bar`, the following ordered set of search paths would be added:

- C:\foo\include\somearch
- C:\foo\include
- C:\foo\bin
- D:\bar\include\somearch
- D:\bar\include
- D:\bar

When using CMake 3.16 or later, the `CMAKE_FIND_USE_SYSTEM_ENVIRONMENT_PATH` variable can be used to control the default behavior in a similar way as for `CMAKE_FIND_USE_CMAKE_PATH`.

Cache variables (platform-specific)

The platform-specific cache variable locations are very similar to those used for the CMake-specific ones. The names change slightly but the pattern is the same. The variable names are `CMAKE_SYSTEM_PREFIX_PATH`, `CMAKE_SYSTEM_INCLUDE_PATH`, and `CMAKE_SYSTEM_FRAMEWORK_PATH`. These platform-specific variables are not intended to be set by the project or the developer. Rather, they are set automatically by CMake as part of setting up the platform toolchain so that they reflect locations specific to the platform and compilers being used. The exception to this is where a developer provides their own toolchain file, in which case it may be appropriate to set these variables within the toolchain file.

When using CMake 3.16 or later, the `CMAKE_FIND_USE_CMAKE_SYSTEM_PATH` variable can be used to control the default behavior in a similar way as for `CMAKE_FIND_USE_CMAKE_PATH`.

For some platforms, the install prefix (see [Section 35.1.2, “Base Install Location”](#)) is included in the `CMAKE_SYSTEM_PREFIX_PATH`. This might not always be desirable, it can lead to finding unintended things. CMake 3.24 added support for a `NO_CMAKE_INSTALL_PREFIX` keyword, which makes the command ignore an install prefix in the `CMAKE_SYSTEM_PREFIX_PATH`. The default behavior can also be set with the `CMAKE_FIND_USE_INSTALL_PREFIX` variable (set it to true to block searching an install prefix by default). For CMake 3.23 and earlier, the `CMAKE_FIND_NO_INSTALL_PREFIX` variable serves a similar purpose, but with a negated meaning. Prefer to use the new variable where possible, as it overrides the older one if both are defined.

HINTS and PATHS

Each group of variables discussed above is intended to be set by something outside the project, but the `HINTS` and `PATHS` options are where the project itself should inject additional search paths. The main difference between `HINTS` and `PATHS` is that `PATHS` are generally fixed locations that never change and don't depend on anything else. `HINTS` are usually computed from other values, such as the location of

something already found previously, or a path dependent on a variable or property value. PATHS are the last directories searched, but HINTS are searched before any platform- or system-specific locations.

Both HINTS and PATHS support specifying environment variables which may contain a list of paths in the host's native format (i.e. colon-separated for Unix systems, semicolon separated on Windows). This is done by preceding the name of the environment variable with ENV, such as PATHS ENV FooDirs. Prefer to use this form instead of \$ENV{FooDirs} when the environment variable's contents may use the platform-specific path separator.

With CMake 3.24 or later, HINTS and PATHS can refer to registry locations when building on Windows hosts. Both 32-bit and 64-bit views of the registry can be consulted. The REGISTRY_VIEW keyword can be used to control these views, or if omitted, the behavior will be determined by policy CMP0134. Including registry values and using registry views are covered in detail in the official CMake documentation, so that material is not repeated here.

All but the HINTS and PATHS search locations have an associated skip option of the form NO_..._PATH which can be used to skip just that set of locations. In addition, the NO_DEFAULT_PATH option can be used to bypass all but the HINTS and PATHS locations, forcing

the command to search just specific places controlled by the project. These `NO_...` options override any default provided by `CMAKE_FIND_USE_...` variables.

The `PATH_SUFFIXES` option can be used to provide a list of additional subdirectories to check below each search location. Each search location is used with each suffix in turn, then without any suffix at all before moving on to the next search location. Use this option with care, as it greatly expands the total number of locations to be searched.

In many cases, projects only need to specify a single file name to search for and the complexities of the search order are not of particular interest. Perhaps just a few additional paths to search might need to be provided (equivalent to the `PATHS` option). In such cases, a shorter form of the command can be used:

```
find_file(outVar name [path1 [path2...]])
```

Whether the short or long form is used, the ordering of the search locations is designed to search in more specific locations ahead of more generic ones. While this is typically the desired behavior, there may be situations where this is not the case.

For example, a project may wish to always look in specific paths first ahead of any search locations provided through cache or environment variables. Projects can enforce a different priority

by calling `find_file()` multiple times with different options controlling the search locations. Once the file is found, the location is cached and all subsequent calls will skip their search. This is where the various `NO_..._PATH` options are most useful. For example, the following forces searching in the location `/opt/foo/include` first, and only if not found there will the full set of default locations be searched:

```
find_file(FOO_HEADER foo.h
  PATHS /opt/foo/include
  NO_DEFAULT_PATH
)
find_file(FOO_HEADER foo.h)
```

An important requirement for this to work is that the same result variable must be used for each call. It is that variable that gets set and that controls skipping subsequent calls once the file has been found.

Because the result variable is a cache variable by default, it should follow that naming convention and be all uppercase, with underscores separating words. The `DOC` option can be used to add documentation to that cache variable, but it is very rarely used. Prefer instead to choose a variable name that is self-documenting, making the need for explicit documentation unnecessary.

When using CMake 3.20 or earlier, certain corner cases related to the result variable may yield surprising behavior. Care must

be exercised when a non-cache variable with the same name as the result variable already exists before `find_file()` is called. The non-cache variable might be ignored, depending on whether a cache variable also exists and whether such a cache variable has a type (see [Section 6.3, “Cache Variables”](#)). CMake 3.21 added policy `CMP0125`, which ensures that a non-cache variable will be handled more like how one would intuitively expect. The `NO_CACHE` option was also added in CMake 3.21 as a way to assign the result only to a non-cache variable, but projects should generally avoid using it. `NO_CACHE` adversely affects the performance of the configure stage by forcing `find_file()` to always repeat the search on every run.

If the file could not be found, the value stored in the variable will evaluate to false if used in an `if()` expression. The test only needs to be made after the final call to `find_file()`.

```
find_file(FOO_HEADER foo.h
    PATHS /opt/foo/include
    NO_DEFAULT_PATH
)
find_file(FOO_HEADER foo.h)

if(NOT FOO_HEADER)
    message(FATAL_ERROR "Could not find foo.h")
endif()
```

The above form works for any CMake version, but from CMake 3.18, the `REQUIRED` option can be used to express the logic more concisely:

```
find_file(FOO_HEADER foo.h
  PATHS /opt/foo/include
  NO_DEFAULT_PATH
)
find_file(FOO_HEADER foo.h REQUIRED)
```

34.1.1. Apple-specific Behavior

Although the `find_file()` command can be used to find any file, it has its origins in searching for header files. This is why some of the default search paths have an `include` subdirectory appended. On Apple platforms, frameworks sometimes contain their own header files (see [Section 25.3, “Frameworks”](#)) and the `find_file()` command has additional behaviors related to searching in the appropriate subdirectories within them. For each search location, the command may treat the location as a framework, as an ordinary directory, or both.

The behavior is controlled by the `CMAKE_FIND_FRAMEWORK` variable, which is expected to hold one of the values `FIRST`, `LAST`, `ONLY`, or `NEVER`. `FIRST` means to treat the search location as though it was the top directory of a framework and to append the appropriate subdirectories to descend into the `Headers` location within it. If the named file cannot be found there, then the search location is treated as an ordinary directory rather than a framework and searched again. `LAST` reverses that order, `ONLY` will not treat the location as an ordinary directory, and `NEVER` will skip the step that treats the location as a framework. The default for Apple systems is `FIRST`, which is usually the desired behavior.

34.1.2. Cross-compilation Controls

For cross-compiling scenarios, the set of search locations becomes considerably more complex. Cross compiling toolchains are often collected under their own directory structure to keep them separate from the default host toolchain. When conducting searches for a particular file, it is generally desirable to first look in the toolchain's directory structure ahead of those of the host so that a target platform-specific version of the file will be found. This is especially important when finding programs and libraries. Even for finding files, it may be the case that the content of files could change between platforms (e.g. a platform-specific configuration header).

To support cross-compilation scenarios, the entire set of search locations can be re-rooted to a different part of the file system. The `CMAKE_FIND_ROOT_PATH` variable can be set to a list of additional directories at which to re-root the set of search locations (i.e. prepend each item in the list to every search location). The `CMAKE_SYSROOT` variable can also affect the search root in a similar way. It is intended to specify a single directory acting as the system root for a cross-compiling scenario. It affects flags used during compilation as well. From CMake 3.9, the more specialized variables `CMAKE_SYSROOT_COMPILE` and `CMAKE_SYSROOT_LINK` also have a similar effect. All of these variables should only be set in a toolchain file, not by the project.

If any of the non-rooted locations are already under one of the locations specified by `CMAKE_FIND_ROOT_PATH`, `CMAKE_SYSROOT`, `CMAKE_SYSROOT_COMPILE` or `CMAKE_SYSROOT_LINK`, it will not be re-rooted. A non-rooted path that sits under a path specified by the variable `CMAKE_STAGING_PREFIX` will also not be re-rooted. Furthermore, an undocumented behavior of all `find_...()` commands is to not re-root any non-rooted path that starts with a `~` character. This is intended to avoid re-rooting directories that sit under the user's home directory.

The default order of searching among the re-rooted and non-rooted locations is controlled by the `CMAKE_FIND_ROOT_PATH_MODE_INCLUDE` variable. That can also be overridden on a per-call basis by providing one of the `CMAKE_FIND_ROOT_PATH_BOTH`, `ONLY_CMAKE_FIND_ROOT_PATH` or `NO_CMAKE_FIND_ROOT_PATH` options to the `find_file()` command. The following table summarizes the effects of this mode variable, the associated options and the final search order:

Find Mode	<code>find_file()</code> Option	Search order
BOTH	<code>CMAKE_FIND_ROOT_PATH_BOTH</code>	<ul style="list-style-type: none">▪ <code>CMAKE_FIND_ROOT_PATH</code>▪ <code>CMAKE_SYSROOT_COMPILE</code>▪ <code>CMAKE_SYSROOT_LINK</code>▪ <code>CMAKE_SYSROOT</code>▪ All non-rooted locations

Find Mode	find_file() Option	Search order
NEVER	NO_CMAKE_FIND_ROOT_PATH	<ul style="list-style-type: none"> ▪ All non-rooted locations
ONLY	ONLY_CMAKE_FIND_ROOT_PATH	<ul style="list-style-type: none"> ▪ CMAKE_FIND_ROOT_PATH ▪ CMAKE_SYSROOT_COMPILE ▪ CMAKE_SYSROOT_LINK ▪ CMAKE_SYSROOT ▪ Any non-rooted locations already under one of the re-rooted locations or under CMAKE_STAGING_PREFIX

Developers should be aware that `find_file()` can only provide one location, but some cross compiling situations support build arrangements that can switch between device and simulator builds without re-running CMake. This means that if the results of `find_file()` depend on which of the two is being used, they are unreliable. This aspect is even more important for finding libraries and is discussed in more detail in [Section 34.3, “Finding Libraries”](#) further below.

Cross-compilation scenarios also sometimes require ignoring certain paths during the search. See [Section 34.5, “Ignoring Search Paths”](#) for a discussion of that topic.

34.1.3. Validators

Typically, the existence of a file is enough for it to be accepted as the found file. In more advanced scenarios, the file may need to pass other criteria for it to be accepted. With CMake 3.25 or later, the `VALIDATOR` keyword can be used to specify a function that implements an arbitrary check on each candidate file. A validator function must take two arguments:

- The name of a result variable to be set in the calling scope.
- The absolute path to the file.

Unless the function sets the result variable to false in the calling scope before returning, the candidate file is accepted as the result of the call to `find_file()`. The following two examples demonstrate the usage.

```
# Only accept files that define a version string
function(has_version result_var file)
    file(STRINGS "${file}" version_line
        REGEX "#define +THING_VERSION" LIMIT_COUNT 1
    )

    if(version_line STREQUAL "")
        set(${result_var} FALSE PARENT_SCOPE)
    endif()
endfunction()

find_file(THING_HEADER thing.h VALIDATOR has_version)
```

```
# Require a companion version file in the same directory
function(has_version_file result_var file)
    cmake_path(GET file PARENT_PATH dir)

    if(NOT EXISTS "${dir}/thing_version.h")
```

```
    set(${result_var} FALSE PARENT_SCOPE)
endif()
endfunction()

find_file(THING_HEADER thing.h VALIDATOR has_version_file)
```

34.1.4. Finding Paths

A project may wish to find the directory containing a particular file rather than the actual file itself. The `find_path()` command provides this functionality and is identical to `find_file()` in every way, except that the directory of the file to be found is stored in the result variable.

34.2. Finding Programs

Finding programs is only slightly different to finding files. The `find_program()` command takes exactly the same set of arguments as `find_file()`, as well as one more optional argument, `NAMES_PER_DIR`. The `find_program()` command also supports a similar short form. The following describes the differences for `find_program()` compared to `find_file()`, and while it may seem complicated, for the most part it just describes the differences one might logically expect, but with a few exceptions highlighted:

Cache variables (CMake-specific)

- When searching under `CMAKE_PREFIX_PATH`, `find_file()` appends `include` to each item. `find_program()` instead

appends bin and sbin as search locations to be checked. The CMAKE_LIBRARY_ARCHITECTURE variable has no effect for `find_program()`.

- CMAKE_PROGRAM_PATH replaces CMAKE_INCLUDE_PATH but is otherwise used in exactly the same way. CMAKE_PROGRAM_PATH is used only by `find_program()`.
- CMAKE_APPBUNDLE_PATH replaces CMAKE_FRAMEWORK_PATH but is otherwise used in exactly the same way. It is used only by `find_program()` and `find_package()`.

Environment variables (system-specific)

- The search locations for standard system environment variables are handled in a considerably simpler manner. INCLUDE has no meaning for `find_program()`, and each item in the PATH is checked without any modification. The behavior is the same on all platforms.

General

- Normally, all search locations are checked for a given name before moving on to search for the next name in the list when the NAMES option is used to provide multiple names. The `find_program()` command supports a NAMES_PER_DIR option which reverses this order, checking each name for a particular search location before moving

on to the next location. The NAMES_PER_DIR option was added in CMake 3.4.

- On Windows (including Cygwin and MinGW), file extensions .com and .exe are automatically checked as well, so there is no need to provide such extensions as part of the program name to find. These extensions are checked first before names without the extensions. Note that .bat and .cmd files will not be searched for automatically.
- Whereas `find_file()` uses `CMAKE_FIND_FRAMEWORK` to determine the search order between framework and non-framework paths, `find_program()` uses `CMAKE_FIND_APPBUNDLE`. It provides similar control between app bundle and non-bundle paths for Apple platforms. The supported values are the same for both variables, and they have the expected equivalent meaning for bundles. Whereas finding files will look in a Headers subdirectory, finding programs will look in the Contents/MacOS subdirectory and set the result to the executable within the app bundle.
- `CMAKE_FIND_ROOT_PATH_MODE_INCLUDE` has no effect on `find_program()`, it is replaced by the `CMAKE_FIND_ROOT_PATH_MODE_PROGRAM` variable which has the equivalent effect but applies exclusively to `find_program()` only. When cross-compiling, it is usually the case that it is

a host platform tool being sought rather than a program on the target platform, so `CMAKE_FIND_ROOT_PATH_MODE_PROGRAM` is frequently set to NEVER.

34.3. Finding Libraries

Finding libraries is also similar to finding files. The `find_library()` command supports the same set of options as `find_file()` plus an additional `NAMES_PER_DIR` option. The following differences apply:

Cache variables (CMake-specific)

- When searching under `CMAKE_PREFIX_PATH`, `find_file()` appends `include` to each item, whereas `find_library()` instead appends `lib`. The `CMAKE_LIBRARY_ARCHITECTURE` variable is also honored in the same way as for `find_file()`.
- `CMAKE_LIBRARY_PATH` replaces `CMAKE_INCLUDE_PATH` but is otherwise used in exactly the same way. `CMAKE_LIBRARY_PATH` is used only by `find_library()`. The `CMAKE_FRAMEWORK_PATH` variable is used in exactly the same way as for `find_file()`.

Environment variables (system-specific)

- The search locations for standard system environment variables are handled in a very similar way to `find_file()`. Instead of `INCLUDE`, the `LIB` environment variable is consulted. Furthermore, the search locations based on `PATH` follow the same complex logic as for `find_file()`, except that `lib` is appended to each prefix rather than `include`.

General

- The `NAMES_PER_DIR` option has exactly the same meaning as it does for `find_program()`. It is only available with CMake 3.4 or later.
- Both `find_file()` and `find_library()` use `CMAKE_FIND_FRAMEWORK` to determine the search order between framework and non-framework paths. In the case of `find_library()`, if a framework is found then the name of the top level `.framework` directory is stored in the result variable.
- `CMAKE_FIND_ROOT_PATH_MODE_INCLUDE` has no effect on `find_library()`, it is replaced by the `CMAKE_FIND_ROOT_PATH_MODE_LIBRARY` variable which has the equivalent effect but applies exclusively to `find_library()`. On Apple platforms, consider carefully before setting `CMAKE_FIND_ROOT_PATH_MODE_LIBRARY` to `ONLY`, as libraries may be built as universal binaries which support multiple

target platforms. These universal binaries might not reside under target platform-specific paths, so it may still be necessary to search host platform paths to find them.

Further behavioral differences apply with `find_library()`. Platforms have different library name conventions, such as prepending `lib` on most Unix platforms. File extensions are also platform-specific. DLLs on Windows can have an associated import library with a different file extension.

The `find_library()` command does its best to abstract away most of these differences, allowing projects to specify just the base name of the library as the name to search for. Where a directory contains both static and shared libraries, the shared library will be the one found. Most of the time, this abstraction works well, but in some circumstances it can be useful to override this behavior. One common case is to give priority to static libraries ahead of shared libraries, potentially only on some platforms and not others. The following naive example would prefer a static `foobar` library ahead of shared on Linux and macOS, but not on Windows:

```
# WARNING: Not robust!
find_library(FOOBAR_LIBRARY NAMES libfoobar.a foobar)
```

Keep in mind that if the `NAMES_PER_DIR` option is used, the priority override only applies to libraries found within a particular directory. This becomes relevant in situations where

a library may have a number of different names, and the user intends for the locations in `CMAKE_PREFIX_PATH` to be treated as a prioritized list such that locations under a prefix should be searched for all library names before moving on to the next prefix. Libraries may have different names due to a change in the upstream project over time, such as adding or removing a major version number in the library's base name. Different packaging systems may choose to package the library differently, which can also result in differences in the library name. In such scenarios, the following slightly modified example will not work:

```
# WARNING: This doesn't prioritize names correctly
find_library(FOOBAR_LIBRARY
    NAMES libfoobar.a libfoobar-2.a libfoobar-1.a
        foobar foobar-2 foobar-1
    NAMES_PER_DIR
)
```

The intention behind the above example is to prioritize finding a static library over a shared library. An unintended consequence of using `NAMES_PER_DIR` like this is that if it encounters a directory containing a shared library but no static library, that shared library will be selected and the search stops, even if another directory under the same prefix contains a static library. This violates the user's expectation that `CMAKE_PREFIX_PATH` should be treated as a prioritized list of locations. The right way to handle this situation is to separate

the static and shared libraries across two separate calls to `find_library()`:

```
# WARNING: This still doesn't handle Windows correctly

# Static libraries now have priority across all locations
find_library(FOOBAR_LIBRARY
    NAMES libfoobar.a libfoobar-2.a libfoobar-1.a
    NAMES_PER_DIR
)
find_library(FOOBAR_LIBRARY
    NAMES foobar foobar-2 foobar-1
    NAMES_PER_DIR
)
```

Note that with CMake 3.24 or earlier, the above techniques cannot be used on Windows because static libraries and the import library for shared libraries (i.e. DLLs) have the same file name, including suffix (e.g. `foobar.lib`). Therefore, the file name cannot be used to differentiate between the two types of libraries. With CMake 3.25 or later, a `VALIDATOR` can be used to work out whether a file is an import library or not. The Visual Studio toolchain includes a `lib` tool which can be used to list the contents of a static or import library. CMake will make the location of this tool available through the `CMAKE_AR` variable. If the content list obtained from that tool includes the same file except with `.lib` replaced by `.dll`, then that is a reasonable hint that the file is very likely to be an import library. The following shows a basic implementation of that logic:

```

function(is_import_lib result_var file)
    cmake_path(GET file FILENAME filename)
    string(TOLOWER "${filename}" filename_lower)
    string(REGEX REPLACE "\\.lib$" ".dll"
        dll_filename_lower "${filename_lower}")
    )
    # This assumes we are using the MSVC toolchain
    execute_process(
        COMMAND ${CMAKE_AR} /nologo /list "${file}"
        RESULT_VARIABLE result
        OUTPUT_VARIABLE output
        ERROR_VARIABLE errors
    )
    string(TOLOWER "${output}" output_lower)
    if(result OR
        NOT errors STREQUAL "" OR
        NOT output_lower MATCHES
        "(^|\n|\\\\\$)${dll_filename_lower}(\n|\$)")
        set(${result_var} FALSE PARENT_SCOPE)
    endif()
endfunction()

```

One could then do a more robust search that prefers static libraries like so:

```
if(MSVC)
    find_library(FOOBAR_LIBRARY foobar.lib
                  VALIDATOR is_import_lib
    )
else()
    find_library(FOOBAR_LIBRARY libfoobar.a)
endif()
find_library(FOOBAR_LIBRARY foobar)
```

Another complication unique to library handling is that many platforms support both 32- and 64-bit architectures. There may be both 32- and 64-bit versions of libraries installed to different

locations, but with the same file names. The directory structure used to separate the different architectures on such multilib systems can vary, even between distributions for the same platform. For example, some distributions place 64-bit libraries under `lib` directories and 32-bit libraries under `lib32`. Others place 64-bit libraries under `lib64` and the 32-bit libraries under `lib`. Other platforms use yet another variation, a `libx32` subdirectory. CMake is generally aware of the variations and when setting up the platform defaults, it populates the global properties

`FIND_LIBRARY_USE_LIB32_PATHS`,

`FIND_LIBRARY_USE_LIB64_PATHS`

and

`FIND_LIBRARY_USE_LIBX32_PATHS` with appropriate values to control which architecture-specific directories should be searched first, if any. Projects can override these with their own custom prefix using the `CMAKE_FIND_LIBRARY_CUSTOM_LIB_SUFFIX` variable, but the need for this should be very rare.

When an architecture-specific suffix is active (whether from one of the above global properties or from the `CMAKE_FIND_LIBRARY_CUSTOM_LIB_SUFFIX` variable), the logic used to augment the search locations with architecture-specific locations is non-trivial. Any directory anywhere in the search location path that ends with `lib` is augmented with an architecture-specific equivalent. This occurs recursively throughout the path, so a search location like `/opt/mylib/foo/lib` may result in the set of search locations being expanded out to `/opt/mylib64/foo/lib64`,

`/opt/mylib64/foo/lib`, `/opt/mylib/foo/lib64` and `/opt/mylib/foo/lib` on some 64-bit systems. Even if a search location does not end with `lib`, it will still be augmented with an architecture-suffixed location, so a search location `/opt/foo` may result in `/opt/foo64` and `/opt/foo` being searched on some 64-bit systems.

The details of the architecture-specific search path augmentation are not typically something developers need to concern themselves with. In those situations where undesirable libraries are being found or desired libraries are being missed, it may be more straightforward to coerce the result using variables like `CMAKE_LIBRARY_PATH` rather than trying to manipulate the architecture-specific logic. A detailed knowledge of the intricacies involved is not typically needed, a simple awareness of the above points should generally be sufficient, if for no other reason than to reduce some of the mystery around how CMake finds libraries in architecture-specific locations.

Special care needs to be exercised when working with a CMake generator that supports switching between device and simulator configurations at build time. Any `find_library()` results would generally be unusable for such cases, since they could only ever find a library for either the device or the simulator, but not both. Even if CMake is re-run, it would retain its cached results and so would not update the library location

unless the relevant cache entry was manually deleted first. This is a particularly common problem with Xcode builds where projects might want to use `find_library()` to locate various frameworks or common libraries such as `zlib`. For these situations, projects have little choice but to specify the linker flags directly without paths instead, leaving the linker to find the library on its search path. For Apple frameworks, this means specifying two values, since frameworks are added using `-framework <FrameworkName>`. For ordinary libraries like `zlib`, the more traditional `-lz` would be sufficient.

34.4. Finding Packages

The various `find_...()` commands discussed in the preceding sections all focus on finding one specific item. Quite often, however, these items are just one part of a larger package. The package as a whole may have its own characteristics that projects could be interested in, such as a version number, or support for certain features. Projects will generally want to find the package as a single unit rather than piece together its different parts manually.

There are two main ways packages are defined in CMake, either as a module or through config details. Config details are usually provided as part of the package itself, and they are more closely aligned with the functionality of the various `find_...()` commands discussed in the preceding sections. Modules, on the

other hand, are typically defined by something unrelated to the package, usually by CMake or by projects themselves. As a result, modules are harder to keep up to date as the package evolves over time.

Module and config files typically define variables and imported targets for the package. These may provide the location of programs, libraries, flags to be used by consuming targets and so on. Functions and macros can also be defined. There is no set of requirements for what will be provided, but there are some conventions which are stated in the CMake developer manual. Project authors must consult the documentation of each module or package to understand what is provided. As a general guide, older modules tend to provide variables that follow a fairly consistent pattern, whereas newer modules and config implementations usually define imported targets. Where both variables and imported targets are provided, projects should prefer the latter due to their superior robustness and better integration with CMake's transitive dependency features.

Projects normally look for a package using the `find_package()` command, which has a short form and a long form. The short form should generally be preferred because of its greater simplicity, and because it supports both module and config packages, whereas the long form does not support modules. The long form does, however, provide more control over the search, making it preferable in certain situations.

The short form has only a few options and can be summarized as follows:

```
find_package(packageName
[version [EXACT] ]
[QUIET] [REQUIRED]
[ [COMPONENTS] component1 [component2...] ]
[OPTIONAL_COMPONENTS component3 [component4...] ]
[GLOBAL]           # CMake 3.24 or later
[REGISTRY_VIEW viewMode] # CMake 3.24 or later
[MODULE]
[NO_POLICY_SCOPE]
)
```

The optional `version` argument indicates that the package must be of the specified version or higher, or match exactly if `EXACT` is also given. When using CMake 3.19 or later, the `version` can be specified as a `version range` instead. Version ranges are expressed in the form `versionMin...versionMax` or `versionMin...<versionMax`. The `versionMin` part of the range is treated just like a single version number. It is the minimum required version of the package. For the upper end of the version constraint, the first form requires the package version to be no greater than `versionMax`, whereas the second form requires it to be strictly less than `versionMax`. The `EXACT` keyword cannot be given if a version range is used.

Be aware that packages may not know about version ranges. Their module or config file may have a fairly old implementation that pre-dates CMake's version range support.

In these cases, the packages will typically ignore the `versionMax` part of the requirement. [Section 35.9.1, “Config Files For CMake Projects”](#) discusses further implications for how packages may handle version ranges. [Section 39.5, “Integration With `find_package\(\)`”](#) and [Chapter 41, *Dependency Providers*](#) discuss scenarios in which the version constraint may be ignored entirely.

A package may be optional, meaning the project can use it if available or work without it if an appropriate package cannot be found. If a package is mandatory, the `REQUIRED` option should be provided so that CMake will halt with an error if an appropriate package could not be found. Unlike the other `find_…()` commands, all CMake versions support the `REQUIRED` option for `find_package()`.

Normally, `find_package()` will log messages for failures, but the `QUIET` option can be used to suppress them for optional packages (failure messages for a mandatory package cannot be suppressed). `QUIET` will also suppress messages that would normally be printed the first time a package is found. A typical use for `QUIET` is to prevent messages for a missing optional package so that developers are less likely to think it is an error.

The component-related options allow a project to indicate what parts of the package they are interested in. Not all packages support components, it is up to the module or config

implementation whether components are defined and what the components represent. An example where components may be useful is a large package like Qt, where not all components might be installed. It may not be enough for a project to just say it wants Qt, it may also need to say which parts of Qt. The `find_package()` command allows the project to specify components as mandatory with the `COMPONENTS` arguments, or as optional with the `OPTIONAL_COMPONENTS` arguments. For example, the following call requires Qt 5.9 or later, the Gui component must be available, and DBus is optional:

```
find_package(Qt5 5.9 REQUIRED
    COMPONENTS Gui
    OPTIONAL_COMPONENTS DBus
)
```

When the `REQUIRED` option is present, the `COMPONENTS` keyword can be omitted and the mandatory components placed after `REQUIRED`. This is common when there are no optional components:

```
find_package(Qt5 5.9 REQUIRED Gui Widgets Network)
```

If a package defines components but no components are given to `find_package()`, it is up to the module or config definition how this is handled. For some packages, it may be treated as though all components were listed. For others, it may be interpreted as no components are required (basic details of the package may still be defined though, such as base libraries,

package version, etc.). Another possibility is that the lack of components could be treated as an error. Given the variation in behavior, developers should consult the documentation for the package they wish to find.

Packages typically create imported targets. By default, these only have visibility in the current directory scope and below. This historical CMake behavior exists to support finding different versions of the same package in different directory scopes. Since the imported targets for the different versions are created in unrelated directory scopes, the targets do not clash. In practice, the need for such flexibility is very rare, and mixing versions within a build doesn't fit well with modern practices. More recent CMake features strengthen the notion that there is only one version of a dependency throughout a build. With CMake 3.24 or later, the project can force the package to create global imported targets by adding the `GLOBAL` keyword to the `find_package()` call. The `CMAKE_FIND_PACKAGE_TARGETS_GLOBAL` variable is used as the default if no `GLOBAL` keyword is given, so projects can use that variable to set behavior for all of its `find_package()` calls. Consumers of the project may not expect it to force those imported targets to be global, so use this facility with care.

The remaining options of the short form are less frequently used. The `REGISTRY_VIEW` keyword controls how registry paths are interpreted (only supported with CMake 3.24 or later).

Consult the official CMake documentation for a full explanation of that functionality. The NO_POLICY_SCOPE keyword is a historical hangover from the CMake 2.6 era and projects should avoid using it. The MODULE keyword restricts the call to searching only for modules and not config packages. Projects should generally avoid using this option since they should not have to concern themselves with the implementation details of how a package is defined, only with stating the requirements on the package. When MODULE is not present, the short form of the `find_package()` command will first search for a matching module, then if no such module is found it will search instead for a config package. CMake 3.15 added support for the `CMAKE_FIND_PACKAGE_PREFER_CONFIG` variable, which can be set to true to reverse the search preference (it is unset by default to preserve the pre-3.15 behavior).

Modules were first discussed back in [Chapter 12, *Modules*](#). While non-package modules are incorporated into a project using the `include()` command, package modules have a file name of the form `Find<packageName>.cmake` and are intended to be processed by a call to `find_package()` instead. For this reason, they are commonly referred to as *Find modules*. Both `include()` and `find_package()` respect the `CMAKE_MODULE_PATH` variable as a list of directories that CMake should search in before the set of modules that come as part of every CMake release.

Find modules are responsible for implementing all aspects of the `find_package()` call, including locating the package, performing version checks, fulfilling component requirements, and logging or not logging messages as appropriate. Not all find modules honor these responsibilities, and they may choose to ignore some or all of the information provided beyond the package name. Therefore, as always, consult the module documentation to confirm the expected behavior.

Find modules are usually implemented in terms of calls to the various `find_...()` commands. As a result, they can sometimes be affected by the cache and environment variables relevant to those commands. The `CMAKE_PREFIX_PATH` variable is especially convenient for influencing find modules because each path specified acts as a base point below which each `find_...()` command appends its own command-specific subdirectories. For packages that follow a reasonably standard layout, adding just the base install location of the package to `CMAKE_PREFIX_PATH` is often enough for the find module to find all the package components it needs.

Compared to find modules, packages with config details offer a much richer, more robust way for projects to retrieve information about that package. A much more extensive set of `find_package()` options are available in config mode, with the full long form of the command having many similarities to the other `find_...()` commands:

```
find_package(packageName
[version [EXACT] ]
[QUIET | REQUIRED]
[ [COMPONENTS] component1 [component2...] ]
[OPTIONAL_COMPONENTS component3 [component4...] ]
[NO_MODULE | CONFIG]
[NO_POLICY_SCOPE]
[NAMES name1 [name2 ...] ]
[CONFIGS fileName1 [fileName2...] ]
[HINTS path1 [path2 ... ] ]
[PATHS path1 [path2 ... ] ]
[PATH_SUFFIXES suffix1 [suffix2 ...] ]
[REGISTRY_VIEW viewMode]      # CMake 3.24 or later
[CMAKE_FIND_ROOT_PATH_BOTH |
 ONLY_CMAKE_FIND_ROOT_PATH |
 NO_CMAKE_FIND_ROOT_PATH]
[<skip-options>]      # See further below
)
```

When `find_package()` is called with an option only supported by the long form, the search for a Find module is skipped. The `NO_MODULE` or `CONFIG` keywords force a call that would match the short form to be treated as long form (both keywords are equivalent).

When searching for config details, `find_package()` looks for a file named `<packageName>Config.cmake` or `<lowercasePackageName>-config.cmake` by default. The `CONFIGS` option can be used to specify a different set of file names to search for instead, but this is discouraged. Non-default file names require every project wanting to find that package to be aware of the non-default file name.

When a config file is found, `find_package()` also looks for an associated version file in the same directory. The version file has `Version` or `-version` appended to the base name, so `FooConfig.cmake` would result in looking for a version file named `FooConfigVersion.cmake` or `FooConfig-version.cmake`, while `foo-config.cmake` would result in looking for `foo-configVersion.cmake` or `foo-config-version.cmake`. Packages are not required to provide a version file, but they usually do. If version details are included in a call to `find_package()` but there is no version file for that package, the version requirements are deemed to have failed.

The locations searched follow a similar pattern to the other `find_...()` commands, except package registries are also supported. Each search location is then treated as a possible package install base point below which a variety of subdirectories may be searched:

```
<prefix>/  
<prefix>/(cmake|CMake)/  
<prefix>/<packageName>*/  
<prefix>/<packageName>*/(cmake|CMake)/  
<prefix>/<packageName>*/(cmake|CMake)/<packageName>*/ ①  
<prefix>/(lib/<arch>|lib*|share)/cmake/<packageName>*/  
<prefix>/(lib/<arch>|lib*|share)/<packageName>*/  
<prefix>/(lib/<arch>|lib*|share)/<packageName>*/(cmake|CMake)/  
<prefix>/<packageName>*/(lib/<arch>|lib*|share)/cmake/<packageName>*/  
<prefix>/<packageName>*/(lib/<arch>|lib*|share)/<packageName>*/  
<prefix>/<packageName>*/(lib/<arch>|lib*|share)/<packageName>*/(cmake|CMake)/
```

① This path is only searched if using CMake 3.25 or later.

The following are also checked on Apple platforms:

```
<prefix>/<packageName>.framework/Resources/  
<prefix>/<packageName>.framework/Resources/CMake/  
<prefix>/<packageName>.framework/Versions/*/Resources/  
<prefix>/<packageName>.framework/Versions/*/Resources/CMake/  
<prefix>/<packageName>.app/Contents/Resources/  
<prefix>/<packageName>.app/Contents/Resources/CMake/
```

In the above, `<packageName>` is treated case-insensitively and the `lib/<arch>` subdirectories are only searched if `CMAKE_LIBRARY_ARCHITECTURE` is set. The `lib*` subdirectories represent a set of directories that may include `lib64`, `lib32`, `libx32`, and `lib`, the last of which is always checked. If the `NAMES` option is given to `find_package()`, all the above directories are checked for each name provided.

The set of search location base points checked follow the order defined in the table below. Most search locations can be disabled by adding the associated `NO_...` keyword.

Location	Skip Option
Package root variables	<code>NO_PACKAGE_ROOT_PATH</code>
Cache variables (CMake-specific)	<code>NO_CMAKE_PATH</code>
Environment variables (CMake-specific)	<code>NO_CMAKE_ENVIRONMENT_PATH</code>
Paths specified via the <code>HINTS</code> option	

Location	Skip Option
Environment variables (system-specific)	NO_SYSTEM_ENVIRONMENT_PATH
User package registry	NO_CMAKE_PACKAGE_REGISTRY
Cache variables (platform-specific)	NO_CMAKE_SYSTEM_PATH
System package registry	NO_CMAKE_SYSTEM_PACKAGE_REGISTRY
Paths specified via the PATHS option	

Package root variables

As for the other `find_...()` commands, support for package root variables was added as a search location in CMake 3.9.0, removed in 3.9.1 due to backward compatibility issues and re-added again in CMake 3.12. Each time `find_package()` is called, it pushes `<packageName>_ROOT` CMake and environment variables onto an internally maintained stack of paths. These paths are used in exactly the same way as `CMAKE_PREFIX_PATH`, not just for the current call to `find_package()`, but all `find_...()` commands that might be called as part of the `find_package()` processing. In practice, this means if a `find_package()` call loads a Find module, then any `find_...()` commands the Find module calls internally will use each path in the stack as though it was a `CMAKE_PREFIX_PATH` first before checking any other paths.

For example, say a `find_package(Foo)` call resulted in `FindFoo.cmake` being loaded. Any `find_...()` command within `FindFoo.cmake` would first search `${Foo_ROOT}` and `$ENV{Foo_ROOT}` (if they were set) before moving on to check other search locations. If `FindFoo.cmake` contained a call like `find_package(Bar)` that resulted in `FindBar.cmake` being loaded, then the stack would contain `${Bar_ROOT}`, `$ENV{Bar_ROOT}`, `${Foo_ROOT}`, and `$ENV{Foo_ROOT}`. This feature means nested Find modules will search the prefix locations of each of their parent Find modules first, so that information doesn't have to be manually propagated down via `CMAKE_PREFIX_PATH` or another similar method. For the most part, projects can ignore this functionality, since it should work transparently without any specific action by the project. It should mostly just be thought of as an automatic convenience.

CMake 3.27 and later also support `<PACKAGENAME>_ROOT` CMake and environment variables (i.e the uppercase package name equivalents). This is primarily as a compatibility measure for some Find modules, which may have used these uppercase variable names at some point instead of the canonical case-sensitive names. Where possible, projects should not use these uppercase variables, relying instead on the canonical case-sensitive variable names where they achieve the desired behavior. The uppercase names are only

supported when policy `CMP0144` is set to `NEW` anyway, so either way the project would need to be updated in some way.

Cache variables (CMake-specific)

The CMake-specific cache variable locations are derived from the cache variables `CMAKE_PREFIX_PATH`, `CMAKE_FRAMEWORK_PATH` and `CMAKE_APPBUNDLE_PATH`. These work the same way as for the other `find_...()` commands except that `CMAKE_PREFIX_PATH` entries already correspond to package install base points, so no directories like `bin`, `lib`, `include`, etc. are appended.

Environment variables (CMake-specific)

These have the same relationship to the cache variables above as other `find_...()` commands. The environment variables `CMAKE_PREFIX_PATH`, `CMAKE_INCLUDE_PATH`, and `CMAKE_FRAMEWORK_PATH` all use the platform-specific path separator (colons on Unix platforms, semicolons on Windows). An additional environment variable `<packageName>_DIR` is also checked before the other three.

Environment variables (system-specific)

The only supported system-specific environment variable is `PATH`. Each entry is used as a package install base point, except any trailing `bin` or `sbin` is removed. This is the point at which default system locations like `/usr` are likely to be searched on most systems.

Cache variables (platform-specific)

The platform-specific cache variable locations follow the same pattern as the other `find_...()` commands, providing ...
`_SYSTEM_...` equivalents of the CMake-specific cache variables. The names of these system variables are `CMAKE_SYSTEM_PREFIX_PATH`, `CMAKE_SYSTEM_FRAMEWORK_PATH`, and `CMAKE_SYSTEM_APPBUNDLE_PATH`. They are not intended to be set by the project.

HINTS and PATHS

These work exactly the same way as the other `find_...()` commands except they do not support items of the form `ENV someVar`.

Package registries

Unique to `find_package()`, the user and system package registries are intended to provide a way to make packages easily findable without having them installed in standard system locations. See [Section 34.4.1, “Package Registries”](#) further below for a more detailed discussion.

The various `NO_...` options work the same way as for the other `find_...()` commands, allowing each group of search locations to be bypassed individually. The `NO_DEFAULT_PATH` keyword causes all but the `HINTS` and `PATHS` to be bypassed.

With CMake 3.16 or later, the various `CMAKE_FIND_USE_...` variables also have the same effects as for the other `find_...`() commands. These variables allow the default behavior of each search location to be controlled individually. `CMAKE_FIND_USE_INSTALL_PREFIX` is also supported with CMake 3.24 or later. The `PATH_SUFFIXES` option has the expected effect too, accepting further subdirectories to check below each search location.

The `find_package()` command also supports the same search re-rooting logic as the other `find_...`() commands. `CMAKE_SYSROOT`, `CMAKE_STAGING_PREFIX`, and `CMAKE_FIND_ROOT_PATH` are all considered in the same way as the other commands, and the meanings of the `CMAKE_FIND_ROOT_PATH_BOTH`, `ONLY_CMAKE_FIND_ROOT_PATH`, and `NO_CMAKE_FIND_ROOT_PATH` options are also equivalent. The default re-root mode when none of these three options is provided is controlled by the `CMAKE_FIND_ROOT_PATH_MODE_PACKAGE` variable, which has the predictable set of valid values (`ONLY`, `NEVER` or `BOTH`).

Unlike the other `find_...`() commands, when looking for a config file, `find_package()` does not necessarily stop searching at the first package it finds that matches the criteria. Parts of the search consider a family of search locations and the search results may return multiple matches for that particular sub-branch of the search. Typically, this might occur if there are multiple versions of the package installed under some common

directory, each of which has a versioned subdirectory below that common point. In such cases, the following variables are consulted to sort the candidates based on their version details.

CMAKE_FIND_PACKAGE_SORT_DIRECTION

Supported sort direction values are DEC for descending (choose the newest) or ASC for ascending (choose the oldest). If this variable is not set, DEC is the default behavior.

CMAKE_FIND_PACKAGE_SORT_ORDER

This controls the type of sorting. Supported values are NAME, NATURAL or NONE. If set to NONE or not set at all, no sorting is performed and the first valid package found will be used. The NAME setting sorts lexicographically, while NATURAL sorts by comparing sequences of digits as whole numbers. The following table demonstrates the difference between the last two methods when sorting in descending order:

NAME	NATURAL
1.9	1.10
1.10	1.9
1.0	1.0

With CMake 3.24 or later, a special directory is always checked first before any other location mentioned above. This location is given by the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` variable and

cannot be disabled. See [Section 39.5.3, “Redirections Directory”](#) for a discussion of its purpose and usage.

In practice, the intricacies of the search logic are usually well beyond the level of detail needed to use the `find_package()` command effectively. As long as a package follows one of the more common directory layouts and sits under one of the higher level base install locations, the `find_package()` command will usually find its config file without further help.

Once a suitable config file for a package has been found, the `<packageName>_DIR` cache variable will be set to the directory containing that file. Subsequent calls to `find_package()` will then look in that directory first, and if the config file still exists, it is used without further searching. `<packageName>_DIR` is ignored if there is no longer a config file for the package at that location. This ensures subsequent calls to `find_package()` for the same package are much faster, even from one invocation of CMake to the next, but the search is still performed if the package is removed.

Be aware that the caching of the package location can also mean that CMake might not get an opportunity to become aware of a newly added package in a more preferable location. For example, the operating system might come with a fairly old version of a package pre-installed. The first time CMake is run on a project, it finds that old version and stores its location in

the cache. The user sees that an old version is being used and decides to install a newer version of the package under some other directory, adds that location to `CMAKE_PREFIX_PATH`, and re-runs CMake. In this scenario, the old version will still be used because the cache still points to the older package's location. The `<packageName>_DIR` cache entry would need to be removed, or the old version uninstalled before the newer version's location would be considered.

Further controls are available to influence the handling of specific packages. It is possible to disable every non-REQUIRED call to `find_package()` for a given `packageName` by setting the `CMAKE_DISABLE_FIND_PACKAGE_<packageName>` variable to true early in the project, ideally at the top level or as a cache variable. This can be thought of as a way of turning off an optional package, preventing it from being found via `find_package()` calls. Note that it will not prevent such calls if they include the REQUIRED keyword.

With CMake 3.22 or later, a `CMAKE_REQUIRE_FIND_PACKAGE_<packageName>` variable is also supported. Setting it to true for a particular `<packageName>` forces all `find_package()` calls for that package to behave as though they used the REQUIRED keyword. This can be used to catch situations where a package is expected to be available, forcing CMake to halt with an error if it is missing. Testing of logic that relies on optional packages is an example scenario where this

variable may be useful, but it has its limits. There are scenarios where this variable breaks project logic. For example, the following is a common way to prefer finding a package at a specific location if available, falling back to the regular search order otherwise:

```
find_package(MyThing PATHS /some/location NO_DEFAULT_PATH)
find_package(MyThing)
```

Setting `CMAKE_REQUIRE_FIND_PACKAGE_MyThing` to true would break the above logic. The package would have to be found at `/some/location`, otherwise the first call would give a fatal error and the second call would never be reached.

34.4.1. Package Registries

Packages tend to be found in standard system locations or in directories CMake has been told about through `CMAKE_PREFIX_PATH` or similar. For non-system packages, it can be tedious or undesirable to have to specify the location for each package if they don't all share a common install prefix. CMake supports a form of package registry which allows references to arbitrary locations to be collected together in one place. This allows the user to maintain an account- or system-wide registry which CMake will consult automatically without further direction. The locations referenced by the registry don't have to be a full package install. They can also be a directory within a

build tree for the package (or any other directory for that matter), as long as the required files are there.

On Windows, two registries are provided. A user registry is stored in the Windows registry under the `HKEY_CURRENT_USER` key, while a system package registry is stored under `HKEY_LOCAL_MACHINE`:

```
HKEY_CURRENT_USER\Software\Kitware\CMake\Packages\<packageName>\  
HKEY_LOCAL_MACHINE\Software\Kitware\CMake\Packages\<packageName>\
```

For a given `packageName`, each entry under that point is an arbitrary name holding a `REG_SZ` value. The value is expected to be a directory in which a config file for that package can be found. On Unix platforms, there is no system package registry, only a user package registry stored under the user's home directory and entries under that point have the same meaning as for Windows:

```
~/.cmake/packages/<packageName>/
```

CMake provides very little assistance with how to actually create these entries on any platform. No automated mechanism is provided for installed packages, but the `export()` command can be used within a project's `CMakeLists.txt` files to add parts of a project's build tree to the user registry:

```
export(PACKAGE packageName)
```

This command can add the specified package to the user package registry and point that registry entry to the current binary directory associated with wherever `export()` was called (see below for conditions that can prevent this). It is then up to the project to ensure that an appropriate config file for the package exists in that directory. If no such config file exists and a `find_package()` call is made for that package for any project, the registry entry will be automatically removed if permissions allow it. It is common practice for the name of each entry in the package registry to be the MD5 hash of the directory path it points to. This avoids name collisions and is the naming strategy employed by the `export(PACKAGE)` command.

Adding locations from a build tree to the package registry has its dangers. While `export(PACKAGE)` is available to add a location to the registry, there is no corresponding mechanism to remove it again other than to manually delete the registry entry or to remove the package config file from the build directory. It can be easy to forget to do this, so an old build tree left behind from past experiments can easily be picked up unexpectedly. The use of `export(PACKAGE)` also has the potential to play havoc with continuous integration systems by making projects pick up build trees of other projects built on the same machine.

Because of the dangers associated with `export(PACKAGE)`, developers will frequently want to disable it. CMake provides two ways to achieve this, one using an opt-out method available

since CMake 3.1 and another introduced in CMake 3.15 which uses a superior opt-in mechanism. With CMake 3.14 or earlier, the `export(PACKAGE)` command will modify the package registry unless the `CMAKE_EXPORT_NO_PACKAGE_REGISTRY` variable is set to true. Because that variable is undefined by default, the `export(PACKAGE)` command will modify the package registry by default. In CMake 3.15, the default behavior was changed via policy `CMP0090` such that when that policy is set to `NEW`, the `export(PACKAGE)` command will be disabled unless the `CMAKE_EXPORT_PACKAGE_REGISTRY` variable is set to true (note the different variable name). If policy `CMP0090` is set to `OLD` or is not set, then the CMake 3.14 and earlier behavior is used. For most practical scenarios, developers can set `CMAKE_EXPORT_NO_PACKAGE_REGISTRY` to true and regardless of policy settings or CMake version, the `export(PACKAGE)` command will be disabled.

Whereas `CMAKE_EXPORT_NO_PACKAGE_REGISTRY` and `CMAKE_EXPORT_PACKAGE_REGISTRY` control writing to the registry, CMake provides a separate set of variables to control reading from it. The `CMAKE_FIND_PACKAGE_NO_PACKAGE_REGISTRY` and `CMAKE_FIND_PACKAGE_NO_SYSTEM_PACKAGE_REGISTRY` variables can be used to specify the default behavior of `find_package()` calls, controlling whether to read from the user and system package registries respectively. CMake 3.16 deprecated both variables, replacing them with `CMAKE_FIND_USE_PACKAGE_REGISTRY` and

`CMAKE_FIND_USE_SYSTEM_PACKAGE_REGISTRY` to maintain more consistent naming and behavior with the other `CMAKE_FIND_USE_...` variables mentioned earlier in this chapter. These newer variables take precedence over the old ones where both the old and new variables are defined.

While the two sets of `CMAKE_EXPORT_...` and `CMAKE_FIND_...` variables described above are complementary, the `CMAKE_FIND_...` variables are more effective at isolating a build from the package registry and are usually more relevant for developers.

In practice, package registries are seldom used. The limited help provided for adding and removing entries means maintaining the registry is somewhat of a manual process. When a package is installed via the host's standard package management system, it could conceivably add itself to either the system or user registry as appropriate, then the package's uninstaller could remove that same entry. While the package locations are well defined and their definition is conceptually easy, few packages bother to do the work to register and unregister themselves. The various different ways a package may find its way onto an end user's machine makes it somewhat difficult to implement such register/unregister features robustly and simply.

34.4.2. FindPkgConfig

The `find_package()` command will generally be the preferred method for finding and incorporating a package into a CMake project, but in certain cases the results can be less than ideal. Some Find modules are yet to be updated to more modern practices and do not provide imported targets, relying instead on defining a collection of variables that consuming projects must handle manually. Other modules may fall behind the latest package releases, leading to incompatibilities or incorrect information being provided.

In some instances, a package may have support for `pkg-config`, a tool that provides similar information to `find_package()` but in a different form. If such `pkg-config` details are available, then the `PkgConfig` Find module may be used to read that information and provide it in a more CMake-friendly way. Imported targets can be automatically created, freeing projects from having to handle various variables manually. The `pkg-config` details are also likely to match the installed version of the package, since they are typically provided by the package itself.

The `FindPkgConfig` module locates the `pkg-config` executable and defines a few functions that invoke it to find and extract details about packages that have `pkg-config` support. If the module finds the executable, it sets the `PKG_CONFIG_FOUND` variable to true and the `PKG_CONFIG_VERSION_STRING` variable to the tool's version (except for CMake versions before 2.8.8). The

PKG_CONFIG_EXECUTABLE variable is set to the location of the tool. CMake 3.22 and later also sets PKG_CONFIG_ARGN to any additional arguments to pass to the executable with each call. The user can explicitly set PKG_CONFIG_EXECUTABLE and PKG_CONFIG_ARGN if the module's defaults need to be overridden.

In practice, projects should rarely need to use the PKG_CONFIG_EXECUTABLE or PKG_CONFIG_ARGN variables. The module defines two functions which wrap the tool to provide a more convenient way to query package details. These two functions, pkg_check_modules() and pkg_search_module(), accept exactly the same set of options and have similar behavior. The main difference between the two is that pkg_check_modules() checks all the modules given in its argument list, whereas pkg_search_module() stops at the first one it finds that satisfies the criteria. The use of the term *module* rather than *package* is historical and may cause some confusion, but they have no direct relationship to regular CMake modules and can essentially be thought of as packages.

```
pkg_check_modules(prefix
  [REQUIRED] [QUIET]
  [IMPORTED_TARGET [GLOBAL] ]
  [NO_CMAKE_PATH]
  [NO_CMAKE_ENVIRONMENT_PATH]
  moduleSpec1 [moduleSpec2...]
)
```

```
pkg_search_module(prefix
  [REQUIRED] [QUIET]
  [IMPORTED_TARGET [GLOBAL] ]
```

```
[NO_CMAKE_PATH]
[NO_CMAKE_ENVIRONMENT_PATH]
moduleSpec1 [moduleSpec2...]
)
```

The behavior of these functions has some similarities to `find_package()`. The REQUIRED and QUIET arguments have the same effect here as they do for the `find_package()` command. With CMake 3.1 or later, `CMAKE_PREFIX_PATH`, `CMAKE_FRAMEWORK_PATH`, and `CMAKE_APPBUNDLE_PATH` are all considered as search locations in the same way too, and the `NO_CMAKE_PATH` and `NO_CMAKE_ENVIRONMENT_PATH` keywords also have the same meaning here. The `PKG_CONFIG_USE_CMAKE_PREFIX_PATH` variable can be set to change the default behavior for whether these search locations are considered. It will be treated as a boolean switch to turn the search locations on or off. Projects should generally avoid it unless they need to support CMake versions older than 3.1.

The `IMPORTED_TARGET` option is only supported with CMake 3.6 or later. When given, if the requested module is found then an imported target with the name `PkgConfig::<prefix>` is created. This imported target will have interface details populated from the module's .pc file, providing such things as header search paths, compiler flags, etc. For this reason, it is highly recommended that this option be used if the minimum CMake version required by the project is 3.6 or later. If using CMake 3.13 or later, the `GLOBAL` keyword can also be added to make

imported targets have global visibility instead of only to the current directory scope and below.

The functions expect one or more `moduleSpec` arguments to define what to search for. These can be a bare module/package name or they can combine the name with a version requirement. Such version requirements have the form `name=version`, `name<=version` or `name>=version`. With CMake 3.13 or later, `<` and `>` are also supported. When no version requirement is included, any version is accepted.

Upon return, the functions set a number of variables in the calling scope by calling `pkg-config` with the appropriate option(s) to extract the relevant part of the package details. Where multiple items are returned by a set of options (e.g. multiple libraries or multiple search paths), the corresponding variable will hold a CMake list.

Variable	<code>pkg-config</code> options used
<code>prefix_LIBRARIES</code>	<code>--libs-only-l</code>
<code>prefix_LIBRARY_DIRS</code>	<code>--libs-only-L</code>
<code>prefix_LDFLAGS</code>	<code>--libs</code>
<code>prefix_LDFLAGS_OTHER</code>	<code>--libs-only-other</code>
<code>prefix_INCLUDE_DIRS</code>	<code>--cflags-only-I</code>

Variable	pkg-config options used
prefix_CFLAGS	--cflags
prefix_CFLAGS_OTHER	--cflags-only-other
prefix_STATIC_LIBRARIES	--static --libs-only-l
prefix_STATIC_LIBRARY_DIRS	--static --libs-only-L
prefix_STATIC_LDFLAGS	--static --libs
prefix_STATIC_LDFLAGS_OTHER	--static --libs-only-other
prefix_STATIC_INCLUDE_DIRS	--static --cflags-only-I
prefix_STATIC_CFLAGS	--static --cflags
prefix_STATIC_CFLAGS_OTHER	--static --cflags-only-other

The above variables are only set if the module requirements are satisfied. The canonical way to check this is using the `prefix_FOUND` and `prefix_STATIC_FOUND` variables. For `pkg_check_modules()`, all `moduleSpec` requirements must be satisfied for these variables to have a value of true, whereas `pkg_search_module()` only has to find one matching `moduleSpec`. With CMake 3.16 or later, `pkg_search_module()` populates the `<prefix>_MODULE_NAME` with the module that was found.

For `pkg_check_modules()`, some additional per-module variables are also set when modules are found successfully. In the

following, if only one moduleSpec is given then `YYY` = `prefix`, otherwise `YYY` = `prefix_moduleName`.

`YYY_VERSION`

The version of the module found, extracted from output of the `--modversion` option.

`YYY_PREFIX`

The module's prefix directory. This is obtained by querying for a variable named `prefix`, which most `.pc` files typically define and which `pkg-config` provides by default anyway.

`YYY_INCLUDEDIR`

The result of querying for a variable named `includedir`. This is a common but not required variable.

`YYY_LIBDIR`

The result of querying for a variable named `libdir`. Again, this is a common but not required variable.

In CMake 3.4 and later, the `FindPkgConfig` module provides an additional function which can be used to extract arbitrary variables from `.pc` files:

```
pkg_get_variable(resultVar moduleName variableName  
    [DEFINE_VARIABLES key=value...] # CMake 3.28 or later  
)
```

This is used internally by `pkg_check_modules()` to query the `prefix`, `includedir` and `libdir` variables, but projects can use it to query the value of any arbitrary variable. The `DEFINE_VARIABLES` keyword is supported with CMake 3.28 or later. Each `key=value` will be passed to `pkg-config` as a `--define-variable=key=value` option. This is primarily intended for overriding things like `prefix` when evaluating another variable, which may be helpful when building in a container.

Before CMake 3.15, a bug in `pkg_get_variable()` resulted in it effectively ignoring `CMAKE_PREFIX_PATH`. Consider making CMake 3.15 the minimum version if using this function.

For most common systems, the functions provided by the `FindPkgConfig` module work fairly reliably. The implementations of those functions do, however, rely on features introduced in `pkg-config` version 0.20.0. Some older systems (e.g. Solaris 10) come with older versions of `pkg-config` which result in all calls to the `FindPkgConfig` functions failing to find any modules successfully. No error message is logged to highlight that the `pkg-config` version is too old.

34.5. Ignoring Search Paths

In some situations, it may be desirable to force the `find_...()` commands to ignore certain search paths. This is mostly relevant when cross-compiling, where some specific host paths

may need to be ignored so that files for the target platform are found rather than files for the host platform. The variables described below apply regardless of whether cross-compiling or not, but it would be unusual for them to be set when not cross-compiling.

The `CMAKE_IGNORE_PATH` variable is intended to be set by the user or by the project. It can be set to a list of directories to exclude from the search. The `CMAKE_SYSTEM_IGNORE_PATH` variable does the same thing, but is intended to be populated by the toolchain setup.

For `find_file()`, `find_path()`, `find_library()` and `find_program()`, the ignored directories should be the directories of the file being searched for. The ignored paths are not recursive, so they cannot be used to exclude a whole section of a directory structure. They must specify the absolute path of each individual directory to ignore.

For `find_package()`, the variables only affect searching in `CONFIG` mode. They can be used to ignore specific directories that contain config package files (`PackageNameConfig.cmake` or `packageName-config.cmake`). They can also be used to ignore search prefixes (e.g. those defined by `CMAKE_PREFIX_PATH`, `CMAKE_SYSTEM_PREFIX_PATH`, etc.). Importantly, `CMAKE_IGNORE_PATH` and `CMAKE_SYSTEM_IGNORE_PATH` do not affect the search for Find

modules, but they do affect `find_...()` commands called from within Find module implementations.

CMake 3.23 added support for two more variables, `CMAKE_IGNORE_PREFIX_PATH` and `CMAKE_SYSTEM_IGNORE_PREFIX_PATH`. These affect the search prefixes of all `find_...()` commands, not just `find_package()`. Because of this more consistent behavior, they should be preferred over using `CMAKE_IGNORE_PATH` or `CMAKE_SYSTEM_IGNORE_PATH` when specifying a search prefix to ignore. Note that these two newer variables do not affect search prefixes for Find modules either.

All ignored directories and prefixes will be automatically re-rooted in the same way as the search paths, as described in [Section 34.1.2, “Cross-compilation Controls”](#). Paths intended to ignore host locations may also result in the corresponding paths in re-rooted locations being ignored too. Consider carefully the interaction of ignored paths with variables like `CMAKE_FIND_ROOT_PATH`, `CMAKE_SYSROOT`, `CMAKE_STAGING_PREFIX` and so on to avoid unexpectedly ignoring paths for the target platform.

34.6. Debugging `find_...()` Calls

As the preceding sections demonstrate, the logic for the locations and names CMake searches for the various `find_...()` commands is complex. When a search returns something unexpected or it fails to find something that was thought to

exist, it can be non-trivial to work out what went wrong. To help with this, CMake 3.17 added a new `--debug-find` command-line option which enables logging for calls to the built-in `find_...`() commands. This output may include a brief summary of the search settings and a list of each location and name that was checked. If a `find_...`() command call uses a cached value rather than actually performing a search, that call may produce no debug output.

CMake 3.23 added some more targeted options to help focus the debug output on specific things of interest. The `--debug-find-pkg=pkg1,pkg2,...` option shows debug output only with `find_package()` calls for the specified package(s). The `--debug-find-var=var1,var2,...` option does the same for the other `find_...`() commands, where the call uses one of the specified result variables.

```
cmake --debug-find-pkg=Boost,fmt ...
cmake --debug-find-var=CCACHE_EXECUTABLE ...
```

The first example will show debug output for `find_package()` calls looking for Boost or `fmt`. This includes any other `find_...`() commands made as part of those calls to `find_package()`. The second example will provide debug output for calls like `find_program(CCACHE_EXECUTABLE ccache)`.

The `--debug-find` option applies to the whole build, so for large projects with many `find_...`() calls, the verbose output can be

overwhelming. The more targeted `--debug-find-pkg` and `--debug-find-var` options may help reduce the volume of output, but they may not always be enough. If developers only want to target a specific call or section of a project, a more effective strategy is to only enable `find_...()` command debugging around the specific calls of interest. This can be achieved by setting a variable called `CMAKE_FIND_DEBUG_MODE` to true before the calls of interest and to false after them (support for this variable was added in CMake 3.17). For example:

```
set(CMAKE_FIND_DEBUG_MODE TRUE)
find_program(...)
set(CMAKE_FIND_DEBUG_MODE FALSE)
```

The debugging output is meant as a development aid for human consumption. It should not be used as input to any script or other form of automated processing, since the format and contents could change from one CMake version to another.

34.7. Recommended Practices

From CMake 3.0, there has been a conscious shift toward the use of imported targets to represent external libraries and programs rather than populating variables. This allows such libraries and programs to be treated as a coherent unit. For libraries, these targets collect together not just the location of the relevant binary, but also the associated header search paths, compiler defines, and further library dependencies that

consuming targets will need. This makes external libraries and programs as easy to use within a project as any other regular target the project defines. This shift in focus means that finding packages has become much more important than finding individual files, paths, etc. There is an increasing push for projects to make themselves consumable by other CMake projects as packages. Finding individual files, etc. still has its uses, and it is helpful to understand how that can be done, but developers should see it as a stepping stone to packages and imported targets rather than an end in itself. Wherever possible, prefer to find packages rather than individual things within packages.

When finding packages, most complications that arise are related to situations where multiple versions are installed in different locations. The user may not be aware of all the installed versions or there may be expectations about which one should be found ahead of the others. Rather than the project trying to predict such situations, it is generally more advisable to not deviate too far from the default search behavior and let the user provide their own overrides via cache or environment variables. `CMAKE_PREFIX_PATH` is usually the most convenient way to do this due to the way CMake automatically searches a range of common directory layouts below each prefix path listed.

Be aware that `find_package()` calls can be redirected to completely different mechanisms for fulfilling those requests. Features were added in CMake 3.24 which integrate `find_package()` with the `FetchContent` module, along with related support for supplying dependencies via custom, developer-specified dependency providers. [Section 39.5, “Integration With `find_package\(\)`”](#) and [Chapter 41, *Dependency Providers*](#) discuss these topics in detail.

Do not rely heavily on the version range support for `find_package()`, perhaps not even on the version constraint at all. Version ranges are only available with CMake 3.19 or later, and older packages will typically ignore the upper end of the version range constraint. Consider the upper limit to be advisory rather than strictly enforced. The entire version constraint can be ignored altogether in some situations too, as discussed in [Section 39.5, “Integration With `find_package\(\)`”](#) and [Chapter 41, *Dependency Providers*](#). It may ultimately not be worth the effort to specify any form of version constraint.

All the `find_...()` commands except `find_package()` work in a similar way. By default, they cache a successful result to avoid having to repeat the whole find operation the next time the `find_...()` command is asked to find the same thing. This is cached even across multiple CMake invocations. Given the potentially large number of locations and directory entries each call may search through, the caching mechanism can save a

non-trivial amount of time when there are many such `find_...()` invocations throughout the project. There are, however, at least two consequences of this that developers need to be aware of. Firstly, once a `find_file()`, `find_path()`, `find_program()` or `find_library()` command succeeds, it will stop searching for all subsequent invocations, even if running the command would return a different result or if the entity found previously no longer exists. If the entity is removed, this can result in build errors that can only be rectified by removing the out-of-date entries from the cache. Developers often just delete their entire cache and rebuild again from scratch rather than trying to figure out which cache variables need to be removed. The other aspect of this find behavior that developers should be aware of is that where a call to one of these `find_...()` commands fails to find the desired entity, the search will be repeated for *every* call, even within the same project. An unsuccessful call is *not* cached. If a project has many such calls, this can slow down the configure step. In extreme cases, tens of thousands of locations may be checked on each call. Developers should therefore carefully consider how the project uses `find_...()` commands and try to minimize the likelihood and number of unsuccessful searches. If the minimum CMake version can be set to 3.21 or later, policy `CMP0125` also allows some subtle surprising behaviors to be avoided.

The situation with `find_package()` is a little more complicated. If the package is found via a Find module, then it is likely that all

the above concerns will also apply to the package, since the logic is likely to be built upon the other `find_...()` commands. If the package is instead found via config mode, then `find_package()` will cache a successful result and check that location first on subsequent invocations. If the package no longer has an appropriate config file at that location, the command proceeds with its normal search logic. This unique behavior for config mode is much more robust and is closer to what developers would naturally want.

A particularly tricky situation where the caching of `find_...()` results can lead to subtle problems is with continuous integration systems. If incremental builds are being used where the CMake cache of a previous run is kept, then changes made in a project to the way it searches for things might not be reflected in the build. Only when the CMake cache is cleared might such changes take effect. The caching often also means that no details are logged about the entity being found, so the build output gives little clue about the use of the old search details. One might therefore be tempted to require all CI builds to build from scratch, but this may not be feasible for longer builds. A strategy which may help reduce the problem is to schedule a daily build job at a time of low CI load where the build tree is cleared and then the project is built as per normal. This will still keep the incremental behavior during regular hours, and it will usually make any cache-related problems self-resolving within a day. The effectiveness of this strategy is

reduced during periods where changes are being made on a branch, and CI builds are alternating between that branch and other branches. But one would hope that such periods are not common and can be tolerated, as long as developers are made aware of potential consequences during that time.

The package registry features of the `find_package()` command should be approached with caution. They have the potential to give unexpected results for continuous integration systems where projects may want to find packages that are also built on the same machine. Unfortunately, there is no environment variable that can be set to disable the use of the registries, but it can be enforced by the projects themselves by setting the `CMAKE_FIND_PACKAGE_NO_PACKAGE_REGISTRY` CMake variable to off. CI jobs would not normally have the required permissions to modify the system package registry, so setting `CMAKE_FIND_PACKAGE_NO_SYSTEM_PACKAGE_REGISTRY` as well should be unnecessary. In practice, few projects write into the package registry, so unless it is known that such a project might be using the CI system, the need to add this CMake variable to every potentially affected project is low. Projects should also avoid making calls to `export(PACKAGE)` within CI jobs, and arguably, they should avoid such calls in general.

Use of the `FindPkgConfig` module should be reserved only for those situations where `find_package()` is not suitable. Typically this is for a package where CMake provides a find module, but

that find module is fairly old and does not provide imported targets, or where it falls behind the more recent package releases. The `FindPkgConfig` module is also useful for searching for packages that CMake knows nothing about, and where the package does not provide its own CMake config file, but it does provide a `pkg-config` (i.e. `.pc`) file.

When using a toolchain file for cross-compilation, prefer to set `CMAKE_SYSROOT` rather than `CMAKE_FIND_ROOT_PATH`. While both affect the search paths of the various `find_...()` commands in the same way, only `CMAKE_SYSROOT` also ensures that the compiler and linker flags are properly augmented so that header inclusions and library linking work correctly.

In cross-compiling scenarios, it is also typical that searches for programs expect to find binaries that will run on the host, whereas searches for files and libraries typically expect to find things for the target. Therefore, it is very common to see the following in toolchain files to enforce such behavior by default:

```
set(CMAKE_FIND_ROOT_PATH_MODE_PROGRAM NEVER)
set(CMAKE_FIND_ROOT_PATH_MODE_LIBRARY ONLY)
set(CMAKE_FIND_ROOT_PATH_MODE_INCLUDE ONLY)
```

One could argue that this should be set in the project rather than relying on it being set in a toolchain file. Technically the developer is free to use any toolchain file if they wish and it is the project that implicitly relies on default behavior that it then chooses to override or not. An added complexity here is that

toolchain files may be re-read for each `project()` or `enable_language()` call, so if a project wants to enforce a particular combination of defaults, it would have to do so after every such call. A reasonable compromise, therefore, is for projects to include the above block before its first `project()` call and for toolchain writers to also include it. Then, if toolchain authors do not include such a block, at least the project still gets sensible defaults. If a toolchain file changes the defaults to something else, they will then be applied consistently throughout the whole project. Developers should be very wary of using settings other than those shown in the example just above, since it is such a common pattern that projects frequently assume it.

For situations where the developer is able to switch between device and simulator builds without re-running CMake (e.g. when using Xcode for an iOS project), avoid calls to `find_library()`. Any results obtained by such calls can only ever point to one of either the device or simulator library, not both. Add the underlying linker flags that link only by name and not by path in such cases, such as `-framework ARKit`, `-lz` or `$<LINK_LIBRARY:FRAMEWORK,abc>`. If the frameworks or libraries cannot be found on the default linker search path, the project will also need to provide linker options to extend the search paths to allow them to be found.

It is quite common for online examples and blog posts to show conflicting recommendations over whether to use `CMAKE_MODULE_PATH` or `CMAKE_PREFIX_PATH` to control where CMake searches for things. An easy way to remember the difference is that `CMAKE_MODULE_PATH` is only used by CMake when searching for `FindXXX.cmake` files or when a module is brought in via an `include()` command. For everything else, including searching for config package files, `CMAKE_PREFIX_PATH` is used.

When specifying directories to ignore in searches conducted by `find_...()` commands, prefer using `CMAKE_IGNORE_PREFIX_PATH` when ignoring a search prefix is sufficient. This works for all `find_...()` commands with CMake 3.23 or later and avoids the need to specify every possible search location under a prefix. For earlier CMake versions, `CMAKE_IGNORE_PATH` can be used to ignore prefixes only for `find_package()`. For the other `find_...()` commands, every directory to ignore has to be added individually. Neither of these variables prevent searching in locations for a Find module, although they may affect the implementation of a Find module if it calls one of the `find_...()` commands internally.

35. INSTALLING

After all the hard work of developing the source code of a project, creating its various resources, making the build robust, and implementing automated tests, the final step of making the software available for distribution is critical. It has a direct effect on the end user's first impressions of the project. If done poorly, it may result in the software being rejected before it even gets a chance to be used.

Developers and users may have different expectations for how a project should be made available. For some, simply providing access to the source code repository and expecting end users to check out and build it themselves is adequate. While this may be part of the delivery model, not all end users may want to get involved at such a low level. Instead, they will frequently expect a pre-built binary package that they can install and use on their machine, preferably via some already familiar package management system. Given the variety of package managers and delivery formats involved, this can present a daunting challenge for project maintainers. Nevertheless, there are enough common elements between most of them that with some judicious planning, it is possible to support most of the popular ones and cover all major platforms.

The earlier in a project's life cycle the delivery phase is considered, the smoother the final packaging and deployment phases are likely to be. A good starting point is to ask the following questions before development begins, or as early as possible for existing projects:

- What platforms should be supported, both initially and potentially in the future? Are there minimum platform API or SDK version requirements in order to support the features of the project?
- What are the package formats that users will be familiar with on each platform? Can the project be delivered in those formats? Are there any specific package formats that are more important than others or that are mandatory?
- Do any of the required or desirable package formats have requirements for how software must be laid out, built or delivered? Do project resources have to be provided in specific formats, resolutions, locations, etc.?
- Might end users want to install multiple versions of the software simultaneously?
- Should the software support being installed without administrative privileges?
- Can the software be made relocatable so that users can install it anywhere on their system (including on any drive, in the case of Windows)?
- Does the project expect one or more of its executables to be made available on the deployment machine through the user's PATH

environment variable? Are there parts of the project that should not be exposed on the PATH?

- Does the project provide anything that other CMake projects may want to use in their own builds (libraries, executables, headers, resources, etc.)?

These questions will strongly impact how the software is laid out when installed, which in turn affects how the source code needs to access its own resources and so on. It may even impact the functionality available to the software, so understanding these things early can save wasted effort later.

This chapter focuses on the layout aspects and how to assemble the necessary files in their required locations. It also demonstrates how to make a project easy for other CMake projects to consume by providing config package support. Developers from some backgrounds may identify with these aspects as belonging to the realm of `make install`. The next two chapters complete the picture by discussing the various package formats that CMake and CPack can produce. The implementation of that support uses the `install` functionality described here to install to a clean staging area and then produce the final packages from those contents.

35.1. Directory Layout

Understanding the constraints imposed by the deployment platform(s) is an essential step before decisions can be made about how an installed product should be laid out. Only once those details are clear can a CMake project go about defining what to install to where. A few high-level observations can

be made which potentially have a strong influence on the installed layout of a project.

- Apple formats (bundles, frameworks, etc.) are heavily prescribed and offer little flexibility, but that also makes it very clear how a project needs to structure its deliverables. As covered back in [Chapter 25, Apple Features](#), CMake already handles most of this automatically as part of the build phase, making the app ready for the last part of the Xcode-driven process that performs the final app signing, package creation and submission to the app store. If an install stage is used in CMake/CPack at all, it will largely be to simply package up bundles that follow the prescribed layout.
- For projects intending to support being included as part of a Linux distribution, there will almost certainly be very specific guidelines on where each type of file should be installed. The Filesystem Hierarchy Standard forms the basis of most distributions' layout, and many other Unix-based systems follow a similar structure. Even if not aiming for inclusion in a distribution directly, the FHS still serves as a good guide for how to structure a package to achieve a smooth and robust installation on many Unix-based systems.
- Some projects may want to make one or more executables available on the user's PATH so they can be invoked easily from a terminal or command line. On Windows, if a project installation modifies the PATH by adding a directory that also contains some of its own DLLs, other applications may then pick up those DLLs instead of the ones that were expected (e.g. from their own private directories or one of the standard

system-wide locations). DLLs from popular toolkits such as Qt regularly fall victim to this scenario as a result of packages modifying the PATH in ways they shouldn't. If a project wants to augment the PATH for its own executables, it should ensure that no DLLs are present in that directory, but this is directly at odds with the need to have the DLLs in the same directory as executables so that Windows can find them at run time. The typical solution to this is to create a directory containing only launch scripts, which can then safely be added to the PATH.

35.1.1. Relative Layout

Except for deployments to Apple platforms, there is a large degree of commonality (or at least potential commonality) across all the major platforms. The install location can be thought of as consisting of a base path and a relative layout below that path. The base path may be something like `/usr/...`, `/opt/...`, or `C:\Program Files`, and obviously varies widely between platforms. But the relative layout below that base point is often very similar. A common arrangement sees executables (and for Windows, also DLLs) installed to a `bin` directory, libraries to `lib` or some variant thereof, and headers under an `include` directory. Other file types have somewhat more variability in where they are typically installed, but these three already cover some of the most important file types a project will install.

On Windows, another variation is for packages to put executables and DLLs at the base install location rather than under a `bin` subdirectory. While this may be a relatively common practice, it can lead to a fairly

crowded base directory, making it harder for users to find other package components. Another variation is for launch scripts to be located in a subdirectory named `cmd`, which keeps them separated from DLLs in other locations such as `bin`.

Finding a directory structure that works for most platforms is desirable, since it minimizes the platform-specific logic that has to be implemented by the project's source code. If the project uses the same relative layout on all platforms, it is easier for an application to find things it needs at run time.

In the absence of any other requirements, CMake's `GNUInstallDirs` module provides a very convenient way to use a standard directory layout. It is consistent with the common cases mentioned above, and it also provides various other standard locations that conform to both GNU coding standards and the FHS. Putting aside the parts that relate to the base install path (covered in the next section), the layout can even be used for Windows deployments. Starting with CMake 3.14, a number of install-related commands take their defaults from `GNUInstallDirs` or fall-back locations that are very similar.

Using the `GNUInstallDirs` module is fairly straightforward, it is included like any other module:

```
# Minimal inclusion, but see caveat further below
include(GNUInstallDirs)
```

This will create cache variables of the form `CMAKE_INSTALL_<dir>` where `<dir>` denotes a particular location. The module's documentation

gives full details of all the defined locations, but some of the more commonly used ones and their intended use include:

BINDIR

Executables, scripts, and symlinks intended for end users to run directly.
Defaults to `bin`.

SBINDIR

Similar to `BINDIR` except intended for system admin use. Defaults to `sbin`.

LIBDIR

Libraries and object files. Defaults to `lib` or some variation of that, depending on the host/target platform (including possibly a further architecture-specific subdirectory).

LIBEXECDIR

Executables not directly invoked by users, but might be run via launch scripts or symlinks located in `BINDIR` or by other means. Defaults to `libexec`.

INCLUDEDIR

Header files. Defaults to `include`.

DATAROOTDIR

Root point of read-only architecture-independent data. Not typically referred to directly, except perhaps to work around caveats for `DOCDIR`.

DATADIR

Read-only architecture-independent data such as images and other resources. Defaults to the same as DATAROOTDIR and is the preferred way to refer to locations for arbitrary project data not covered by other defined locations.

MANDIR

Documentation in the `man` format. Defaults to DATAROOTDIR/`man`.

DOCDIR

Generic documentation. Defaults to DATAROOTDIR/doc/PROJECT_NAME (see notes below for why relying on this default value is relatively unsafe).

Since each location is defined as a cache variable, they can be overridden if needed. Developers would not normally change them, as install locations should be under the control of the project. Even for the project though, changing the locations from the defaults is not generally advisable, but it can be useful if the project wants to mostly follow the standard layout and only needs to make a few small tweaks.

The DOCDIR location deserves special mention, as it defaults to a value that incorporates the PROJECT_NAME variable. PROJECT_NAME is updated by each call to `project()` and therefore can vary throughout the project hierarchy. The `GNUInstallDirs` module sets cache variables only if they are not already defined, so the value of CMAKE_INSTALL_DOCDIR will be determined by where the

`GNUInstallDirs` module is first included. To protect against this and allow the default documentation directory to follow the project hierarchy, projects may want to explicitly set the `DOCDIR` location every time the module is included (the non-cache variable will override the cache variable):

```
# Explicitly set DOCDIR location each time
include(GNUInstallDirs)
set(CMAKE_INSTALL_DOCDIR
    ${CMAKE_INSTALL_DATAROOTDIR}/doc/${PROJECT_NAME}
)
```

For the remainder of this chapter, examples will use the `CMAKE_INSTALL_<dir>` variables for most relative install destinations.

35.1.2. Base Install Location

After the relative layout of installed files has been determined, the base install location of that layout must be decided. A number of considerations impact this decision, but perhaps the first question to answer is whether the install should be relocatable. This just means that any install base point can be used and as long as the relative layout is preserved, the installed project will still work as intended. Being relocatable is highly desirable and should be the goal of most projects, since it opens up more use cases, such as:

- Multiple versions can be installed simultaneously.
- Relocatable packages can be installed to shared drives which may have different mount points on different end users' machines.

- A set of self-contained relocatable files can be more easily packaged up by a wider range of packaging systems.
- Non-admin users can install a relocatable project locally under their own account.

Not all projects can be made relocatable, some need to place their files in very specific locations (e.g. kernel packages). Some projects can be relocatable except for a few configuration files, in which case a useful strategy can sometimes be to handle those specific files as a scripted post-install step (the next chapter discusses some aspects of this for specific packaging systems).

The choice of base install location is closely tied to the target platform, with each one having its own common practices and guidelines. On Windows, the base install location is usually a subdirectory of `C:\Program Files`, whereas on most other systems, it is `/usr/local` or a subdirectory of `/opt`. CMake provides a number of controls for managing the base install location to mostly abstract away these platform differences. Perhaps the most important is the `CMAKE_INSTALL_PREFIX` variable, which controls the base install location when the user builds the `install` target (the target may be called `INSTALL` with some generator types). The default value of `CMAKE_INSTALL_PREFIX` is `C:\Program Files\${PROJECT_NAME}` on Windows and `/usr/local` on Unix-based platforms. With CMake 3.29 and later, this default can be changed with the `CMAKE_INSTALL_PREFIX` environment variable.

When installing on Linux, the default value does not conform to the File System Hierarchy standard. The FHS requires system packages to use a base location of / or /usr, with the latter more likely to be the desired choice. For add-on packages, they should be installed to /opt/<package> or /opt/<provider>, with a recommendation to use /opt/<provider>/<package>. If <provider> is used, it is formally expected to be a LANANA-registered name or just the lowercase fully qualified domain name of the organization providing the package. This is to avoid clashes between different packages trying to use the same base install location.

For most projects, on non-Windows platforms it is advisable to explicitly set CMAKE_INSTALL_PREFIX to a FHS-compliant /opt/... path. This should generally be done only in the top level CMakeLists.txt and it should be protected by an appropriate check that the project is in fact the top level of the source tree (to support hierarchical project arrangements).

```
if(NOT WIN32 AND
    CMAKE_SOURCE_DIR STREQUAL CMAKE_CURRENT_SOURCE_DIR)
  set(CMAKE_INSTALL_PREFIX
      "/opt/mycompany.com/${PROJECT_NAME}"
  )
endif()
```

For cross-compiling scenarios, the CMAKE_STAGING_PREFIX variable can be defined to provide an override for where the install rule installs to. This is to allow installing to an alternate part of the file system while still preserving all the other effects of CMAKE_INSTALL_PREFIX, such as embedding of paths in the installed binaries (covered in [Section 35.2.1](#),

[“`RPATH`”](#) later in this chapter). `CMAKE_STAGING_PREFIX` also affects the search paths of most `find_...()` commands.

For some packaging scenarios and to allow testing the install process in a location off to the side, CMake supports the common `DESTDIR` functionality for non-Windows platforms. `DESTDIR` is not a CMake variable, but rather it is a variable passed to the build tool or set as an environment variable for the build tool to read. It allows the install base location to be placed under some arbitrary location rather than the root of the file system. It is typically used on a command line when invoking the build tool directly, such as:

```
make DESTDIR=/home/me/staging install  
env DESTDIR=/home/me/staging ninja install
```

The `DESTDIR` functionality is conceptually similar to `CMAKE_STAGING_PREFIX`, but `DESTDIR` is specified only at install time and does not affect things like `find_...()` commands. `CMAKE_STAGING_PREFIX` is saved as a cache variable, whereas `DESTDIR` is an environment variable and is not saved between invocations of the build tool. See [Section 35.10, “Executing An Install”](#) for an even more flexible and more convenient method for carrying out an install when using CMake 3.15 or later.

The combination of `CMAKE_INSTALL_PREFIX`, `CMAKE_STAGING_PREFIX`, and `DESTDIR` gives the project and the developer the flexibility to set the base install location as needed, and to

perform test installs without actually touching the final intended install location. Be aware, however, that the various packaging formats may have their own default base install locations, and they may completely ignore these three variables in preference to their own package-specific ones.

35.2. Installing Project Targets

With the structure of the install area defined, attention can now move to the installed content itself. Projects use the `install()` command to define what to install, where those things should be located, and so on. This command has a number of different forms, each focused on a particular type of entity which is specified by the first argument to the command. One of the key forms is for installing one or more targets provided by the project (as opposed to [imported targets](#) provided by something external to the project):

```
install(TARGETS targets...
        [EXPORT exportName]
        [CONFIGURATIONS configs...]
        [RUNTIME_DEPENDENCIES runtimeDepArgs... | ①
         RUNTIME_DEPENDENCY_SET runtimeSetName]
        # One or more blocks of the following
        [ entityType]
            [DESTINATION dir] ②
            [PERMISSIONS permissions...]
            [NAMELINK_ONLY | NAMELINK_SKIP]
            [COMPONENT component]
            [NAMELINK_COMPONENT component] ③
            [EXCLUDE_FROM_ALL]
            [OPTIONAL]
            [CONFIGURATIONS configs...]
        ]...
        # Special case
```

```
[INCLUDES DESTINATION incDirs...]  
)
```

- ① `RUNTIME_...` dependency options require CMake 3.21 or later.
- ② `DESTINATION` is mandatory for CMake 3.13 and earlier.
- ③ `NAMELINK_COMPONENT` requires CMake 3.12 or later.

With CMake 3.12 or earlier, each of the `targets` must be defined in the same directory scope as the `install()` command, but CMake 3.13 removed this restriction. The `entityType` blocks specify how to handle installing the various parts of each target. After the `entityType`, various options can be listed, which only apply to that entity type.

RUNTIME

Install executable binaries. On Windows, this also installs the DLL part of library targets. Apple bundles are excluded.

LIBRARY

Install shared libraries on all platforms except Windows. Apple frameworks are excluded.

ARCHIVE

Install static libraries (all platforms). On Windows, this also installs the import library (i.e. `.lib`) part of shared library targets. Apple frameworks are excluded.

OBJECTS

(CMake 3.9 or later) Install the objects associated with object libraries.

FRAMEWORK

On Apple platforms, install frameworks (shared or static), including any content that has been copied into them (e.g. by `POST_BUILD` custom rules).

BUNDLE

On Apple platforms, install bundles, including any content that has been copied into them.

PUBLIC_HEADER

On non-Apple platforms, this installs files listed in a framework library target’s `PUBLIC_HEADER` property. On Apple platforms, these header files are handled as part of the `FRAMEWORK` entity type instead. See [Section 35.5.2, “Explicit Public And Private Headers”](#) for further discussion.

PRIVATE_HEADER

Analogous to the `PUBLIC_HEADER` entity type, except the affected target property is `PRIVATE_HEADER`.

RESOURCE

On non-Apple platforms, this installs files listed in a framework or bundle target’s `RESOURCE` property. On Apple platforms, they are installed as part of the framework or bundle instead.

FILE_SET

(CMake 3.23 or later) This must be followed by the name of a file set to install (see [Section 35.5.1, “File Sets”](#)).

CXX_MODULES_BMI

(CMake 3.28 or later) For targets that export C++20 modules, this controls where to install BMI files. Note that this may not be of practical use (see [Section 35.6, “Installing C++20 Modules”](#)).

The following shows how to install libraries in a way that puts the respective parts in their expected place on all platforms (assuming they are not Apple frameworks):

```
install(TARGETS MySharedLib MyStaticLib
    RUNTIME DESTINATION ${CMAKE_INSTALL_BINDIR}
    LIBRARY DESTINATION ${CMAKE_INSTALL_LIBDIR}
    ARCHIVE DESTINATION ${CMAKE_INSTALL_LIBDIR}
)
```

The above example shows how the `DESTINATION` option can specify different locations for different parts of the same target. The command is flexible enough to handle multiple targets of different types all at once. For `MySharedLib`, on Windows the DLL would go to the `RUNTIME` destination and the import library to the `ARCHIVE` destination. On other platforms, the shared library would be installed to the `LIBRARY` destination. The static library of the `MyStaticLib` target would be installed to the `ARCHIVE` destination.

CMake will usually issue a warning or error if a target provides a particular entity for which there is no corresponding `entityType` section (e.g. one

of the targets is a static library but no ARCHIVE section is provided). As an exception to this, the entityType can be omitted, in which case the options that follow the list of targets will apply to all entity types. This is usually only done when it is obvious that there can only be one entity type for the targets listed:

```
# Targets are both executables, so specifying the entity
# type isn't needed
install(TARGETS exe1 exe2
        DESTINATION ${CMAKE_INSTALL_BINDIR})
)
```

For CMake 3.13 and earlier, a DESTINATION must be provided. CMake 3.14 relaxed this requirement, allowing default destinations for executables, static libraries and shared libraries, but not module libraries, Apple bundles or frameworks. Public and private headers attached to library targets also have default destinations available, as do HEADERS file sets (see [Section 35.5.1, “File Sets”](#)). For the supported target types, the default destinations are given by the same CMAKE_INSTALL_... variables that the `GNUInstallDirs` module provides for those entities. If no such variables are defined (i.e. the `GNUInstallDirs` module has not been included), hard-coded defaults that mostly follow the same defaults as the `GNUInstallDirs` module will be used instead. Note that the hard-coded defaults lack the logic for handling subtle differences across various Linux/Unix distributions, so projects should generally include the `GNUInstallDirs` module to obtain the broadest platform support. The hard-coded defaults are detailed in the CMake documentation for the `install()` command.

```
include(GNUInstallDirs)

# Only legal with CMake 3.14 or later
install(TARGETS MyExe MySharedLib MyStaticLib)
```

The above would install `MyExe` to `CMAKE_INSTALL_BINDIR`, `MyStaticLib` to `CMAKE_INSTALL_LIBDIR` and `MySharedLib` to one or both of those two locations depending on the platform. Any public or private headers or `HEADERS` file sets attached to these targets would be installed to `CMAKE_INSTALL_INCLUDEDIR`. While this can be very convenient and concise, it forces the project to require CMake 3.14 as its minimum version. For the remainder of this chapter, the destinations are still explicitly given in most examples so that they remain applicable to the broadest range of CMake versions.

Options following an entity type can specify more than just the destination. They can also override the default permissions with the `PERMISSIONS` option, specifying one or more of the same values as for the `file(COPY)` command described back in [Section 21.2, “Copying Files”](#):

```
OWNER_READ OWNER_WRITE OWNER_EXECUTE
```

```
GROUP_READ GROUP_WRITE GROUP_EXECUTE
```

```
WORLD_READ WORLD_WRITE WORLD_EXECUTE
```

```
SETUID      SETGID
```

As for `file(COPY)`, permissions not supported for the platform will simply be ignored. Note that CMake usually sets appropriate permissions for all targets by default. One would typically only need to explicitly provide permissions if the installed location needs more restrictive permissions than normal or if one of the SETUID or SETGID permissions needs to be added. The following example demonstrates both scenarios.

```
# Intended to only be run by an administrator,  
# so only allow the owner to have access  
install(TARGETS OnlyOwnerCanRunMe  
    DESTINATION ${CMAKE_INSTALL_SBINDIR}  
    PERMISSIONS  
        OWNER_READ OWNER_WRITE OWNER_EXECUTE  
)  
  
# Install with set-group permission  
install(TARGETS RunAsGroup  
    DESTINATION ${CMAKE_INSTALL_BINDIR}  
    PERMISSIONS  
        OWNER_READ OWNER_WRITE OWNER_EXECUTE  
        GROUP_READ GROUP_EXECUTE SETGID  
)
```

For the `LIBRARY` entity type, some platforms support the creation of symbolic links when version details have been provided for a library target (see [Section 23.3, “Shared Library Versioning”](#)). The set of files and symlinks that might exist for a shared library typically look something like this:

```
libMyShared.so.1.3.2          ①  
libMyShared.so.1 --> libMyShared.so.1.3.2  ②  
libMyShared.so    -> libMyShared.so.1      ③
```

① The actual versioned binary built by the project.

- ② Symbolic link whose name is the soname of the library. When following semantic versioning, this will contain only the major part of the version in its name.
- ③ Namelink with no version details embedded in the file name. This is required for the library to be found when a linker command line contains an option like `-lMyShared`.

When installing `LIBRARY` entities, the `NAMELINK_ONLY` or `NAMELINK_SKIP` options can be given. The `NAMELINK_ONLY` option will result in only the namelink being installed, whereas `NAMELINK_SKIP` will result in all but the namelink being installed. If a library target has no version details or the platform doesn't support namelinks, the behavior of these two options changes. `NAMELINK_ONLY` will then install nothing and `NAMELINK_SKIP` will install the real library. These options are especially useful when creating separate runtime and development packages, with the namelink part going into the development package, and the other files/links going into the runtime package.

When a `NAMELINK_ONLY` option is given, CMake will not warn about missing entity type blocks for other parts of the library not mentioned in that `install()` command. This is needed because `NAMELINK_SKIP` and `NAMELINK_ONLY` cannot both be given in the same `install()` call, the two have to be split across separate calls (see example below).

Each `entityType` section can also specify a `COMPONENT` option. Components are a logical grouping used mainly for packaging and are discussed in detail in the next chapter. For now, think of them as a way of separating out different install sets. The above-mentioned scenario for separate runtime and development packages could be set up as follows:

```

install(TARGETS MyShared MyStatic
        RUNTIME
            DESTINATION ${CMAKE_INSTALL_BINDIR}
            COMPONENT MyProj_Runtime
        LIBRARY
            DESTINATION ${CMAKE_INSTALL_LIBDIR}
            NAMELINK_SKIP
            COMPONENT MyProj_Runtime
        ARCHIVE
            DESTINATION ${CMAKE_INSTALL_LIBDIR}
            COMPONENT MyProj_Development
    )

# Because NAMELINK_ONLY is given, CMake won't complain
# about a missing RUNTIME block
install(TARGETS MyShared
        LIBRARY
            DESTINATION ${CMAKE_INSTALL_LIBDIR}
            NAMELINK_ONLY
            COMPONENT MyProj_Development
    )

```

From CMake 3.12, a simpler way of splitting out the namelink to a different component is available using the `NAMELINK_COMPONENT` option. This option can be used in conjunction with `COMPONENT`, but only within a `LIBRARY` block. Using this new option, the above can be expressed more concisely:

```

install(TARGETS MyShared MyStatic
        RUNTIME
            DESTINATION ${CMAKE_INSTALL_BINDIR}
            COMPONENT MyProj_Runtime
        LIBRARY
            DESTINATION ${CMAKE_INSTALL_LIBDIR}
            COMPONENT MyProj_Runtime
            NAMELINK_COMPONENT MyProj_Development ①
        ARCHIVE

```

```
DESTINATION ${CMAKE_INSTALL_LIBDIR}
COMPONENT MyProj_Development
)
```

① `NAMELINK_COMPONENT` requires CMake 3.12 or later.

If no `COMPONENT` is given for a block, it is associated with a default component whose name is given by the variable `CMAKE_INSTALL_DEFAULT_COMPONENT_NAME`. If that variable is not set, `Unspecified` is used as the default component name. An example where it can be helpful to change the default component name is where a third party child project doesn't use any install components. To keep that child project's install artifacts separate from the main project, the default name can be changed just before calling `add_subdirectory()` to pull the child project into the main build.

The `EXCLUDE_FROM_ALL` option can be used to restrict an entity block to only get installed for component-specific installs. By default, an install is not component-specific and all components are installed, but packaging implementations may install specific components individually. Documentation was added in CMake 3.12 to show how to do this from the command line as well. For most projects, `EXCLUDE_FROM_ALL` is unlikely to be needed.

The `OPTIONAL` keyword is also rarely used. If the entity type of a target is expected to be present, but it is missing (e.g. the import library of a Windows DLL for an `ARCHIVE` entity type section), CMake will not consider it an error. Use this option with caution, as it has the ability to mask misconfiguration of the build/install logic.

An entity type block can also be made configuration-specific by adding a `CONFIGURATIONS` option to it. That entity type will only be installed if the current build type is one of those listed. An entity type cannot be listed more than once for a single `install()` command, so if different configurations need different details, multiple calls are needed. The following example shows how to install the Debug and Release versions of static libraries in different directories:

```
install(TARGETS MyStatic
        ARCHIVE
        DESTINATION ${CMAKE_INSTALL_LIBDIR}/Debug
        CONFIGURATIONS Debug
    )

install(TARGETS MyStatic
        ARCHIVE
        DESTINATION ${CMAKE_INSTALL_LIBDIR}/Release
        CONFIGURATIONS Release RelWithDebInfo MinSizeRel
    )
```

The `CONFIGURATIONS` keyword can also precede all entity blocks and act as a default for those that don't provide their own configuration override. In the following example, all blocks get installed only for `Release` builds, except for the `ARCHIVE` block which is installed for `Debug` and `Release`.

```
install(TARGETS MyShared MyStatic
        CONFIGURATIONS Release
        RUNTIME
        DESTINATION ${CMAKE_INSTALL_BINDIR}
        LIBRARY
        DESTINATION ${CMAKE_INSTALL_LIBDIR}
        ARCHIVE
```

```
DESTINATION ${CMAKE_INSTALL_LIBDIR}
CONFIGURATIONS Debug Release
)
```

See [Section 35.8.1, “Runtime Dependency Sets”](#) for how to use the `RUNTIME_DEPENDENCIES` and `RUNTIME_DEPENDENCY_SET` keywords.

The `install()` command also supports specifying one or more header search paths with `INCLUDES DESTINATION`. To better understand how it can be used, consider the following example, which is a modified version of the one presented back in [Section 16.3.1, “Building, Installing, And Exporting”](#):

```
add_library(MyStatic STATIC ...)
set(incDir ${CMAKE_CURRENT_BINARY_DIR}/static_exports)
target_include_directories(MyStatic
    PUBLIC
        $<BUILD_INTERFACE:${incDir}>
        $<INSTALL_INTERFACE:${CMAKE_INSTALL_INCLUDEDIR}>
)

install(TARGETS MyStatic EXPORT Funcs DESTINATION ...)
install(EXPORT Funcs DESTINATION ...)
```

While the header search path within the build tree may vary from target to target, it is common for the targets to share the same header search path once installed. In the above example, `${CMAKE_INSTALL_INCLUDEDIR}` is likely to be repeated for every target, but specifying it individually for each one is not the most convenient approach. The `INCLUDES DESTINATION` option of the `install()` command can be used instead to specify the same information for a group

of targets. All the directories given after `INCLUDES DESTINATION` are added to the `INTERFACE_INCLUDE_DIRECTORIES` property of each installed target listed. And since the `install()` command only affects the install context, there's no need for the `$<INSTALL_INTERFACE:>` generator expression. This leads to a more concise description of header search paths.

```
add_library(MyStatic STATIC ...)
add_library(MyHeaderOnly INTERFACE ...)

set(incDir ${CMAKE_CURRENT_BINARY_DIR}/static_exports)
target_include_directories(MyStatic
    PUBLIC $<BUILD_INTERFACE:${incDir}>
)
target_include_directories(MyHeaderOnly
    INTERFACE $<BUILD_INTERFACE:${CMAKE_CURRENT_LIST_DIR}>
)

install(TARGETS MyStatic MyHeaderOnly
    ARCHIVE DESTINATION ${CMAKE_INSTALL_LIBDIR}
    INCLUDES DESTINATION ${CMAKE_INSTALL_INCLUDEDIR}
)
```

Unlike the other entity type blocks, multiple directories can be listed for `INCLUDES DESTINATION` if required, although this tends to be less common in practice. Also note that an `INCLUDES` block supports none of the other details that other `entityType` blocks support. It may only specify a `DESTINATION` keyword followed by one or more locations.

35.2.1. RPATH

When the operating system loads a library or executable, it has to find all the other shared libraries the binary has been linked against. Different platforms have different ways of handling this. Windows relies on finding all required libraries by searching the locations in the PATH environment variable, as well as the directory in which the binary is located. Other platforms use different environment variables specifically intended for the purpose, such as LD_LIBRARY_PATH or variations thereof, in conjunction with other mechanisms such as libraries listed in conf files. A drawback to the dependence on environment variables is that it relies on the person or process loading the binary to set up the environment correctly.

In many cases, the package providing the binary already knows where many of the dependent libraries can be found, since they may have been part of the same package. Most non-Windows platforms support binaries being able to encode library search paths directly into the binaries themselves. The generic name for this feature is *run path* or RPATH support, although the actual name may have platform-specific variations. With embedded RPATH details, a binary can be self-contained and not have to rely on any paths being provided by the environment or system configuration. Furthermore, an RPATH can contain certain placeholders that allow it to effectively define relative paths that are only resolved to absolute paths at run time. The placeholders allow that resolution to be made based on the location of the binary, so relocatable packages can define RPATH details that only hard-code paths based on the package's relative layout.

Just as was the case for interface properties in the previous section, there are conflicting needs for RPATH in the build tree and for installed binaries.

In the build tree, developers need the binaries to be able to find the shared libraries they link to so that executables can be run (e.g. for debugging, test execution, and so on). On platforms that support RPATH, CMake will embed the required paths by default, thereby giving developers the most convenient experience without requiring any further setup. These RPATH details are only suitable for that particular build tree though, so when the targets are installed, CMake rewrites them with replacement paths (the default replacement yields an empty RPATH).

The RPATH defaults are a reasonable starting point, but they are unlikely to be suitable for installed targets. Projects will want to override the default behavior to ensure that both build tree and installed scenarios are suitably catered for. CMake allows separate control of the build and install RPATH locations, so projects can implement a strategy that best fits their needs. The following target properties and variables can be useful for influencing the RPATH behavior:

BUILD_RPATH

This target property can be used to provide additional search paths to be embedded in the build tree's binary. This will be in addition to the paths automatically added by CMake for that binary's link dependencies, so only extra paths CMake cannot work out on its own should be specified. This property should only be needed if the binary loads non-linked libraries at run time using `dlopen()` or some equivalent mechanism, such as when loading optional plugin modules. This property is initialized by the value of the `CMAKE_BUILD_RPATH` variable at the

time the target is created by `add_library()` or `add_executable()`. While the automatically added paths have been supported in CMake for a long time, the `BUILD_RPATH` property and the `CMAKE_BUILD_RPATH` variable were only added in CMake 3.8.

BUILD_RPATH_USE_ORIGIN

This target property is only supported for CMake 3.14 or later. For platforms that support `$ORIGIN` in an RPATH (see further below), setting this property to true causes CMake to embed `$ORIGIN`-relative paths rather than absolute paths in the build tree's binaries. This enables making reproducible, relocatable builds. The initial value for `BUILD_RPATH_USE_ORIGIN` is taken from the `CMAKE_BUILD_RPATH_USE_ORIGIN` variable at the time the target is created. This property will only affect those paths CMake determines automatically, it will not affect any paths specified in the `BUILD_RPATH` property. It will also not have any effect on the embedded RPATH of installed binaries.

INSTALL_RPATH

This target property specifies the RPATH of the binary when it is installed. Unlike the build RPATH, CMake does not provide any install RPATH contents by default, so the project should set this property to a list of paths that reflect the installed layout. Details further below discuss how this can be done. This property is initialized by the value of the `CMAKE_INSTALL_RPATH` variable when the target is created.

INSTALL_RPATH_USE_LINK_PATH

When this target property is set to true, the path of each library this target links to is added to the set of install RPATH locations, but only if the path points to a location outside the project's source and binary directories. This is mainly useful for embedding absolute paths to external libraries that are not part of the project, but that are expected to be at the same location on all machines the project will be deployed to. Use this with caution, as such assumptions can reduce the robustness of the installed package (paths may change with future releases of the external libraries, system administrators may choose non-default installation configurations, etc.). This property is initialized by the value of the `CMAKE_INSTALL_RPATH_USE_LINK_PATH` variable when the target is created.

BUILD_WITH_INSTALL_RPATH

Some projects use a build layout that mirrors the installed layout. Targets may expect to find certain files relative to their own location, or they could be self-contained app bundles with embedded frameworks. For these cases, the install RPATH may also be suitable for the build tree. By setting this target property to true, the build RPATH is not used and the install RPATH will be embedded in the binary at build time instead. Note that this may cause problems during linking if using placeholders supported by the loader but not the linker (discussed below). This property is initialized by the `CMAKE_BUILD_WITH_INSTALL_RPATH` variable when the target is created.

SKIP_BUILD_RPATH

When this target property is set to true, no build RPATH is set. `BUILD_RPATH` will be ignored and CMake will not automatically add RPATH entries for libraries the target links to. Note that this can cause builds to fail if dependent libraries link to other libraries, so use with caution. This property is initialized by the value of the `CMAKE_SKIP_BUILD_RPATH` variable when the target is created. It is also overridden by `BUILD_WITH_INSTALL_RPATH` if that property is set to true.

`CMAKE_SKIP_INSTALL_RPATH`

This variable is the install equivalent of `CMAKE_SKIP_BUILD_RPATH`. Setting it to true causes `INSTALL_RPATH` target properties to be ignored and will likely cause the installed targets to fail to find their dependent libraries at run time, so its usefulness is questionable. Note that there is no `SKIP_INSTALL_RPATH` target property, only the `CMAKE_SKIP_INSTALL_RPATH` variable.

`CMAKE_SKIP_RPATH`

Setting this variable to true causes all RPATH support to be disabled, and all the above properties and variables will be ignored. It is generally not desirable to do this unless the project is managing the run time library loading itself in some other way, but in general the RPATH functionality should generally be preferred.

Install RPATH locations should ideally be based on relative paths. This is achieved on most Unix-based platforms by using the `$ORIGIN` placeholder

to represent the location of the binary in which the RPATH is embedded. For example, the following is a common way of defining install RPATH details for projects that follow a similar layout to that defined by the `GNUInstallDirs` module:

```
set(CMAKE_INSTALL_RPATH $ORIGIN $ORIGIN/../lib)
```

To make this more robust and account for potential changes from the default layout, a little more work is needed. One has to work out the relative path from the executables directory to the libraries directory, which can be achieved as follows:

```
include(GNUInstallDirs)
file(RELATIVE_PATH relDir
    ${CMAKE_CURRENT_BINARY_DIR}/${CMAKE_INSTALL_BINDIR}
    ${CMAKE_CURRENT_BINARY_DIR}/${CMAKE_INSTALL_LIBDIR}
)
set(CMAKE_INSTALL_RPATH $ORIGIN $ORIGIN/${relDir})
```

All targets defined after the above will have an `INSTALL_RPATH` that directs the loader to look in the same directory as the binary as well as something like `../lib` or its platform equivalent relative to the binary's location. Thus, for executables installed to `bin` and shared libraries installed to `lib`, this will ensure both can find any other libraries provided by the project. This is highly recommended as a starting point when first adding RPATH support to projects. Note that Apple targets work a little differently and may have a considerably different layout, so the above needs to be adapted further to cover that platform (discussed in the next section).

One weakness to be aware of is that while loaders understand `$ORIGIN`, the linker most likely will not. This can lead to problems when something links to a library which itself links to another library. The first level of linking does not present a problem, since the library will be listed directly on the linker command line, but the second level of library dependency has to be found by the linker. When the linker doesn't understand `$ORIGIN`, it can't find the second level library via `RPATH` details. Therefore, unless the path is also specified by some other option like `-L`, linking will fail, even though the first level library technically contains all the information needed. This is a known issue that is not specific to CMake, it is a weakness of popular linkers (notably the GNU `ld` linker).

Depending on the various properties and variables mentioned above, CMake may be required to change the embedded `RPATH` details of a target when it is being installed. There are two ways this can be done. If the binary is in the ELF format, then by default, CMake uses an internal tool to rewrite the `RPATH` directly in the installed binary. From CMake 3.20, equivalent functionality for the XCOFF format on AIX is also provided (the feature is called `LIBPATH` for XCOFF, but within CMake it is still referred to as `RPATH` for convenience). CMake ensures there will be enough space for the install `RPATH` by padding the build `RPATH` if necessary. The details of how this is done are largely hidden from the developer, other than perhaps some odd-looking options on the linker command line at build time. For other binary formats, CMake re-links the binary at install time, specifying the install `RPATH` details instead. Historically, this can sometimes confuse developers who wonder why something that has already been built needs to

be linked again, but ultimately the re-linking is a pragmatic way to get the desired end result. The re-linking behavior can be forced for ELF or XCOFF binaries too by setting the `CMAKE_NO_BUILTIN_CHRPATH` variable to true, but this should not generally be used unless the internal RPATH rewriting fails for some reason.

When cross compiling, a few other variables can modify the RPATH locations embedded in binaries. Any RPATH location that starts with the `CMAKE_STAGING_PREFIX` will automatically have that prefix replaced with the `CMAKE_INSTALL_PREFIX`. This is true for both build and install RPATH locations. Any install RPATH location that begins with the `CMAKE_SYSROOT` will have that prefix stripped entirely.

35.2.2. Apple-specific Targets

Apple's loader and linker work a little differently to other Unix platforms. Whereas libraries on platforms like Linux encode just the library name into a shared library (i.e. the *soname*), Apple platforms encode the full path to the library. This full path is referred to as the `install_name` and the path part of the `install_name` is sometimes called the `install_name_dir`. Anything linking to the library also encodes the full `install_name` as the library to search for.

When everything is installed to the expected location, this works well, but for relocatable packages (which includes most app bundles), this is too inflexible. As a way of dealing with this, Apple supports relative base points similar to `$ORIGIN`, but the placeholders are different:

@loader_path

This is more or less Apple's equivalent of `$ORIGIN`, but the linker is able to understand it and therefore doesn't suffer the problems other linkers experience with being unable to decode `$ORIGIN`.

@executable_path

This will be replaced by the location of the program being executed. For libraries pulled in as dependencies of other libraries, this is less helpful, since it requires the libraries to know the location of any executable that may use them. This is generally undesirable, so `@loader_path` is usually the better choice.

@rpath

This can be used as a placeholder for all or part of the `install_name_dir`.

The combination of `@loader_path` and `@rpath` can provide equivalent behavior to `$ORIGIN` on other platforms. CMake provides additional Apple-specific controls to help set things up appropriately:

`MACOSX_RPATH`

When this target property is set to true, CMake automatically sets the `install_name_dir` to `@rpath` when building for Apple platforms. This is the default behavior since CMake 3.0 and is almost always desirable. It can be overridden by `INSTALL_NAME_DIR`. If the `CMAKE_MACOSX_RPATH` variable is set at the time the target is

created, it is used to initialize the value of the `MACOSX_RPATH` property.

INSTALL_NAME_DIR

This target property is used to explicitly set the `install_name_dir` part of the library's `install_name`. The default `install_name` usually has the form `@rpath/libsomefilename.dylib`, but for cases where `@rpath` is not appropriate, `INSTALL_NAME_DIR` can specify an alternative. The property is initialized with the value of the `CMAKE_INSTALL_NAME_DIR` variable at the time it is created. This property is ignored on non-Apple platforms.



A long-standing bug in CMake versions before 3.20.1 results in mishandling of the `install_name_dir` when targeting iOS, watchOS or tvOS. The bug forces the `install_name_dir` to be the full path to the binary instead of the default `@rpath`. Furthermore, the `INSTALL_NAME_DIR` target property has no effect. If an app bundle contains embedded frameworks (see [Section 25.11, “Embedding Frameworks And Other Things”](#)), the app will fail to run because it is unable to find its frameworks at run time. The full paths that were embedded won't exist on the device or a device simulator. Use CMake 3.20.1 or later to avoid this problem.

For non-bundle layouts, the `$ORIGIN` behavior can be extended to cover the Apple case as well:

```
if(APPLE)
    set(base @loader_path)
else()
    set(base $ORIGIN)
```

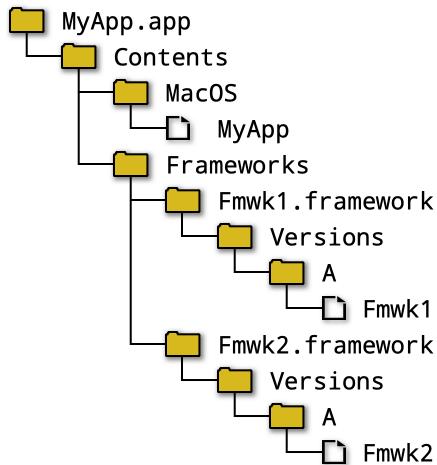
```

endif()

include(GNUInstallDirs)
file(RELATIVE_PATH relDir
    ${CMAKE_CURRENT_BINARY_DIR}/${CMAKE_INSTALL_BINDIR}
    ${CMAKE_CURRENT_BINARY_DIR}/${CMAKE_INSTALL_LIBDIR}
)
set(CMAKE_INSTALL_RPATH ${base} ${base}/${relDir})

```

Once Apple bundles or frameworks are used, the layout is completely different and alternative strategies are needed for defining the run time search paths. For example, a macOS app bundle may end up with the following structure after installing the relevant targets or as a result of embedding frameworks (discussed in [Section 25.11, “Embedding Frameworks And Other Things”](#)). Only relevant parts of the bundle structure are shown:



To obtain appropriate RPATH details for the above, set the `INSTALL_RPATH` target property of `MyApp` to `@executable_path/.../Frameworks`, and for `Fmwk1` and `Fmwk2` set it to `@loader_path/.../...`. For an iOS app, the paths would be

@executable_path/Frameworks and @loader_path/.. instead. The install RPATH details should also be used at build time so that embedded frameworks are handled correctly. In the following example, only the RPATH-related properties are shown. See [Section 25.6, “Signing And Capabilities”](#), [Section 25.7, “Creating And Exporting Archives”](#) and [Section 25.11, “Embedding Frameworks And Other Things”](#) for additional details that would be needed.

```
set(CMAKE_BUILD_WITH_INSTALL_RPATH YES)
add_executable(MyApp MACOSX_BUNDLE ...)
add_library(Fmwk1 SHARED ...)
add_library(Fmwk2 SHARED ...)

# Direct linking like this assumes CMake 3.19 or later
target_link_libraries(MyApp PRIVATE Fmwk1)
target_link_libraries(Fmwk1 PRIVATE Fmwk2)

set_target_properties(MyApp PROPERTIES
    INSTALL_RPATH @executable_path/../Frameworks
)
set_target_properties(Fmwk1 Fmwk2 PROPERTIES
    FRAMEWORK TRUE
    INSTALL_RPATH @loader_path/.../...
)

# Install the frameworks into the installed app bundle
install(TARGETS Fmwk1 Fmwk2 MyApp
    BUNDLE DESTINATION .
    FRAMEWORK DESTINATION MyApp.app/Contents/Frameworks
)
```

Frameworks can also contain headers. When present, these would be installed as part of the framework. [Section 35.5.2, “Explicit Public And Private Headers”](#) discusses that area in more detail.

35.3. Installing Exports

Project targets can specify the name of an export set they belong to using the `EXPORT` option with `install(TARGETS)`. That export set is then installed using a different form of the command:

```
install(EXPORT exportName
        DESTINATION dir
        [FILE name.cmake]
        [NAMESPACE namespace]
        [CXX_MODULES_DIRECTORY modDir]    # CMake 3.28+
        [PERMISSIONS permissions...]
        [EXPORT_LINK_INTERFACE_LIBRARIES]
        [COMPONENT component]
        [EXCLUDE_FROM_ALL]
        [CONFIGURATIONS configs...])
)
```

Installing an export set creates a file at the nominated destination `dir` with the specified `name.cmake` file name (it must end in `.cmake`). If the `FILE` option is not given, a default file name based on the `exportName` is used. The generated file will contain CMake commands that define an imported target for each target in the export set. The purpose of this file is for other projects to include it so that they can refer to this project's targets and have full information about the interface properties and inter-target relationships. With some limitations, the consuming project can then treat the imported targets just like any of its own regular targets. These export files are not usually included directly by projects, they are intended to be used by a config package, which is then found by other projects using the `find_package()` command (this is covered in more detail in [Section 35.9, “Writing A Config Package File”](#) later in this chapter).

When the `NAMESPACE` option is given, each target will have `namespace` prepended to its name when creating its associated imported target. Consider the following example:

```
add_library(MyShared SHARED ...)  
add_library(BagOfBeans::MyShared ALIAS MyShared)  
  
install(TARGETS MyShared  
        EXPORT BagOfBeans  
        DESTINATION ${CMAKE_INSTALL_LIBDIR}  
)  
install(EXPORT BagOfBeans  
        DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/BagOfBeans  
        NAMESPACE BagOfBeans::  
)
```

The above example follows the advice from [Section 19.4, “Recommended Practices”](#) where each regular target also has a namespaced `ALIAS` associated with it. When installing the export for the non-alias `MyShared` target, the same namespace is used as for the alias target (i.e. `BagOfBeans::`). This allows projects that consume the exported details to refer to the target in the same way as this project can refer to the alias (`BagOfBeans::MyShared`). Consuming projects can then elect to add this project directly via `add_subdirectory()` or pull in the export file via `find_package()`, yet still use the same `BagOfBeans::MyShared` target name regardless of which method was chosen. This important pattern is emerging as a fairly common expectation on projects among the CMake community, so it is in most projects’ interests to try to follow it.

One problem that can arise when combining multiple projects into a single build via `add_subdirectory()` (a powerful technique covered in depth in [Chapter 39, FetchContent](#)) is that different projects may define targets with the same name. CMake requires all global targets to be unique, so such projects cannot be combined in that way. To avoid this situation, projects can give their targets a project-specific name, such as `MyProj_Algo` rather than just `Algo`. Whatever is used as a namespace prefix for an export will typically also serve as a suitable prefix for a target name (replacing the `::` with an underscore or removing it completely). With this strategy, to avoid repeating the prefix in the exported name, the target's `EXPORT_NAME` target property can be set to a different name for use only when exporting the target. The `OUTPUT_NAME` target property can be used to also override the name of the target's built binaries (both during the build and at install time). It is very common for `EXPORT_NAME` and `OUTPUT_NAME` to be the same, but this is by no means a requirement. If the `OUTPUT_NAME` is not project-specific, it may clash with binaries from other projects. For example:

```
add_library(MyProj_Algo SHARED ...)
add_library(MyProj::Algo ALIAS MyProj_Algo)

set_target_properties(MyProj_Algo PROPERTIES
    OUTPUT_NAME MyProjAlgo
    EXPORT_NAME Algo
)

install(TARGETS MyProj_Algo
    EXPORT MyProj
    DESTINATION ${CMAKE_INSTALL_LIBDIR}
)
install(EXPORT MyProj
```

```
DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/MyProj  
NAMESPACE MyProj::  
)
```

With the above example, `MyProj_Algo` will end up with the exported name `MyProj::Algo` instead of `MyProj::MyProj_Algo`. The library will have file names like `libMyProjAlgo.so` or `MyProjAlgo.dll`, depending on the platform. Projects are encouraged to make use of these features to minimize the chances of target name clashes with other projects and still provide concise exported target names.

The name of the export set given after the `EXPORT` keyword does not have to be related to the `NAMESPACE`. The namespace is usually closely associated with the project name, but a range of different strategies can be appropriate for the naming of export sets. For example, a project could define multiple export sets with targets that share a single namespace and where the export sets might correspond to logical units that could be installed as a whole. These export sets might each correspond to a single install `COMPONENT` or they might collect together multiple components.

The following demonstrates these cases:

```
# Single component export  
install(TARGETS algo1 EXPORT MyProj_algoFree  
        DESTINATION ... COMPONENT MyProj_free  
)  
install(EXPORT MyProj_algoFree  
        DESTINATION ... COMPONENT MyProj_free  
)
```

```
# Multi component export  
install(TARGETS algo2 EXPORT MyProj_algoPaid
```

```
        DESTINATION ... COMPONENT MyProj_licensed_A
    )
install(TARGETS algo3      EXPORT      MyProj_algoPaid
        DESTINATION ... COMPONENT MyProj_licensed_B
)
install(EXPORT MyProj_algoPaid
        DESTINATION ... COMPONENT MyProj_licensed_dev
)
```

In the single component example above, the export set contains just the `algo1` target, which is a member of the `MyProj_free` component. The export file is also a member of the `MyProj_free` component, so when that component is installed, both the library and the export file will be installed together. For the multi component example, the export set contains `algo2` from the `MyProj_licensed_A` component and `algo3` from the `MyProj_licensed_B` component, but the export file is in its own separate component. Therefore, the targets can be installed with or without the export file based on whether the `MyProj_licensed_dev` component is installed.

The multi-component export case above highlights an important aspect of how export sets and components need to be installed. It is an error to install the export file without also installing the actual targets that the export file points to. Thus, if the user installs the `MyProj_licensed_dev` component, then the `MyProj_licensed_A` and `MyProj_licensed_B` components must also be installed.

The `CXX_MODULES_DIRECTORY` option only has an effect if one or more targets in the export set exports a C++20 module. See [Section 35.6, “Installing C++20 Modules”](#) for further discussion of that topic.

Of the remaining options of the `install(EXPORT)` command, a number have similar effects as they do for `install(TARGETS)`. The `PERMISSIONS`, `EXCLUDE_FROM_ALL`, `CONFIGURATIONS`, and `DESTINATION` options apply to the installed export file rather than the targets, but are otherwise equivalent. The `DESTINATION` also has some conventions that may be useful to follow. The motivations for these are tied to the main way the exported files are used as part of config packages, so discussion of this topic is delayed to [Section 35.9, “Writing A Config Package File”](#) further below.

The `EXPORT_LINK_INTERFACE_LIBRARIES` option is for supporting old pre-3.0 CMake behavior and relates to link interface libraries. Its use is discouraged and projects are advised to update to at least 3.0 as a minimum CMake version instead.

There is a very similar form of the `install()` command specifically for exporting targets for use with Android `ndk-build` projects:

```
install(EXPORT_ANDROID_MK exportName
        DESTINATION dir
        [FILE name.mk]
        [NAMESPACE namespace]
        [PERMISSIONS permissions...]
        [EXPORT_LINK_INTERFACE_LIBRARIES]
        [COMPONENT component]
        [EXCLUDE_FROM_ALL]
        [CONFIGURATIONS configs...])

```

Whereas `install(EXPORT)` creates a file for other CMake projects to consume, `install(EXPORT_ANDROID_MK)` creates an `Android.mk` file that `ndk-build` can include. The `Android.mk` file provides all the usage requirements attached to the exported targets, so the `ndk-build` project will be aware of all the compiler defines, header search paths and so on needed to link to them. The name of the exported file can be changed with the `FILE` option, but the name must end with `.mk`. All other options have the same behavior as for the `install(EXPORT)` form. `install(EXPORT_ANDROID_MK)` requires CMake 3.7 or later, but projects may want to require at least 3.11 to avoid a bug that affected static libraries with private dependencies.

In some situations, it may be desirable to have an export file without actually having to do an install. Example scenarios include sub-builds that compile for a different platform to the main build or third party projects that cannot be added to the main build directly due to clashing target names, misuse of variables like `CMAKE_SOURCE_DIR`, and so on. For these sorts of situations, CMake provides the `export()` command which writes an export file directly into the build tree:

```
export(EXPORT exportName
      [NAMESPACE namespace]
      [FILE fileName]
)
```

The above is essentially equivalent to a simplified `install(EXPORT)` command, except the export file is written immediately. [Section 16.3.1, “Building, Installing, And Exporting”](#) also discusses some further

differences with how certain generator expressions are expanded. The reduced set of available options all have the same meaning as they do for `install(EXPORT)`, although the `fileName` can include a path (it must still end in `.cmake`).

Some other forms of the `export()` command allow exporting individual targets instead of an export set. But if export sets are already defined, the above form is likely to be the easiest to use and maintain, and should therefore be preferred.

35.4. Installing Imported Targets

With CMake 3.21 or later, the runtime artifacts of imported targets can also be installed. This is useful when the installed package needs to be fully self-contained, but some of the project's targets link to shared libraries provided by external packages.

```
install(IMPORTED_RUNTIME_ARTIFACTS targets...
        [RUNTIME_DEPENDENCY_SET runtimeSetName]
        [ [entityType]
            [DESTINATION dir]
            [PERMISSIONS permissions...]
            [COMPONENT component]
            [EXCLUDE_FROM_ALL]
            [OPTIONAL]
            [CONFIGURATIONS configs...]
        ]...
    )
```

With this form, `entityType` can only be one of `LIBRARY`, `RUNTIME`, `FRAMEWORK` or `BUNDLE`. When building for Apple platforms, the entire

framework or bundle will be installed, including headers, resources, etc. When building for Windows, only the DLL binary is installed, not any associated import library (because the latter is a build time rather than a run time artifact). For other platforms, only the shared library is installed.

All the per-entity-type keywords have the same meaning as for the `install(TARGETS...)` form. See [Section 35.8.1, “Runtime Dependency Sets”](#) for details on the use of the `RUNTIME_DEPENDENCY_SET` keyword.

In the following example, the externally-provided `ExtProj::Blah` imported target is expected to be the only dependency of `MyApp`. Since the location of the `ExtProj::Blah` target is already known, it can be installed directly. No runtime dependencies need to be computed, so no runtime dependency set is required. [Section 35.2.1, “RPATH”](#) details have been omitted for brevity, but would be needed for a more complete example to allow `MyApp` to find the dependency library at run time.

```
add_executable(MyApp ...)
find_package(ExtProj REQUIRED)
target_link_libraries(MyApp PRIVATE ExtProj::Blah)

install(TARGETS MyApp)
install(IMPORTED_RUNTIME_ARTIFACTS ExtProj::Blah)
```

The `install(IMPORTED_RUNTIME_ARTIFACTS)` command has an important limitation. It will halt with an error if asked to find the runtime artifacts of an imported target that is a library of unknown type. Imported targets are often created by [Find modules](#), some of which will define a

library as UNKNOWN rather than SHARED or STATIC. They do this because the actual library type is determined later after the library target has been created. Such imported targets cannot be used with `install(IMPORTED_RUNTIME_ARTIFACTS)`.

35.5. Installing Files

CMake supports a number of ways to install files. Which method is most appropriate for a project will depend on a few factors. Some methods offer a degree of integration with CMake targets, others are completely separate. The minimum CMake version supported by the project may limit which methods can be used. Varying support for frameworks may also be a factor.

35.5.1. File Sets

[Section 16.2.7, “File Sets”](#) introduced the concept of file sets, which are supported with CMake 3.23 and later. Each file set contains files of a specific type, and the set as a whole also has PRIVATE, PUBLIC, or INTERFACE visibility. One of the supported types is HEADERS, and the group visibility specifies whether those headers are intended for use by the target, its consumers, or both. Such file sets populate the `INCLUDE_DIRECTORIES` and `INTERFACE_INCLUDE_DIRECTORIES` properties of the target the file set is attached to. For review, the following example was given earlier in [Section 16.2.7, “File Sets”](#):

somewhere/CMakeLists.txt

```
target_sources(Colors
    PUBLIC
```

```

FILE_SET HEADERS
BASE_DIRS
    include
    ${CMAKE_CURRENT_BINARY_DIR}/include
)
add_subdirectory(include/Colors)

```

somewhere/include/Colors/CMakeLists.txt

```

include(GenerateExportHeader)
generate_export_header(Colors)

target_sources(Colors
    PUBLIC
        FILE_SET HEADERS
        FILES
            colors.h
            ${CMAKE_CURRENT_BINARY_DIR}/colors_export.h
)

```

While the population of the target's `INCLUDE_DIRECTORIES` and `INTERFACE_INCLUDE_DIRECTORIES` properties is a useful benefit, a primary advantage of file sets is their install behavior. `PUBLIC` and `INTERFACE` file sets can be installed as part of the target. For `HEADERS` file sets, each file in the set installs to the relative location below their base directory. This is done with the `FILE_SET` entity type of the `install(TARGETS)` command. Continuing the above example:

```

include(GNUInstallDirs)
install(TARGETS Colors
    RUNTIME ...
    LIBRARY ...
    ARCHIVE ...
    FILE_SET HEADERS
    INCLUDES DESTINATION ${CMAKE_INSTALL_INCLUDEDIR}
)

```

Since no `DESTINATION` was specified after `FILE_SET`, the default destination provided by `CMAKE_INSTALL_INCLUDEDIR` for `HEADERS` file sets will be used. The example then adds that location to the header search path of consumers of the installed target with the `INCLUDES DESTINATION` line.

The files in the file set have relative paths `Colors/colors.h` and `Colors/colors_export.h`. These paths are the relative locations of the files below their relevant base directory from the set of `BASE_DIRS` given in the `target_sources()` command. Assuming `CMAKE_INSTALL_INCLUDEDIR` has its default value, the headers will be installed to `include/Colors/colors.h` and `include/Colors/colors_export.h` respectively. Note how even though the two headers were under different base directories, only their relative paths under their respective base directories matter for their install destinations.

The above example demonstrates a key advantage of file sets. The common install location of all headers can be defined in one place (the `install(TARGETS)` command), with the default destination typically being appropriate. The relative path of each file below that point is determined by the file set. Other methods for installing files typically don't preserve these relative paths, or they require the relative paths be specified as part of the `install()` command.

Installing `CXX_MODULES` file sets is a more complex topic involving multiple aspects. See [Section 35.6, “Installing C++20 Modules”](#) for a

detailed discussion.

35.5.2. Explicit Public And Private Headers

Installing files with different relative paths below a base install location is not always necessary. For some project targets, all headers might be installed to the same directory. For frameworks, this is the typical arrangement. It allows those headers to be included with the canonical form:

```
#include <FrameworkName/somefile.h>
```

The PUBLIC_HEADER and PRIVATE_HEADER target properties can be used to conveniently handle both the framework and non-framework case. [Section 25.3.2, “Headers”](#) covered these properties in detail, focusing on their use with frameworks. Files listed in these properties are copied into the framework at build time. This makes them suitable for use with the Xcode generator, where frameworks may be signed directly in the build directory without going through an install step. If the framework *is* installed, the headers are installed as part of it.

If the target is not a framework, or if building for a non-Apple platform, no special handling is performed at build time. When the target is installed, files listed in these properties are also installed, but with their paths removed. This path stripping is another key difference compared to file sets. The end result is that an `#include` line like the one shown above can be made to work for both the framework and non-framework cases like so:

```

# Headers must be added as sources if using PUBLIC_HEADER
add_library(SomeThings SHARED somewhere/somefile.h ...)
set_target_properties(SomeThings PROPERTIES
    FRAMEWORK      TRUE
    PUBLIC_HEADER   somewhere/somefile.h
)

set(destHeaders ${CMAKE_INSTALL_INCLUDEDIR}/SomeThings)
install(TARGETS SomeThings
    # Apple framework case
    FRAMEWORK ...
    # Non-framework case
    RUNTIME ...
    LIBRARY ...
    ARCHIVE ...
    PUBLIC_HEADER DESTINATION ${destHeaders} ...
    PRIVATE_HEADER DESTINATION ${destHeaders} ...
)

```

The PUBLIC_HEADER and PRIVATE_HEADER properties have been supported by CMake for much longer than file sets. For projects that need to support frameworks, they are the more suitable method for installing headers.

35.5.3. Simple Files And Programs

When neither of the two preceding approaches are suitable, or for file types other than headers, a more direct, manual method is available. CMake provides the following form of the `install()` command for installing individual files:

```

install(<FILES | PROGRAMS> files...
    DESTINATION dir | TYPE type
    [RENAME newName]
    [PERMISSIONS permissions...]

```

```
[COMPONENT component]
[EXCLUDE_FROM_ALL]
[OPTIONAL]
[CONFIGURATIONS configs...]
)
```

The main difference between `install(FILES)` and `install(PROGRAMS)` is that the latter adds execute permissions by default if `PERMISSIONS` is not given. This is intended for installing things like shell scripts which need to be executable, but are not CMake targets. Most of the options are already familiar and have the same meaning as they do for `install(TARGETS)`. The `RENAME` option can only be given if `files` is a single file. It allows that file to be given a different name when installed.

CMake 3.13 and earlier require the `DESTINATION` option to be provided, but from CMake 3.14, the `TYPE` option can be given instead. Unlike for the `install(TARGETS)` case, one of the two must be provided, since CMake cannot infer the file type on its own. The set of supported file types is broader than for targets, since various non-target files can be installed with this form. The destination associated with each type is still defined the same way, taking the appropriate variable from `GNUInstallDirs` or falling back to a hard-coded default if that variable is undefined. See the CMake documentation of the `install()` command for the full set of supported types, variables and fallback values. For the broadest CMake version support, projects may wish to continue to use `DESTINATION` rather than `TYPE`, but they should still base the destination on the appropriate variable from `GNUInstallDirs`.

In some situations, a project may want to install the binaries associated with an imported target, but the `install(TARGETS)` form does not allow imported targets to be installed directly. One way around this is to install the file(s) associated with the imported target as ordinary files. The usage requirements associated with the target won't be preserved, but it does at least allow the binaries to be installed. The `$<TARGET_FILE:>` generator expression and others like it are particularly useful when employing this technique. A disadvantage is that the project has to handle all the platform differences, which is particularly problematic for imported library targets.

```
# Assume MyImportedExe is an imported target for an
# executable not built by this project
install(PROGRAMS $<TARGET_FILE:MyImportedExe>
        DESTINATION ${CMAKE_INSTALL_BINDIR})
)
```

35.5.4. Whole Directories

In some situations, a project may choose to prepare a whole directory structure of files and install them with that structure preserved. Complex resources or data file hierarchies are one example, headers spread across multiple levels of subdirectories is another. Where none of the other methods are suitable, installing a prepared tree of directory contents may be an alternative. Installing directories follows a similar pattern to files, but with more supported options:

```
install(DIRECTORY dirs...
        DESTINATION dir | TYPE type
        [FILE_PERMISSIONS permissions... |
         USE_SOURCE_PERMISSIONS]
```

```

[DIRECTORY_PERMISSIONS permissions...]
[COMPONENT component]
[EXCLUDE_FROM_ALL]
[OPTIONAL]
[CONFIGURATIONS configs...]
[MESSAGE_NEVER]
[FILES_MATCHING]
# The following block can be repeated as needed
[ [PATTERN pattern | REGEX regex]
  [EXCLUDE]
  [PERMISSIONS permissions...]]
)

```

Without any of the optional arguments, for each `dirs` location the entire directory tree starting at that point is installed into the destination `dir`. If the source name ends with a trailing slash, then the contents of the source directory are copied rather than the source directory itself. The same comments regarding the `DESTINATION` and `TYPE` arguments apply to this form as for installing files.

```

# Results in somewhere/blah/...
install(DIRECTORY blah DESTINATION somewhere)

# Results in somewhere/...
install(DIRECTORY blah/ DESTINATION somewhere)

```

The `COMPONENT`, `EXCLUDE_FROM_ALL`, `OPTIONAL` and `CONFIGURATIONS` options have the same meaning as for other `install()` commands. The `MESSAGE_NEVER` option prevents the log message for each file installed, but one could argue that this should not be used for consistency with messages for all other installed contents.

A few options are supported for controlling the permissions of files and directories separately. If `USE_SOURCE_PERMISSIONS` is given, each file installed will retain the same permissions as its source. `FILE_PERMISSIONS` overrides that and uses the specified permissions instead. If neither option is given, files will have the same default permissions as if the `install(FILE)` command had been used. For directories created by the `install`, the `DIRECTORY_PERMISSIONS` option can be used to override the defaults, which are the same as for files except execute permissions are also added.

The remaining options allow the set of files to be filtered according to one or more wildcard patterns or regular expressions. Each pattern or regex is tested against the full path to each file and directory (always specified with forward slashes, even on Windows). Wildcard patterns must match the end of the full path, not just some portion in the middle, whereas a regex can match any part of the path and is therefore more flexible. If the pattern or regex is followed by the `EXCLUDE` keyword, then all matching files and directories will not be installed. This is a useful way of excluding just a few specific things from the directory tree. The reverse can also be implemented by giving the `FILES_MATCHING` keyword (once) before any `PATTERN` or `REGEX` blocks, which then means only those files and directories that *do* match one of the patterns or regexes will be installed. If neither `FILES_MATCHING` nor `EXCLUDE` is given, then the only effect of the pattern or regex is to override the permissions with a `PERMISSIONS` block.

Some examples should help clarify the above points. The following example adapted slightly from the CMake documentation installs all headers from the `src` directory and below, preserving the directory structure.

```
install(DIRECTORY src/
        DESTINATION include
        FILES_MATCHING
        PATTERN *.h
    )
```

The following installs documentation, skipping over some common hidden files:

```
install(DIRECTORY doc/ todo/ licenses
        DESTINATION doc
        REGEX \\.(DS_Store|svn) EXCLUDE
    )
```

The next example installs sample code and scripts, ensuring the latter have executable permission:

```
install(DIRECTORY src/
        DESTINATION samples
        FILES_MATCHING
        REGEX "example\\.(h|c|cpp|cxx)"
        PATTERN *.txt
        PATTERN *.sh
        PERMISSIONS OWNER_READ OWNER_WRITE OWNER_EXECUTE
                    GROUP_READ GROUP_EXECUTE
                    WORLD_READ WORLD_EXECUTE
    )
```

The example below omits any `FILES_MATCHING` or `EXCLUDE` options so that patterns and regexes only modify permissions and not filter the list of files and directories:

```
install(DIRECTORY admin_scripts  
        DESTINATION private  
        PATTERN *.sh  
        PERMISSIONS OWNER_READ OWNER_WRITE OWNER_EXECUTE  
                  GROUP_READ GROUP_EXECUTE  
)
```

In all cases, `install(DIRECTORY)` preserves the directory structure of the source. If the list of sources is empty, the `DESTINATION` will still be created as an empty directory.

```
install(DIRECTORY DESTINATION somewhere/emptyDir)
```

35.6. Installing C++20 Modules



CMake 3.28 is the first version to support C++20 modules. That support is incomplete, and installing modules is an area which exposes a number of shortcomings in CMake's partial support, and in the toolchains.

Before C++20 modules, installing a library that other projects should be able to use and link to would mean that header files defining the library's API also had to be installed. Consuming code would only need the headers during compilation, and only need the library (or its associated import or stub library) at link time.

With C++20 modules, things get more complicated. When compiling code that imports a module from the library, the consumer needs a BMI (built module interface) file for that module, not a header file. The complication comes from how that BMI is provided. Either the installed library provides the BMI directly, or the consumer has to compile one for itself from sources that were installed along with the library.

It would be understandable to think it would be preferable and easier for the library to provide the BMI to its consumers. Unfortunately, that will almost never work. Currently, toolchains tend to be very sensitive to the flags used when building and consuming BMIs. If a consumer doesn't ensure it is building with flags that are compatible with those used when the BMI was built, the compiler will reject the BMI and the build will fail. Some toolchains even require the exact same compiler and compiler version to be used. These constraints are highly restrictive for consumers, and they are unlikely to be satisfied in most cases. Therefore, installing BMIs will rarely be useful for typical scenarios with today's toolchains.

A far more promising approach is for the library to install the sources that the consumer needs to generate its own BMIs. These sources don't need to implement the module, they only need to define its interface. This is very similar to how a non-module library installs headers to define its API, but the library does not have to (and usually doesn't) provide the implementation of that API.

CMake supports both choices for projects that install a library exporting C++20 modules. In fact, both strategies can be used simultaneously. Given the above discussion though, installing BMIs should be considered

questionable, while installing module interface sources should be mandatory.

The example given back in [Section 23.5.3, “Additional Complications With C++20 Modules”](#) illustrates how a separation of interface and implementation may look for C++20 module code. The relevant part of the `CMakeLists.txt` file for that example is reproduced here for easier reference:

```
add_library(Algo SHARED)
target_sources(Algo
PRIVATE
    algo-impl.cpp
PUBLIC
    FILE_SET CXX_MODULES
    FILES
        algo-interface.cppm
)
target_compile_features(Algo PUBLIC cxx_std_20)
```

In this example, the library would need to install `algo-interface.cppm` as a module source, but not `algo-impl.cpp`. This is done by installing the `CXX_MODULES` file set, which is done the same way as installing a `HEADERS` file set. Unlike for `HEADERS` though, there is no default destination for `CXX_MODULES`, so a `DESTINATION` option must be given. The `install(EXPORTS)` command also needs to have a `CXX_MODULES_DIRECTORY` option specifying where to install extra module-related files CMake will generate.

```
install(TARGETS Algo
        EXPORT Algo
```

```

FILE_SET CXX_MODULES
  DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/my_package/src
  ... # Other things to install
)
install(EXPORT Algo
  DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/my_package
  FILE algo-targets.cmake
  CXX_MODULES_DIRECTORY algo
)

```

There is not yet any consensus on where packages should install their module-related files. In the `install(EXPORT)` command, the `CXX_MODULES_DIRECTORY` is treated as being relative to the `DESTINATION`, so it will always be a subdirectory below where the export file is installed. Prior to CMake 3.28.2, the files written to the `CXX_MODULES_DIRECTORY` had file names that were not specific to the export set. If multiple export sets were installed, they would have to use different `CXX_MODULES_DIRECTORY` locations to avoid overwriting each other. With CMake 3.28.2 or later, the generated files have names that are specific to each export set, so they can be installed to the same location. Projects may wish to install to a subdirectory named after the export set, like in the above example, if they need to support CMake 3.28.0 or 3.28.1.

When installing `CXX_MODULES` file sets, the `DESTINATION` isn't restricted to being under the export location, but it may make sense to put them under there. This will collect all module-related files in the one area. This also has the advantage of ensuring that all module-related files, including interface sources, are under `${CMAKE_INSTALL_LIBDIR}`, which may be an architecture-specific location. If needed, the project can then install different variations of the module interface sources for each

architecture. That may be one strategy to avoid the need for compiler definitions to enable or disable sections of a file based on the target architecture.

The above is all that is needed for the installed library to allow consumers to use the library's modules. When building the consumer, CMake will have the information it needs to be able to generate a BMI for the modules in the installed `CXX_MODULES` file set. The consumer will use the same flags when generating that BMI (with some caveats) as when building the rest of the project, so this usually avoids the problem of incompatible BMIs. The consumer does have to use the same C++ language standard as the installed library though, since that information is part of what CMake installs with the file set, and also what CMake uses when the consumer generates BMIs for it.

While not recommended, a project can install BMIs with the library too. This is achieved by adding the `CXX_MODULES_BMI` entity type to the `install(TARGETS)` command. There is no default destination for installing BMIs, so a `DESTINATION` must be provided. The example can be extended to install BMIs as well as the interface sources like so:

```
install(TARGETS Also
        EXPORT Algo
        FILE_SET CXX_MODULES
        DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/my_package/src
        CXX_MODULES_BMI
        DESTINATION
        ${CMAKE_INSTALL_LIBDIR}/cmake/my_package/bmi-$<CONFIG>
        ... # Other things to install
)
```

Note how the destination includes `$<CONFIG>` to ensure that the BMI for each installed configuration goes to a different directory. The file name of a BMI will typically be fixed, so the only way to prevent overwriting BMIs for different configurations is to put them in separate directories. And since a BMI is a built binary, it will definitely be specific to the architecture, so installing it to a location under `${CMAKE_INSTALL_LIBDIR}` is advisable.

When a consumer encounters a library that has both the module interface sources and a BMI installed, CMake currently ignores the BMI and builds its own. To understand why, consider the situation for a shared library that provides a module as part of its API. When controlling symbol visibility, the code has to distinguish between two scenarios: compiling code to put *into* the shared library, and compiling code that *uses* the shared library. When compiling code into the shared library, symbols must be exported, whereas compiling for using the shared library requires importing the symbols. The distinction between these two cases is typically controlled with a compiler definition, as previously presented in [Section 23.5.3, “Additional Complications With C++20 Modules”](#). But BMIs lock in the compiler flags and definitions *as they were when the BMI was built*. If the BMI created when building the shared library is used by a consumer, the consumer will see a BMI that exports symbols instead of importing them. While some toolchains may handle this transparently, it may also cause problems or performance issues. By ignoring the installed BMI and building one from the installed module interface sources instead, CMake avoids problems like this, and it has a much higher chance of using a compatible BMI when building the consumer.

35.7. Custom Install Logic

Sometimes simply copying things into the install area isn't enough. Arbitrary processing may need to be performed as part of the install, such as rewriting parts of a file or generating content programmatically. For these cases, CMake supports adding custom logic to the install step.

```
install(SCRIPT fileName | CODE cmakeCode
        [ALL_COMPONENTS | COMPONENT component]
        [EXCLUDE_FROM_ALL]
)
```

The `CODE` form can be used to embed CMake commands directly as a single string, whereas the `SCRIPT` form will use `include()` to read in the script at install time. The `COMPONENT` and `EXCLUDE_FROM_ALL` options have their usual meanings. CMake 3.21 added support for the `ALL_COMPONENTS` option, which has the effect of executing the custom script or code for every component in a component-based install. It is an error to specify both `ALL_COMPONENTS` and `COMPONENT`.

With CMake 3.13 or earlier, it is unspecified at what point during installation the custom code runs. Generally, `install()` commands are processed in the order they appear in the directory scope, but this does not extend to `install()` calls nested within subdirectories. With CMake 3.14 or later, the order is clearly defined and is controlled by policy `CMP0082`. When this policy is set to `NEW`, install commands are executed in the order they are declared, including accounting for descending into subdirectories. Consider the following example:

```
install(CODE [[ message("Main A") ]])
add_subdirectory(subInstall)
install(CODE [[ message("Main B") ]])
```

subInstall/CMakeLists.txt:

```
install(CODE [[ message("subdir X") ]])
install(CODE [[ message("subdir Y") ]])
```

With policy **CMP0082** unset or set to **OLD**, the output during install would likely contain the following:

```
Main A
Main B
subdir X
subdir Y
```

With policy **CMP0082** set to **NEW**, the order is clearly defined and the installation output would contain:

```
Main A
subdir X
subdir Y
Main B
```

Multiple **SCRIPT** and/or **CODE** blocks can be given, in which case they will be executed in order. The rest of the options can only be specified at most once.

```
install(CODE      [[ message("Starting custom script") ]])
           SCRIPT    myCustomLogic.cmake
           CODE      [[ message("Finished custom script") ]]
```

```
COMPONENT MyProj_Runtime  
)
```

With CMake 3.14 or later, the contents given with `CODE` or the name of the file provided for `SCRIPT` can contain generator expressions (only the file name/path, not the file's contents). This requires policy `CMP0087` to be set to `NEW`, but unlike most other policies, it is the policy's setting at the end of the directory scope that determines the behavior. The value of the `CMP0087` policy when the `install()` command is called is not relevant. This is because CMake defers processing the contents until the end of the directory scope, not immediately as part of the `install()` command.

35.8. Installing Dependencies

When creating packages, a common desire is to make them self-contained. This can extend to including not just the project's own build artifacts, but also external dependencies such as compiler runtime libraries. CMake provides some features which can potentially make this task easier.

35.8.1. Runtime Dependency Sets

CMake 3.21 added direct support to `install()` sub-commands for automatically determining external runtime dependencies and adding them as installed artifacts. The `install(TARGETS)` and `install(IMPORTED_RUNTIME_ARTIFACTS)` sub-commands both support a `RUNTIME_DEPENDENCY_SET` keyword. When `RUNTIME_DEPENDENCY_SET` is given, both sub-commands will add their targets to the named set. The following sub-command is then used to

automatically install all externally provided runtime artifacts needed by any targets in that set:

```
install(RUNTIME_DEPENDENCY_SET setName
        [ entityType]
        [DESTINATION dir]
        [PERMISSIONS permissions...]
        [COMPONENT component]
        [NAMELINK_COMPONENT component]
        [EXCLUDE_FROM_ALL]
        [OPTIONAL]
        [CONFIGURATIONS configs...]
    ]...
    [PRE_INCLUDE_REGEXES regexes...]
    [PRE_EXCLUDE_REGEXES regexes...]
    [POST_INCLUDE_REGEXES regexes...]
    [POST_EXCLUDE_REGEXES regexes...]
    [POST_INCLUDE_FILES files...]
    [POST_EXCLUDE_FILES files...]
    [DIRECTORIES directories...]
)
```

If `entityType` is given, it can only be `LIBRARY`, `RUNTIME` or `FRAMEWORK`, since these are the only type of runtime artifacts that targets can link to. The details following an `entityType` apply to the dependencies that are found, not to the targets in the runtime dependency set. The keywords following `entityType` have the same meaning and effect as for `install(TARGETS)`. As usual, `entityType` can be omitted and the keywords that follow it will apply to all dependency entity types.

The `PRE_...`, `POST_...` and `DIRECTORIES` arguments are forwarded through to an internal call to `file(GET_RUNTIME_DEPENDENCIES)`,

which is used to compute the dependencies of the targets in the set. The official documentation for `file(GET_RUNTIME_DEPENDENCIES)` provides a detailed explanation of these options, so it is not repeated here. Since `file(GET_RUNTIME_DEPENDENCIES)` only supports finding dependencies for Windows, Linux, and macOS target platforms, the same limitations apply to `install(RUNTIME_DEPENDENCY_SET)`. The `file(GET_RUNTIME_DEPENDENCIES)` command is also known to have problems that prevent it from being used in common cross-compiling scenarios. See the following issue for further details:

<https://gitlab.kitware.com/cmake/cmake/-/issues/20753>

The following is a minimal example showing the steps for installing an application and its external dependencies to the default install locations:

```
add_executable(MyApp ...)

install(TARGETS MyApp RUNTIME_DEPENDENCY_SET appDeps ...)
install(RUNTIME_DEPENDENCY_SET appDeps)
```

The `install(TARGETS)` sub-command also provides a `RUNTIME_DEPENDENCIES` option. This combines the two `install()` calls, using a random, internally generated runtime dependency set name:

```
install(TARGETS MyApp RUNTIME_DEPENDENCIES ...)
```

Both forms of the command search for *all* dependencies of targets in the runtime dependency set. This will add system libraries to the set of dependencies to install, which is usually undesirable. Even for a simple

"hello world" executable, building with GCC for a Linux desktop system may add system libraries to satisfy dependencies like `libc.so.6`, `libgcc_s.so.1`, `libm.so.6`, and `libstdc++.so.6`. The `PRE_EXCLUDE_REGEXES` option can be used to skip these dependencies:

```
add_executable(MyApp main.cpp)

install(TARGETS MyApp
        RUNTIME_DEPENDENCY_SET appDeps
)
install(RUNTIME_DEPENDENCY_SET appDeps
        PRE_EXCLUDE_REGEXES
        [[libc\.so\..*]]
        [[libgcc_s\.so\..*]]
        [[libm\.so\..*]]
        [[libstdc\+\+\.\so\..*]])
)
```

A similar situation exists on Windows, where the runtime API sets will be added to the dependencies. These should not be installed, they are abstractions for libraries that will be provided by the operating system. These can be excluded in a similar way (this is just an example, projects will want to tweak the set of regular expressions to suit their needs):

```
install(RUNTIME_DEPENDENCY_SET appDeps
        PRE_EXCLUDE_REGEXES
        [[api-ms-win-.*]]
        [[ext-ms-.*]]
        [[kernel32\.dll]]
        POST_EXCLUDE_REGEXES
        [[.*(\\\|/)system32(\\\|/).*\.\dll]])
)
```

Unfortunately, CMake doesn't provide consistent handling of path separators when performing the regular expression matching. A mix of path separators may be encountered even within a path to a single dependency. Therefore, projects should match both forward slashes and backslashes anywhere a path separator is used in a regular expression intended for Windows.

In some cases, a dependency may itself require further libraries. The `file(GET_RUNTIME_DEPENDENCIES)` command is able to resolve these recursively, including following RPATH locations where appropriate. A common problem though is that an RPATH can contain special strings like `$ORIGIN`. `file(GET_RUNTIME_DEPENDENCIES)` does not handle these and will ignore them, which can lead to some dependencies not being found. A workaround on Linux is to manually specify additional places for the command to look using the `DIRECTORIES` keyword of `install(RUNTIME_DEPENDENCY_SET)`. This can lead to warnings, but will at least allow the operation to succeed.

35.8.2. `InstallRequiredSystemLibraries` Module

The `InstallRequiredSystemLibraries` module is intended to provide projects with the details of relevant run time libraries for the major compilers. It is much more mature than the runtime dependency set support, but also more restricted in the type of dependencies it can install. The module provides compiler runtimes for Intel (all major platforms) and Visual Studio (Windows only). Using the module is fairly straightforward, with projects either choosing to let the module define the `install()`

commands on its behalf, or it can ask for the relevant variables to be populated so it can create the necessary commands for itself. In the simplest case, projects can rely on the defaults, although setting at least the component for the `install()` commands is recommended.

```
set(CMAKE_INSTALL_SYSTEM_RUNTIME_COMPONENT MyProj_Runtime)
include(InstallRequiredSystemLibraries)
```

The default install locations are `bin` for Windows and `lib` for all other platforms. This is likely to match the typical install layout of most projects, but it can be overridden with the `CMAKE_INSTALL_SYSTEM_RUNTIME_DESTINATION` variable:

```
include(GNUInstallDirs)
if(WIN32)
    set(CMAKE_INSTALL_SYSTEM_RUNTIME_DESTINATION
        ${CMAKE_INSTALL_BINDIR})
)
else()
    set(CMAKE_INSTALL_SYSTEM_RUNTIME_DESTINATION
        ${CMAKE_INSTALL_LIBDIR})
)
endif()

set(CMAKE_INSTALL_SYSTEM_RUNTIME_COMPONENT
    MyProj_Runtime
)
include(InstallRequiredSystemLibraries)
```

If a project wants to define the `install()` commands itself, it needs to set `CMAKE_INSTALL_SYSTEM_RUNTIME_LIBS_SKIP` to true before including the module. The project can then access the list of runtime

libraries using the `CMAKE_INSTALL_SYSTEM_RUNTIME_LIBS` variable:

```
set(CMAKE_INSTALL_SYSTEM_RUNTIME_LIBS_SKIP TRUE)
set(CMAKE_INSTALL_SYSTEM_RUNTIME_COMPONENT MyProj_Runtime)
include(InstallRequiredSystemLibraries)

include(GNUInstallDirs)
if(WIN32)
    install(FILES ${CMAKE_INSTALL_SYSTEM_RUNTIME_LIBS}
        DESTINATION ${CMAKE_INSTALL_BINDIR})
)
else()
    install(FILES ${CMAKE_INSTALL_SYSTEM_RUNTIME_LIBS}
        DESTINATION ${CMAKE_INSTALL_LIBDIR})
)
endif()
```

When using Intel compilers, the default `install()` commands install more than just the contents of `CMAKE_INSTALL_SYSTEM_RUNTIME_LIBS`. They also install some directories not provided to the project through any documented variable. For those developers interested in exploring whether these additional contents are desirable or not, search for `CMAKE_INSTALL_SYSTEM_RUNTIME_DIRECTORIES` in the module's implementation to see how these additional contents are constructed.

Some further controls are available when using Visual Studio compilers to install various other run time components, such as Windows Universal CRT, MFC and OpenMP libraries. The installation of debug versions of runtime libraries can also be enforced. These are all described clearly in the

module's documentation, so the interested reader is referred to there for further details.

35.8.3. BundleUtilities And GetPrerequisites

Another pair of modules can also be used to install a project's run time dependencies. The `BundleUtilities` and `GetPrerequisites` modules can be thought of as forerunners to the run time dependency set approach. These two modules directly interrogate the installed binaries using platform-specific tools and recursively copy in missing libraries. These modules can be considerably more difficult to use and should be avoided where either of the approaches presented above can be used.

35.9. Writing A Config Package File

The preferred way for an installed project to make itself available for other CMake projects to consume is to provide a config package file. This file is found by consuming projects using the `find_package()` command, as introduced back in [Section 34.4, “Finding Packages”](#). The name of the config file must match either `<packageName>Config.cmake` or `<lowercasePackageName>-config.cmake`. The former is perhaps a little more common and is consistent with other functionality provided by CMake discussed further below, but both are otherwise equivalent. The file is expected to provide imported targets for all the libraries and executables the installed project wants to make available.

The directory into which the config file is installed should be one of the default locations that `find_package()` will search if the base point of

the install is added to the `CMAKE_PREFIX_PATH` variable. This ensures that the config file will be easy to find. From [Section 34.4, “Finding Packages”](#), the full set of search locations is:

```
<prefix>/  
<prefix>/(cmake|CMake)/  
<prefix>/<packageName>*/  
<prefix>/<packageName>*/(cmake|CMake)/  
<prefix>/<packageName>*/(cmake|CMake)/<packageName>*/  
<prefix>/(lib/<arch>|lib*|share)/cmake/<packageName>*/  
<prefix>/(lib/<arch>|lib*|share)/<packageName>*/  
<prefix>/(lib/<arch>|lib*|share)/<packageName>*/(cmake|CMake)/  
<prefix>/<packageName>*/(lib/<arch>|lib*|share)/cmake/<packageName>*/  
<prefix>/<packageName>*/(lib/<arch>|lib*|share)/<packageName>*/(cmake|CMake)/
```

On Apple platforms, the following subdirectories may also be searched:

```
<prefix>/<packageName>.framework/Resources/  
<prefix>/<packageName>.framework/Resources/CMake/  
<prefix>/<packageName>.framework/Versions/*/Resources/  
<prefix>/<packageName>.framework/Versions/*/Resources/CMake/  
<prefix>/<packageName>.app/Contents/Resources/  
<prefix>/<packageName>.app/Contents/Resources/CMake/
```

That’s a large set of candidates, but the best choice depends somewhat on how the project expects to be installed. When packaging for inclusion in a Linux distribution, the distribution itself may have policies for where such files are expected to be. Rather than forcing each distribution to carry its own patches to the project to ensure the config file is installed according to its policies, projects should ideally provide a way to pass the required

details into the build. A cache variable is ideal for this purpose, since the project can specify a default, but it can be overridden without having to change the project at all. In the absence of any other constraints, two very simple and commonly used locations are `<prefix>/cmake` and `<prefix>/lib/cmake/<packageName>`, with variations on the latter being a little friendlier to multi-architecture deployments (see examples below).

For projects that provide an `Android.mk` file from an `install(EXPORT_ANDROID_MK)` command, CMake has no specific convention for its location. A reasonable arrangement would be to use a dedicated `ndk-build` directory within the package layout, but it is ultimately up to the project.

35.9.1. Config Files For CMake Projects

For simple CMake projects that use only a single export set and have no dependencies, the `install(EXPORT)` command can be used to create a basic config file directly. The install destination of that file should use the variables defined by the `GNUInstallDirs`, which simplifies customization by Linux distributions and other packaging systems.

```
# Use the export file directly as the package config file
# (NOT GENERALLY RECOMMENDED)
include(GNUInstallDirs)
install(EXPORT MyProj
    DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/MyProj
    NAMESPACE MyProj::
    FILE MyProjConfig.cmake
)
```

In practice, the config file is not normally directly generated like this. More typically, a separate config file is prepared which brings in exported files via `include()` commands. A slightly expanded example using two export sets demonstrates the technique:

CMakeLists.txt

```
include(GNUInstallDirs)
install(EXPORT MyProj_Runtime
      DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/MyProj
      NAMESPACE MyProj::
      FILE MyProj_Runtime.cmake
      COMPONENT MyProj_Runtime
)

install(EXPORT MyProj_Development
      DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/MyProj
      NAMESPACE MyProj::
      FILE MyProj_Development.cmake
      COMPONENT MyProj_Development
)

install(FILES MyProjConfig.cmake
      DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/MyProj
)
```

MyProjConfig.cmake

```
include(${CMAKE_CURRENT_LIST_DIR}/MyProj_Runtime.cmake)
include(${CMAKE_CURRENT_LIST_DIR}/MyProj_Development.cmake)
```

The above `MyProjConfig.cmake` is still very simple. No externally provided dependencies are needed. It is also assumed that the runtime and the development components are always both installed. Consider then a scenario where the runtime component depends on some other package named `BagOfBeans`. The config file is responsible for ensuring that the

required targets from `BagOfBeans` are available, which it typically does by calling `find_package()`. As a convenience, the `find_dependency()` macro from the `CMakeFindDependencyMacro` module can be used as a wrapper around `find_package()` to handle the `QUIET` and `REQUIRED` keywords. The `find_dependency()` macro also has the behavior that if it fails to find the requested package, processing of the config file ends as though a `return()` call was made immediately after the failed `find_dependency()` call. In practice, this results in simple, clean specification of dependencies with graceful handling of dependency failures.

MyProjConfig.cmake

```
include(CMakeFindDependencyMacro)
find_dependency(BagOfBeans)

include(${CMAKE_CURRENT_LIST_DIR}/MyProj_Runtime.cmake)
include(${CMAKE_CURRENT_LIST_DIR}/MyProj_Development.cmake)
```

Be aware that prior to CMake 3.15, `find_dependency()` contained an optimization that bypassed the call if it detected that the requested package had previously been found. This optimization worked fine unless later calls needed to request a different set of package components. The first time `find_dependency()` succeeds, the pre-3.15 behavior effectively locks in the set of components found. If later calls to `find_dependency()` pass a different set of components, they would be ignored. Because `find_dependency()` calls are typically made within files that are installed for other projects to use, it usually cannot be guaranteed what

CMake version will ultimately be used. Therefore, if the dependency supports package components, projects should avoid `find_dependency()` and call `find_package()` directly, handling the QUIET and REQUIRED options themselves. These two options are passed to the config file as the variables `_${CMAKE_FIND_PACKAGE_NAME}_FIND_QUIETLY` and `_${CMAKE_FIND_PACKAGE_NAME}_FIND_REQUIRED`. Always use `_${CMAKE_FIND_PACKAGE_NAME}` rather than hard-coding the package name, because there may be upper/lowercase differences.

```
unset(extraArgs)

if(${CMAKE_FIND_PACKAGE_NAME}_FIND_QUIETLY)
    list(APPEND extraArgs QUIET)
endif()
if(${CMAKE_FIND_PACKAGE_NAME}_FIND_REQUIRED)
    list(APPEND extraArgs REQUIRED)
endif()

find_package(BagOfBeans
    COMPONENTS Cheap Expensive
    ${extraArgs}
)
```

If the project wants to support some of its own components being optional, the config file complexity increases significantly. A set of steps to support this can be summarized as follows:

- Build up the set of components to find. Start with the required and optional components given to `find_package()` and add any that are needed to satisfy project dependencies.

- Work out the external dependencies needed by that set of components. Some will be mandatory, others may be optional, so two separate external dependency sets will need to be derived.
- Find the external dependencies and if any required dependencies fail to load, the project find operation must also fail and control should return immediately with an appropriate error message. Missing optional external dependencies should not cause failure or an error message.
- Update the set of project components to remove any that depend on a missing optional external dependency. This may require further culling of the project component set if the removed components are themselves dependencies of other components.
- Load the project components that remain.

Projects also need to decide what to do if no components are specified at all. This could be treated as though all components had been specified as optional components or even as required components. Another strategy is to load the minimal set of essential components and omit all others. The most appropriate strategy will depend on the nature of the project's components. The set of requested components will be available in the `_${CMAKE_FIND_PACKAGE_NAME}_FIND_COMPONENTS` variable, and if a component was specified as being required rather than optional, `_${CMAKE_FIND_PACKAGE_NAME}_FIND_REQUIRED_<comp>` will be true for that component.

Config files should not report errors using `message()`, they should instead store the error message in a variable named

`_${CMAKE_FIND_PACKAGE_NAME}_NOT_FOUND_MESSAGE`. This will be picked up by `find_package()`, which will wrap it with details about where in the project the error was raised. `_${CMAKE_FIND_PACKAGE_NAME}_FOUND` should also be set to false to indicate failure. This allows `find_package()` to properly implement a call that does not use the REQUIRED keyword. If the package config file called `message(FATAL_ERROR ...)`, the package could never be treated as optional.

Another often neglected but highly recommended practice is to avoid creating any imported targets before first checking whether the required components can be satisfied. This prevents imported targets from being created for some components but not others in the event of a failure.

The following example demonstrates how to incorporate the above points. Note the impact of using `if(...IN_LIST...)` in this case, which requires additional checking at the beginning to handle CMake versions 3.2 and older. Projects may wish to avoid using `IN_LIST` and implement equivalent logic using `list(FIND)` instead. `IN_LIST` is used in the example mostly to raise awareness of its consequences and to show how to use it safely in config files.

```
# We use if(...IN_LIST...), make sure it is available
if(CMAKE_VERSION VERSION_LESS 3.3)
    set(${CMAKE_FIND_PACKAGE_NAME}_NOT_FOUND_MESSAGE
        "MyProj requires CMake 3.3 or later"
    )
    set(${CMAKE_FIND_PACKAGE_NAME}_FOUND FALSE)
    return()
endif()
```

```

cmake_minimum_required(VERSION 3.3...3.21)

# Work out the set of components to load
if(${CMAKE_FIND_PACKAGE_NAME}_FIND_COMPONENTS)
    set(comps
        ${${CMAKE_FIND_PACKAGE_NAME}_FIND_COMPONENTS}
    )
    # Ensure Runtime is included if Development was given
    if(Development IN_LIST comps AND
        NOT Runtime IN_LIST comps)
        list(APPEND comps Runtime)
    endif()
else()
    # No components given, look for all components
    set(comps Runtime Development)
endif()

# Find external dependencies, storing comps in a safer
# variable name. In this example, BagOfBeans is required
# by the mandatory Runtime component.
set(${CMAKE_FIND_PACKAGE_NAME}_comps ${comps})
include(CMakeFindDependencyMacro)
find_dependency(BagOfBeans)

# Check all required components are available before
# trying to load any
foreach(comp IN LISTS ${CMAKE_FIND_PACKAGE_NAME}_comps)
    set(compFile
        ${CMAKE_CURRENT_LIST_DIR}/MyProj_${comp}.cmake
    )
    if(${CMAKE_FIND_PACKAGE_NAME}_FIND_REQUIRED_${comp} AND
        NOT EXISTS ${compFile})
        set(${CMAKE_FIND_PACKAGE_NAME}_NOT_FOUND_MESSAGE
            "MyProj missing required component: ${comp}"
        )
        set(${CMAKE_FIND_PACKAGE_NAME}_FOUND FALSE)
        return()
    endif()
endforeach()

foreach(comp IN LISTS ${CMAKE_FIND_PACKAGE_NAME}_comps)

```

```

# All required components are known to exist.
# The OPTIONAL keyword allows the non-required
# components to be missing without error.
include(${CMAKE_CURRENT_LIST_DIR}/MyProj_${comp}.cmake
    OPTIONAL
)
endforeach()

```

A close companion to the config file is its associated version file. If a version file is provided, it must be in the same directory and have a name conforming to either <packageName>ConfigVersion.cmake or <lowercasePackageName>-config-version.cmake. The form of the version file name generally follows the same form as its associated config file (i.e. AlgoConfigVersion.cmake would go with AlgoConfig.cmake, whereas algo-config-version.cmake would typically be paired with algo-config.cmake).

The purpose of the version file is to inform `find_package()` whether the package meets the specified version requirements. `find_package()` sets a number of variables before the version file is loaded:

- `PACKAGE_FIND_NAME`
- `PACKAGE_FIND_VERSION`
- `PACKAGE_FIND_VERSION_MAJOR`
- `PACKAGE_FIND_VERSION_MINOR`
- `PACKAGE_FIND_VERSION_PATCH`
- `PACKAGE_FIND_VERSION_TWEAK`

- PACKAGE_FIND_VERSION_COUNT

These variables contain the version details specified as the `version` argument to `find_package()`. If no such argument was given, then `PACKAGE_FIND_VERSION` will be empty and the other `PACKAGE_FIND_VERSION_*` variables will be set to 0. `PACKAGE_FIND_VERSION_COUNT` holds the number of version components that were specified. The rest of the variables have their obvious meaning.

If the `find_package()` call specified a version *range* rather than just a single version, the above version-related variables refer to the lower end of the version range and the following variables will also be set:

- PACKAGE_FIND_VERSION_RANGE
- PACKAGE_FIND_VERSION_RANGE_MIN
- PACKAGE_FIND_VERSION_RANGE_MAX
- PACKAGE_FIND_VERSION_MIN
- PACKAGE_FIND_VERSION_MIN_MAJOR
- PACKAGE_FIND_VERSION_MIN_MINOR
- PACKAGE_FIND_VERSION_MIN_PATCH
- PACKAGE_FIND_VERSION_MIN_TWEAK
- PACKAGE_FIND_VERSION_MIN_COUNT
- PACKAGE_FIND_VERSION_MAX

- PACKAGE_FIND_VERSION_MAX_MAJOR
- PACKAGE_FIND_VERSION_MAX_MINOR
- PACKAGE_FIND_VERSION_MAX_PATCH
- PACKAGE_FIND_VERSION_MAX_TWEAK
- PACKAGE_FIND_VERSION_MAX_COUNT

CMake 3.19 or later will also set PACKAGE_FIND_VERSION_COMPLETE if a version or version range was given. This will be the exact version specification as provided to `find_package()`.

The version file needs to check the requested details against the actual version of the package and then set the following variables:

PACKAGE_VERSION

This is the actual package version, which is expected to be in the usual *major.minor.patch.tweak* format (not all components are required).

PACKAGE_VERSION_EXACT

Only set to true if the package version and the requested version are an exact match.

PACKAGE_VERSION_COMPATIBLE

Only set to true if the package version is compatible with the requested version details. It is up to the package itself how it determines compatibility. For projects that follow semantic versioning principles as

covered back in [Section 23.3, “Shared Library Versioning”](#), the variable would be set according to the following rules:

- If any version component is missing, treat it as 0.
- If the *major* version components are different, the result is false.
- If the *major* version components are the same, the result is false if the *minor* version component of the package is less than the one required.
- If the *major* and *minor* version components are the same, the result is false if the *patch* version component of the package is less than the one required.
- If the *major*, *minor* and *patch* version components are the same, the result is false if the *tweak* version component of the package is less than the one required.
- For all other cases, the result is set to true.

PACKAGE_VERSION_UNSUITABLE

Only set to true if the version file needs to indicate that the package cannot satisfy any version requirement (basically the package doesn't have a version number, so any version requirement should be treated as a failure).

The `find_package()` command will use this information to pass back the following variables to its caller, all of which are analogous to the similar ones it passed in to the version file (the returned values here will be the actual version of the package, not the version requirements passed to the `find_package()` command):

- <packageName>_VERSION
- <packageName>_VERSION_MAJOR
- <packageName>_VERSION_MINOR
- <packageName>_VERSION_PATCH
- <packageName>_VERSION_TWEAK
- <packageName>_VERSION_COUNT

While projects are free to manually create a version file, a much simpler and most likely more robust approach is to use the `write_basic_package_version_file()` command provided by the `CMakePackageConfigHelpers` module:

```
write_basic_package_version_file(outFile
    [VERSION requiredVersion]
    COMPATIBILITY compat
    [ARCH_INDEPENDENT]    # Requires CMake 3.14 or later
)
```

If a `VERSION` argument is given, the `requiredVersion` is expected to be in the usual *major.minor.patch.tweak* form, but only the *major* part is compulsory. If the `VERSION` option is not given, the `PROJECT_VERSION` variable is used instead (as set by the `project()` command). The `COMPATIBILITY` option specifies a strategy for how the compatibility should be determined. The `compat` argument must be one of the following values (be aware that most of the names are a little misleading):

AnyNewerVersion

The package version must be equal to or greater than the specified version. Version ranges will be supported if CMake 3.19.0 or later is being used to write out the package version file.

SameMajorVersion

The package version must be equal to or greater than the specified version and the *major* part of the package version number must be the same as the one in the `requiredVersion`. This corresponds to the same compatibility requirements as semantic versioning. Note that this strategy will only support version ranges if CMake 3.19.2 or later is being used to write out the package version file.

SameMinorVersion

The package version must be equal to or greater than the specified version and the *major* and *minor* parts of the package version number must be the same as those in the `requiredVersion`. This choice is only supported with CMake 3.11 or later. This strategy will also only support version ranges if CMake 3.19.2 or later is being used to write out the package version file.

ExactVersion

The *major*, *minor* and *patch* parts of the package version number must be the same as those in the `requiredVersion`. The *tweak* part is ignored. This strategy is particularly misleading and discussions are in progress to potentially deprecate it in favor of a new, clearer strategy. It does not support version ranges.

The `ARCH_INDEPENDENT` option (available with CMake 3.14 or later) indicates that the package is architecture-independent. Normally, CMake will check that the package was built for the same architecture, typically by verifying that the package's binaries were built for the same pointer size, but specifying the `ARCH_INDEPENDENT` option disables the check.

Architecture-independent packages usually contain no binaries, since those are normally specific to a particular architecture (universal binaries supporting multiple architectures being a notable exception). Such packages often contain documentation, scripts, images and various other non-executable files. A package consisting of a header-only library could take advantage of this option to create a single package for all architectures.

The `CMakePackageConfigHelpers` module also provides the `configure_package_config_file()` command. It is intended to make it easier for projects to define a relocatable package by providing some path handling conveniences. It is not typically needed for most projects, but when the package config file needs to refer to installed files relative to the base install location rather than the location of the config file itself, it provides a simpler way to do so robustly. The command has the following form:

```
configure_package_config_file(inputFile outputFile
    INSTALL_DESTINATION path
    [INSTALL_PREFIX prefix]
    [PATH_VARS var1 [var2...] ]
    [NO_SET_AND_CHECK_MACRO]
    [NO_CHECK_REQUIRED_COMPONENTS_MACRO]
)
```

The command should be used as a replacement for `configure_file()` to copy a `<Project>Config.cmake.in` file with substitutions. It will replace variables of the form `@PACKAGE_<somevar>@` with the contents of `<somevar>` converted to an absolute path. The original contents are treated as being relative to the base install location. Each variable to be transformed in this way needs to be listed with the `PATH_VARS` option. For this functionality to work, the input file must have `@PACKAGE_INIT@` at or near the top before any use of the variables being replaced (see example further below).

The `INSTALL_DESTINATION` is the directory into which `outputFile` will be installed, relative to the `INSTALL_PREFIX`. When `INSTALL_PREFIX` is omitted, it defaults to `CMAKE_INSTALL_PREFIX`, which is usually the desired value. The `INSTALL_PREFIX` would normally only be provided if the `outputFile` will be used directly in a build tree rather than being installed (i.e. it is used in conjunction with an `export(EXPORT)` command).

The `NO_SET_AND_CHECK_MACRO` and `NO_CHECK_REQUIRED_COMPONENTS_MACRO` options prevent `@PACKAGE_INIT@` from defining some helper functions. Before imported targets became the preferred way to provide package targets, variables needed to be used. To facilitate this, a `set_and_check()` macro was provided by `configure_package_config_file()` which would only set a variable if it was not already defined. Projects providing imported

targets should not need this macro and can add the `NO_SET_AND_CHECK_MACRO` to prevent it being defined.

An example should help clarify the typical usage of this command. The package config file would be generated from an input file such as the following:

MyProjConfig.cmake.in

```
@PACKAGE_INIT@  
  
list(APPEND CMAKE_MODULE_PATH "@PACKAGE_cmakeModulesDir@")  
# Include the project's export files, etc...
```

This would then be transformed by the project into the final package config file, including an appropriate replacement for the `cmakeModulesDir` variable:

CMakeLists.txt

```
include(GNUInstallDirs)  
include(CMakePackageConfigHelpers)  
  
# This will be used to replace @PACKAGE_cmakeModulesDir@  
set(cmakeModulesDir cmake)  
configure_package_config_file(  
    MyProjConfig.cmake.in MyProjConfig.cmake  
    INSTALL_DESTINATION  
    ${CMAKE_INSTALL_LIBDIR}/cmake/MyProj  
    PATH_VARS  
    cmakeModulesDir  
    NO_SET_AND_CHECK_MACRO  
    NO_CHECK_REQUIRED_COMPONENTS_MACRO  
)  
install(  
    FILES ${CMAKE_CURRENT_BINARY_DIR}/MyProjConfig.cmake  
    DESTINATION ${CMAKE_INSTALL_LIBDIR}/cmake/MyProj
```

```
COMPONENT ...
)
```

In the past when all details about a package were provided through variables, it was customary to check whether all required variables were set at the end of the config file before returning. A macro called `check_required_components()` was defined for this purpose, but projects that provide imported targets should perform these checks themselves. The imported targets should only be created if all required components will be found. Otherwise, a failed `find_package()` call will still leave behind targets, which would interfere with any later call to `find_package()` for the same package name but with different arguments (e.g. to search in different locations). This makes the `check_required_components()` macro largely redundant.

CMake 3.29 and later also provides two more commands, `generate_apple_platform_selection_file()` and `generate_apple_architecture_selection_file()`. These Apple-specific commands act like `include()` command dispatchers. They allow the caller to essentially say "if targeting platform or architecture X, then include file Y". This can facilitate supporting multiple platforms and architectures with a single package. The commands are just a convenience though, the project can implement essentially the same logic with simple `if()` statements. A major disadvantage to using these convenience commands in a package's config file is that it would force all consumers to use CMake 3.29 or later. Therefore, consider carefully whether this constraint is worth it.

35.9.2. Config Files For Non-CMake Projects

The config file mechanism isn't restricted to projects built by CMake. It can also be used for non-CMake projects. While CMake projects can make use of CMake features to more easily create the required files, non-CMake projects have to define them manually. For such projects, it is important to keep the files simple, since they will likely be maintained by people less familiar with CMake.

A good first step is to initially forgo component support and just make the package available as a simple set of imported targets. For projects that only need to provide libraries, the following example shows a fairly basic config file that should serve as a good starting point. It includes a few different types of libraries for illustration purposes.

```
# Compute the base point of the install by getting the
# directory of this file and moving up the required number
# of directories
set(_IMPORT_PREFIX "${CMAKE_CURRENT_LIST_DIR}")
foreach(i RANGE 1 NumSubdirLevels)                                ①
    get_filename_component(
        _IMPORT_PREFIX "${_IMPORT_PREFIX}" PATH
    )
    if(_IMPORT_PREFIX STREQUAL "/")
        set(_IMPORT_PREFIX "")
        break()
    endif()
endforeach()

# Use a prefix specific to this project
set(projPrefix MyProj)

# Example of defining a static library imported target
add_library(${projPrefix}::MyStatic STATIC IMPORTED)
set_target_properties(${projPrefix}::MyStatic PROPERTIES
```

```

IMPORTED_LOCATION
    "${_IMPORT_PREFIX}/lib/libMyStatic.a"          ②
)

# Example of defining a shared library imported target with
# version details
add_library(${projPrefix}::MyShared SHARED IMPORTED)
set_target_properties(${projPrefix}::MyShared PROPERTIES
    IMPORTED_LOCATION
        "${_IMPORT_PREFIX}/lib/libMyShared.so.1.6.3" ③
    IMPORTED SONAME
        "libMyShared.so.1"                           ④
)

# Another shared library example, this time for Windows
add_library(${projPrefix}::MyDLL SHARED IMPORTED)
set_target_properties(${projPrefix}::MyDLL PROPERTIES
    IMPORTED_LOCATION
        "${_IMPORT_PREFIX}/bin/MyShared.dll"
    IMPORTED_IMPLIB
        "${_IMPORT_PREFIX}/lib/MyShared.lib"           ⑤
)

```

- ① `NumSubdirLevels` is how many directories this config file is below the base install point. For example, if the file is at `lib/cmake/Algo/AlgoConfig.cmake`, then `NumSubdirLevels` should be 3.
- ② The path to the library relative to the base install point (provided by `_IMPORT_PREFIX`).
- ③ The example shows how the shared library version number would be placed at the end of the file name for platforms such as Linux. This is obviously going to be platform specific.
- ④ For platforms that support sonames, `IMPORTED SONAME` is essentially the name that will be embedded in binaries that link to this target. On Apple platforms, this would typically have a form that includes `@rpath` and potentially some subdirectory components.
- ⑤ For Windows, the location of the import library associated with the DLL must also be provided for anything to be able to link to it. If the intention is only to provide the DLL (e.g. so it is available at run time, but not for directly linking against), the `IMPORTED_IMPLIB` can be omitted.

The above is quite basic, and obviously the various `IMPORTED_...` properties would need to be tailored for each platform. But the non-CMake project is free to use whatever mechanisms it finds convenient to produce the installed config file's contents. For added robustness, each imported library should only be added if it does not already exist, as the following demonstrates:

```
if(NOT TARGET ${projPrefix}::MyStatic)
    add_library(${projPrefix}::MyStatic STATIC IMPORTED)

    set_target_properties(${projPrefix}::MyStatic
        PROPERTIES
            IMPORTED_LOCATION
                "${_IMPORT_PREFIX}/lib/libMyStatic.a"
    )
endif()
```

35.10. Executing An Install

An install is typically done as part of creating a final package, but it can also be run on its own. Developers may wish to check the set of files included in an install and where they get installed to, so installing to a temporary staging area can be desirable. [Section 35.1.2, “Base Install Location”](#) already discussed how to do this by building the `install` target (or `INSTALL` for some generators).

CMake 3.15 added support for invoking an install directly without going through the build tool. The `--install` option can be given as the first argument on the `cmake` command line, followed by the top of the build directory for the CMake project to install. Other command-line arguments

control where to install to, which components to install, which build configuration to use (for multi-configuration generators), and whether to perform stripping before installation. Support for these options is one of the main reasons to use this method instead of building the `install` target. The following examples demonstrate the convenience and flexibility:

Check development component only with a specific build config

```
cmake --install /path/to/build/dir \
--prefix /path/to/staging/area \
--config Debug \
--component MyProj_Development
```

Install to a mounted device directory for testing, stripping binaries to reduce install size

```
cmake --install /path/to/build/dir \
--prefix /mnt/rpi4/staging \
--strip
```

It is also possible to do most of the above using `cmake -P` script mode with the `cmake_install.cmake` file at the top of the build directory, but it is less convenient and lacks a documented equivalent for `--strip`.

35.11. Recommended Practices

Installation is a non-trivial topic that requires good planning and an understanding of each intended deployment platform. It is common for a project to initially focus on only a subset of the intended set of platforms. But delaying any planning for installation and deployment can result in having to deal with unexpected complexities and platform differences late in a project's release cycle. Projects should have a clear understanding of

the installed file and directory structure, as well as the full set of packaging scenarios that will eventually be supported. This can strongly influence project structure, including such fundamental things as how functionality is split between libraries, and what symbols need to be visible in the binaries as a result.

Where possible, projects should prefer to follow standard package layouts. The `GNUInstallDirs` module greatly simplifies that task, even for packages on Windows. CMake 3.14 added support for default install locations based on the type of file or target being installed. Those defaults are based on the variables defined by `GNUInstallDirs`, so there is increasing momentum toward encouraging projects to use the package layout facilitated by that module. If a standard layout is not suitable, projects may still want to at least consider if a common directory structure can be used across all platforms to simplify application development.

Projects are strongly encouraged to make their packages relocatable. Unless the package needs to be installed to a very specific location, relocatable packages have significant advantages. They offer much greater flexibility to end users. They more easily support a wide range of packaging systems. Relocatable packages are also typically easier to test during development.

The selection of the default install base point is platform-specific. The defaults provided by CMake are not always ideal, but package creation often overrides them anyway. Avoid including a package version number in the install base path, especially for relocatable packages. Prefer to leave that decision up to the user doing the install, since different usage scenarios call for different directory structures which might not be compatible with a

version-specific path. Projects should also prefer to follow appropriate standards where relevant, such as the Filesystem Hierarchy Standard for Linux (also generally appropriate for most other Unix-based platforms except Apple). If testing out installs locally, consider using the `cmake --install` feature available with CMake 3.15 or later for its improved flexibility and ease of use.

When defining target usage requirements, use the `$<BUILD_INTERFACE:>` generator expression to properly express header search paths to be used by the build. For any library target that will be installed, prefer to set the header search path using the `INCLUDES DESTINATION` section of the `install(TARGETS)` command rather than using `$<INSTALL_INTERFACE:>` generator expressions on the target itself. This can be more convenient and more concise. Ensure that the `INCLUDES DESTINATION` uses a relative path that is relative to the install base point.

```
add_library(Algo ...)

# Not ideal: embeds build paths in installed export files
target_include_directories(Algo
    PUBLIC ${CMAKE_CURRENT_BINARY_DIR}
)

# Better: separate paths for build and install, with the
# latter added as part of the install() command rather than
# with the target
include(GNUInstallDirs)
target_include_directories(Algo
    PUBLIC ${<BUILD_INTERFACE:${CMAKE_CURRENT_BINARY_DIR}>}
)
install(TARGETS Algo ...)
```

```
INCLUDES DESTINATION ${CMAKE_INSTALL_INCLUDEDIR}  
)
```

If installing headers, choose the most appropriate method based on the project's constraints. If the project does not define framework targets, and it can use CMake 3.23 or later for its minimum version, file sets of type `HEADERS` should be preferred. They preserve relative directory structure, and they conveniently handle include directories within the build and when installed. If the project does define framework targets, file sets cannot be used. The `PUBLIC_HEADER` and `PRIVATE_HEADER` target properties are the more typical way of handling headers when frameworks are involved. These properties have mature support, but they do not preserve relative directory structures. For all other cases, headers can be installed more generically using `install(FILES)` or `install(DIRECTORY)`.

Carefully consider the immaturity of the tooling and the incomplete toolchain implementations before relying on being able to install and use code that exports C++20 modules. Some scenarios have reasonable support, others are not supported at all or are not yet robust.

If installing a library intended for other projects to build against, and that library exports any C++20 modules, always install the sources that define the interface to those modules. The consumer will need them to be able to use the modules. Installing the BMIs as well is optional, but they are generally not useful to consumers and will just be wasted space. CMake will ignore installed BMIs and build its own from the interface sources.

Always assign a **COMPONENT** to each installed entity and use project-specific component names. When the project is used as part of a large project hierarchy, this allows a parent project to control how child components should be treated. A good pattern to follow is `<ProjectName>_<ComponentName>` (e.g. `MyProj_Runtime`). When installing export sets, use the same project name as the namespace, with two colons appended (e.g. `MyProj::`). A similar pattern can be used for target names, using a real target name like `MyProj_Algo` with an exported name `MyProj::Algo`. The **EXPORT_NAME** target property can be used to customize the name appended to the namespace to construct the full exported name for the target. Following these naming conventions will make working with the installed project more intuitive. It will also prevent name clashes with other projects' packages.

If the project provides libraries that other projects are expected to link against, prefer to define separate components for runtime support and for development. This allows a parent hierarchical project to re-use the runtime component to package up just the shared libraries and things needed for execution, and avoid packaging development-only entities like static libraries, header files, and so on. It also potentially reduces the work of package maintainers (e.g. for Linux distributions) where packages are often split up into runtime and development packages.

CMake 3.22 added the ability to use symlinks instead of copying files at install time. The feature is controlled by the **CMAKE_INSTALL_MODE** environment variable and affects the behavior of the `file(INSTALL)` and `install()` commands. While there are some scenarios where this

functionality may be useful, it comes with a number of caveats and can easily be misused. Consider carefully the caveats mentioned in the `CMAKE_INSTALL_MODE` documentation before using this feature.

In package config files, always ensure no imported targets are created unless the `find_package()` call is going to be successful. This means all required components must be available, and all required target dependencies should exist before creating any imported targets. To bring in the dependencies, use `find_dependency()` from the `CMakeFindDependencyMacro` module rather than calling `find_package()` from within a package config file, unless the dependency supports package components. If calling `find_package()` to bring in a dependency, ensure the `QUIET` and `REQUIRED` options are passed through correctly to the dependency's `find_package()` call. Also use the appropriate variables to define success and failure, and to report an error message back to the original `find_package()` command rather than calling `message(FATAL_ERROR...)` or similar.

If a project wants to include all runtime dependencies in its packages, CMake provides a number of ways to find and install them automatically. That said, most projects will be better off spending the effort to work out their actual dependencies and install them directly. This will ensure that the build process is more predictable and reliable.

If the project does want to use one of the automatic dependency find-and-install methods, the functionality offered by the `install(IMPORTED_RUNTIME_ARTIFACTS)` and

`install(RUNTIME_DEPENDENCY_SET)` commands is the most advanced and most actively developed. It is also the least mature and does have known issues (see [Section 35.4, “Installing Imported Targets”](#) and [Section 35.8.1, “Runtime Dependency Sets”](#) for details). If the project is not affected by those deficiencies, or it is able to use suitable workarounds, this method should still be considered the preferred choice.

The `InstallRequiredSystemLibraries` module is suitable if only compiler runtime dependencies need to be automatically found and installed. This module allows the project to avoid having to duplicate all the complex logic for finding the appropriate files for different Visual Studio versions, SDKs, toolkit selection, etc. If support for Intel compilers is important, understand the various libraries that this module installs by default and decide whether these libraries are all needed. In particular, projects using OpenMP will most likely want to use the default install commands rather than define their own so that the required libraries do not have to be manually defined.

Avoid the `BundleUtilities` and `GetPrerequisites` modules. They are difficult to use and have known problems that are unlikely to be fixed. Neither module is being actively developed.

36. PACKAGING

The creation of release packages is an area where developers frequently feel out of their depth. The various packaging systems, platform differences, and conventions can present a very steep learning curve for anyone wanting to master the art of creating robust, well presented packages across multiple platforms. Each package management system invariably uses its own unique form of input specification for what each package contains, how it should be installed, how package components relate to each other, how to integrate with the operating system, and so on. Differences between platforms and even between different distributions of the same platform are not always obvious. These things are frequently only learned after experiencing problems from an unforeseen behavior or constraint. Windows path length restrictions and differing conventions on Linux for system library directory names are great examples of this.

Despite all these differences, there is a substantial degree of commonality in terms of the packaging concepts used. While each system or platform might implement things differently, much of their packaging functionality can be described in a

fairly generic way. CMake and CPack take advantage of this to present a defined interface for specifying these common aspects. Those tools then translate that description into the necessary package system input files and commands to produce packages in various formats. This provides a much shorter learning curve for developers, resulting in a relatively quick path to producing packages across the platforms of interest.

CMake and CPack not only abstract away the common aspects of packaging, they also simplify the use of many packager-specific features. By providing a simpler interface to these features, CMake and CPack enable developers to exploit more advanced packaging features in a more familiar way. For the most part, this is done by setting a few relevant variables or calling functions with the appropriate arguments, all of which are defined in the documentation for the CPack module and the various package generators.

CPack packaging is implemented internally as one or more installs to a staging area, which is then used to produce the final package(s). These installs are controlled by calls to the `install()` command, which were covered in depth in [Chapter 35, *Installing*](#). This chapter here presents the second half of that process, describing the variables and commands that specify the package metadata and configuration of the packages. [Chapter 37, *Package Generators*](#) builds on this, discussing each

supported CPack generator and highlighting their individual controls and behaviors.

36.1. Packaging Basics

Setting up and executing packaging is handled in a similar way to testing. The `cpack` command-line tool reads an input file and produces the appropriate package(s) based on that file's contents. If no input file is explicitly given on the command line, `cpack` will use `CPackConfig.cmake` in the current directory. Typically, this input file is generated by including the CPack module. Projects can customize the content of the file through CMake variables and commands.

The CPack module enables a few default package formats based on the target platform. The set of package formats to be created can be overridden on the `cpack` command line with the `-G` option. If multiple formats should be built, they can be provided as a semicolon-separated list like so:

```
cpack -G "ZIP;RPM"
```

If the CMake project was configured to use a multi-configuration generator like Xcode, Visual Studio or Ninja Multi-Config, `cpack` needs to know which configuration's executables it should package up. This is done by giving a `-C` option to `cpack` (the `-C` option is ignored by single-configuration CMake generators):

```
cpack -C Release
```

The `cpack` command supports a few other options, but `-G` and `-C` are two of the more commonly used ones. Most other details are typically provided through the input file. This is in part because instead of invoking `cpack` directly, developers can build the package build target, which will build the default `all` target before then invoking `cpack` with minimal options. It is therefore more convenient for the project to ensure the `cpack` input file defines all required settings. CMake will automatically create the package target if the top of the build tree contains a file called `CPackConfig.cmake`.

The easiest way to create the `cpack` input file is by including the `CPack` module, which should only be done once for the entire CMake project. At the point where the `CPack` module is included, the `CPackConfig.cmake` file is written to the top of the build tree (i.e. `CMAKE_BINARY_DIR`). The call to `include(CPack)` is best performed at or near the end of the top level `CMakeLists.txt` file, either directly or through a subdirectory's `CMakeLists.txt`. Making the inclusion conditional on whether the project has a parent also ensures the project only tries to define packaging if it is the top level project.

```
cmake_minimum_required(VERSION 3.21)
project(MyProj)

# ...Define targets, add subdirectories, etc...
```

```
# End of the CMakeLists.txt file
if(PROJECT_IS_TOP_LEVEL)
    # include(CPack) will happen inside the following call
    add_subdirectory(packaging)
endif()
```

While defaults are provided for most aspects of the packaging configuration, these defaults are not always appropriate. Most projects will want to set some basic details before including the CPack module to provide better alternatives. In particular, it is recommended that the following variables be explicitly set before calling `include(CPack)`:

CPACK_PACKAGE_NAME

The package name is one of the more fundamental pieces of metadata. It is used as part of the default file name for packages, it may appear in various places within UI installers, and it will most likely be the name that end users will use to refer to the project. Ideally, it would not contain spaces, since spaces are replaced by other characters in some contexts. If this variable is not explicitly set, `CMAKE_PROJECT_NAME` is used as a default.

CPACK_PACKAGE_DESCRIPTION_SUMMARY

This variable provides a short sentence of no more than a few words about the project. It should be suitable for being shown in lists of packages where space is restricted, and it should give end users an idea of what the package is about. It may also be shown to the user in other situations and is

only used for informational purposes. From CMake 3.9, the default value is taken from `CMAKE_PROJECT_DESCRIPTION`, whereas for earlier CMake versions, the default is an empty string.

`CPACK_PACKAGE_VENDOR`

The vendor is usually only used for information rather than affecting package structure or behavior, but it is helpful for end users if it is set appropriately. The default value of `Humanity` is not generally suitable for anything other than acting as a placeholder until it is set properly. Prefer to use a real company or organization name rather than a domain name.

`CPACK_PACKAGE_VERSION_MAJOR`, `CPACK_PACKAGE_VERSION_MINOR`, `CPACK_PACKAGE_VERSION_PATCH`

These are used to construct the overall package version. They may appear as part of package file names, in package metadata, and in installer UIs. The version information is a critical part of packaging that projects should always explicitly set.

From CMake 3.12, the default values for these version variables are taken from the `CMAKE_PROJECT_VERSION_MAJOR`, `CMAKE_PROJECT_VERSION_MINOR`, and `CMAKE_PROJECT_VERSION_PATCH` variables. These variables are set by the `VERSION` details of the `project()` command in the

top level `CMakeLists.txt` file, not the most recent `project()` command. For CMake 3.11 or older, the default values will be 0, 1, and 1 respectively, but these are just placeholders that should never be relied upon for formal release packages. Projects may wish to provide more reliable behavior and always set these variables to their `${PROJECT_VERSION}_...`` counterparts, regardless of CMake version.

`cpack` will automatically populate `CPACK_PACKAGE_VERSION` based on these three variables, but this only occurs when the `CPack` module generates the `CPackConfig.cmake` file. `CPACK_PACKAGE_VERSION` won't be populated in a way that the project can access while CMake is processing its `CMakeLists.txt` files.

`CPACK_PACKAGE_INSTALL_DIRECTORY`

Some packagers will append this to the base install point to create a package-specific directory. Its default value can vary, but may include the package name and version. The presence of the version number in the default value is often undesirable, such as for installers that are able to upgrade a project in-place. To ensure better default behavior, projects may want to set this to the same as `CPACK_PACKAGE_NAME`.

`CPACK_VERBATIM_VARIABLES`

This variable should always be explicitly set to true. It ensures that all contents written to the `cpack` configuration file are properly escaped. The default value is false only to preserve backward compatibility with earlier CMake versions. The old behavior can lead to an ill-formed configuration file and should not be used.

More variables will often be set to improve the end user experience, especially for UI installers:

`CPACK_PACKAGE_DESCRIPTION_FILE`

This is the name of a text file containing a slightly longer description of the project. The contents of the file may be shown in introductory screens of an installer, or added to package metadata. Always use an absolute path to the file. As an alternative, the description can be provided directly as the contents of a variable named `CPACK_PACKAGE_DESCRIPTION`. While this was not documented for CMake 3.11 or earlier, it has been supported even from early versions of CMake.

`CPACK_RESOURCE_FILE_WELCOME`

Some installers show a welcome message in their opening screen. This variable specifies a file name whose contents should be shown for such cases. If it is not set, then for those installers that show a welcome message, CPack provides a default which acts as a placeholder. That placeholder is a relatively poor substitute not suitable for official releases, so

projects should always set this if distributing an installer that shows a welcome screen. Always use an absolute path to the file.

CPACK_RESOURCE_FILE_LICENSE

Most UI installers present a license page to the user and may ask them to accept the license before continuing. The text shown for the license is taken from the file named by this variable. Some generic placeholder text may be used if the variable is not set, so projects are advised to provide their own more suitable license details. Always use an absolute path to the file. See [Section 37.6, “DragNDrop”](#) for discussion of deprecated behavior related to this variable.

CPACK_RESOURCE_FILE_README

Some UI installers provide a separate page showing the contents of the file named by this variable. It serves as an opportunity to give the user some information before they proceed with the installation. A generic default file is provided when this variable is not set, but the contents of that file are typically not suitable for production release packages. Projects should prefer to give a file with some more appropriate content via this variable if they intend to create installers which show such pages. Always use an absolute path to the file.

CPACK_PACKAGE_ICON

This variable may also be commonly set, but be aware that most of the package generators have their own different requirements for the format and use of icons within the package and associated places. Some generators ignore this variable, others use it in different ways.

```
# Example that follows the above guidelines
set(CPACK_PACKAGE_NAME MyProj)
set(CPACK_PACKAGE_VENDOR MyCompany)
set(CPACK_PACKAGE_DESCRIPTION_SUMMARY "Example project")
set(CPACK_PACKAGE_INSTALL_DIRECTORY ${CPACK_PACKAGE_NAME})
set(CPACK_PACKAGE_VERSION_MAJOR ${PROJECT_VERSION_MAJOR})
set(CPACK_PACKAGE_VERSION_MINOR ${PROJECT_VERSION_MINOR})
set(CPACK_PACKAGE_VERSION_PATCH ${PROJECT_VERSION_PATCH})
set(CPACK_VERBATIM_VARIABLES YES)

set(CPACK_PACKAGE_DESCRIPTION_FILE
    ${CMAKE_CURRENT_LIST_DIR}/Description.txt
)
set(CPACK_RESOURCE_FILE_WELCOME
    ${CMAKE_CURRENT_LIST_DIR}/Welcome.txt
)
set(CPACK_RESOURCE_FILE_LICENSE
    ${CMAKE_CURRENT_LIST_DIR}/License.txt
)
set(CPACK_RESOURCE_FILE_README
    ${CMAKE_CURRENT_LIST_DIR}/Readme.txt
)
include(CPack)
```

To facilitate running `cpack` with no arguments and the use of the package build target, the `CPACK_GENERATOR` variable should be set to the desired package formats. If not set, a fairly conservative default set of generators will be used. Since not all

formats are supported or appropriate on all platforms, setting this variable requires logic to specify only those formats that make sense. The following example selects one generic archive format and one native package format for the target platform (if identified):

```
if(WIN32)
    set(CPACK_GENERATOR ZIP WIX)
elseif(APPLE)
    set(CPACK_GENERATOR TGZ productbuild)
elseif(CMAKE_SYSTEM_NAME STREQUAL "Linux")
    set(CPACK_GENERATOR TGZ RPM)
else()
    set(CPACK_GENERATOR TGZ)
endif()
```

The CPack module also defines the necessary details that allow a source package to be produced. It creates a CPackSourceConfig.cmake file which can be used instead of CPackConfig.cmake. When the project is configured to use a Makefiles or Ninja generator, a package_source build target is defined as well. Producing the source package is relatively straightforward, with either of the following two commands achieving the same thing.

```
# All build generators
cpack -G TGZ --config CPackSourceConfig.cmake

# Makefile and Ninja build generators only
cmake --build . --target package_source
```

The source package contains the entire source directory tree. The CPACK_SOURCE_IGNORE_FILES variable can be used to filter out parts of the source tree, holding a list of regular expressions that each full file path will be compared against. All matching files will be omitted from the source package. The default value of this variable ignores repository directories like .git and .svn, as well as some common temporary files. If a project overrides CPACK_SOURCE_IGNORE_FILES, it will need to ensure that it also specifies any such relevant patterns. To avoid problems with escaping and quoting in the regular expressions, it is strongly recommended to set CPACK_VERBATIM_VARIABLES to true.

```
set(CPACK_VERBATIM_VARIABLES YES)

set(CPACK_SOURCE_IGNORE_FILES
    /\\\.git/
    /\\\.swp
    /\\\.orig
    /CMakeLists\\\.txt\\\.user
    /privateDir/
)
```

36.2. Components

If a project defines no components in any of its `install()` commands, then all package generators will produce a single monolithic package that contains all installed contents. When a project does define components, it provides more flexibility for how it can be packaged. Relationships can also be specified between components, allowing hierarchical component

structures to be defined, and dependencies between them to be enforced at install time. Each package generator makes use of these component details in different ways, with some creating separate packages for different components, while others present user selectable components in a single UI installer. Some installers even support downloading individual components on demand at install time.

The previous chapter demonstrated how to define components as part of `install()` commands. Those commands only assign content to components, they do not define any other component details. The relationships between components are specified using commands from the `CPackComponent` module, which is automatically included as part of including the `CPack` module. These commands also provide additional metadata for components which some installers use to present information to the user during installation.

The subsections that follow describe a number of commands related to managing components. The following example will be used to demonstrate how the various pieces fit together to produce a coherent result.

```
set(CPACK_PACKAGE_NAME ...)  
# ... set other variables as per earlier example  
  
include(CPack)  
  
cpack_add_component(MyProj_Runtime  
DISPLAY_NAME Runtime
```

```
DESCRIPTION      "Shared libraries and executables"
REQUIRED
INSTALL_TYPES Full Developer Minimal
)
cpack_add_component(MyProj_Development
    DISPLAY_NAME      "Developer pre-requisites"
    DESCRIPTION       "Headers/static libs needed for building"
    DEPENDS          MyProj_Runtime
    GROUP            MyProj_SDK
    INSTALL_TYPES    Full Developer
)
cpack_add_component(MyProj_Samples
    DISPLAY_NAME      "Code samples"
    GROUP            MyProj_DevHelp
    INSTALL_TYPES    Full Developer
    DISABLED
)
cpack_add_component(MyProj_ApiDocs
    DISPLAY_NAME      "API documentation"
    GROUP            MyProj_DevHelp
    INSTALL_TYPES    Full Developer
    DISABLED
)
cpack_add_component_group(MyProj_SDK
    DISPLAY_NAME    SDK
    DESCRIPTION     "Developer tools, libraries, etc."
)
cpack_add_component_group(MyProj_DevHelp
    DISPLAY_NAME    Documentation
    DESCRIPTION     "Code samples and API docs"
    PARENT_GROUP   MyProj_SDK
)
cpack_add_install_type(Full)
cpack_add_install_type(Minimal)
cpack_add_install_type(Developer
    DISPLAY_NAME "SDK Development"
)
```

The effect of the various `cpack_add_...()` commands used in the above example is to define a range of component-specific variables in the current scope. The `CPackComponent` documentation lists some of these variables and suggests that the variables can be set directly, but this is not recommended. The commands offer a more robust and more readable way of defining component and group details and should be preferred. They should also be called in the same scope as the `include(CPack)` call, ideally immediately after it as shown in the above example. Technically, the constraint is not quite as strict as this, but defining the component details in a different scope can be more fragile.

36.2.1. Defining A Component

The most important command from the `CPackComponent` module is `cpack_add_component()`, which describes a single component:

```
cpack_add_component(componentName
    [DISPLAY_NAME name]
    [DESCRIPTION description]
    [DEPENDS comp1 [comp2...] ]
    [REQUIRED | DISABLED]
    [HIDDEN]
    [GROUP group]
    [INSTALL_TYPES type1 [type2...] ]
    [DOWNLOADED]
    [ARCHIVE_FILE archiveFileName]
    [PLIST plistFileName]
)
```

While all keywords are optional, the `DISPLAY_NAME` and `DESCRIPTION` should at least be provided. This ensures that meaningful details are presented to the user during installation, and that non-UI installers have enough metadata for users to understand what a package is for.

If the component should only be installed if one or more other components are installed, those components should be listed with the `DEPENDS` option. Note that not all CPack generators enforce these dependencies. Therefore, using this keyword may effectively limit the project to using only a subset of the available CPack generators.

The `REQUIRED`, `DISABLED`, and `HIDDEN` keywords are only meaningful for UI-based installers. If a component should always be installed, the `REQUIRED` keyword should be given. The user will then not be able to disable that component through an installer's UI. Without this keyword, the component can be enabled or disabled by the user, with the default initial state being enabled. To change this default to disabled, add the `DISABLED` keyword. Whether a component is required or not, it can also be hidden from installer UIs by adding the `HIDDEN` keyword. A non-required but hidden component would generally also be disabled, and the installer would then only install that component if another enabled component depended on it.

The remaining options have more specialized effects and are covered in the next few subsections. The PLIST option (only available with CMake 3.9 or later) is used exclusively by the productbuild package generator, so discussion of its use is deferred to [Section 37.7, “productbuild”](#).

36.2.2. Component Groups

A `cpack_add_component()` command may use the GROUP keyword to nominate a group the component belongs to. A group is a way of collecting together related components, often presenting them in the installer as a single installable component (see [Section 36.2.5, “Component And Group Selection”](#)). Groups can contain components and other groups, which enables an arbitrarily deep hierarchical structure to be defined. If no components are defined with GROUP details, the components will act as a simple flat list in most UI installers.

A group is defined using the following command from the CPackComponent module:

```
cpack_add_component_group(groupName
    [DISPLAY_NAME name]
    [DESCRIPTION description]
    [PARENT_GROUP parent]
    [EXPANDED]
    [BOLD_TITLE]
)
```

This command can appear before or after `cpack_add_component()` calls that refer to the `groupName`. The `DISPLAY_NAME` and `DESCRIPTION` options serve the same purpose as their counterparts in the `cpack_add_component()` command. The `PARENT_GROUP` is the group's equivalent of the `GROUP` option, allowing it to be placed under another group to support arbitrary group hierarchies. When the `EXPANDED` keyword is given, the group will initially be expanded in the installer UI, and the presence of the `BOLD_TITLE` keyword will make that group show up as bold.

Component names should ideally be project-specific. This allows hierarchical project arrangements to select the components they want to package and how to present them in installers (or in the case of non-UI installers, how to structure the component-specific packages). Group names are less restrictive, since they may contain components and groups from across different projects. A group name cannot be the same as any component name.

36.2.3. Install Types

An install type is a preset selection of components which can be used to simplify the choices a user has to make at install time. A component can be assigned to any number of install types with the `INSTALL_TYPES` option, where each type is a name that is defined separately by the `cpack_add_install_type()` command:

```
cpack_add_install_type(typeName [DISPLAY_NAME uiName])
```

The DISPLAY_NAME option can be omitted if typeName is already sufficiently descriptive. For install types that should be shown using multiple words, DISPLAY_NAME must be used, and uiName will be a quoted string. There are no predefined install types, but it is common to see packages provide install types with names like Full, Minimal or Default.

Of the actively maintained package generators provided by CMake, only NSIS and Inno Setup support the install types feature.

36.2.4. Downloadable Components

Adding the DOWNLOADED keyword to `cpack_add_component()` will enable that component to be downloaded on-demand rather than including it in the package directly. Not all CPack generators support this functionality, with only the IFW, NSIS, and Inno Setup generators currently implementing it. The productbuild generator theoretically supports it too, but the packages produced end up fully embedding the component packages instead of making them downloadable. Other generators will typically silently ignore the DOWNLOADED keyword.

Downloadable components have the benefit of making the main installer smaller. At install time, the user also only needs to download the components they want to install, rather than

all components whether they want them or not. The trade-off is that the user must be connected to a network with access to the download server when they run the installer. This makes the installer unusable in scenarios like air-gapped machines, or those with network restrictions blocking particular servers.

The ARCHIVE_FILE option can be used to customize the file name of the downloadable component, although the default file name is usually appropriate. The default file name includes the package version and the appropriate file suffix for the type of archive created. There is usually little reason to override the default.

The `cpack_configure_downloads()` command is used to specify where to create the archive files, and what URL the installer should download them from when it runs.

```
cpack_configure_downloads(baseUrl  
    [ALL]  
    [UPLOAD_DIRECTORY dir]  
    [ADD_REMOVE | NO_ADD_REMOVE]  
)
```

The `baseUrl` is the location where the installer will look for downloadable components. For example, if a component's archive file is named `MyProj-1.3.7-win64-Thing.zip`, and the `baseUrl` is `https://example.com`, the installer will try to download the file from `https://example.com/MyProj-1.3.7-win64-Thing.zip`. Some installers may also require an additional file to be

provided at the `baseUrl` as a form of index (the [IFW generator](#) is one example of this).

The `UPLOAD_DIRECTORY` argument tells `cpack` where to create the individual component archive files. Once `cpack` has been run to create those archive files, the contents of the directory will need to be copied to the download server for the installer to access.

For testing an installer locally, one can sometimes temporarily use a `baseUrl` like `http://localhost:8080` and run a local http server that serves up the contents of the `UPLOAD_DIRECTORY`. Python provides a simple http server which can do this, making testing an installer with downloadable components a much easier task:

```
python -m http.server --directory <dir> 8080
```

Note that the IFW generator ignores the `UPLOAD_DIRECTORY` option. It creates its own separate directory for the generated packages to upload, along with an index file which must be uploaded as well. See [Section 37.2, “Qt Installer Framework \(IFW\)”](#) for further details.

If the `ALL` keyword is present in a call to `cpack_configure_downloads()`, all components are treated as downloadable, regardless of whether they were explicitly marked to be downloadable or not. This is a convenient way of

making a fully online installer with no embedded packages, which yields the smallest possible installer.

For installers that run on Windows, the ADD_REMOVE keyword directs the installer to make the package available to Windows' Add/Remove Programs functionality. The ALL keyword implies ADD_REMOVE, but giving NO_ADD_REMOVE overrides that behavior.

36.2.5. Component And Group Selection

Project generators can be asked to process components in one of three ways. The CPACK_COMPONENTS_GROUPING variable determines how the generator uses the components to produce packages. It can be set to one of the following values:

ALL_COMPONENTS_IN_ONE

A single package with all requested components will be created. The component and group structure may be used or ignored, depending on the generator.

ONE_PER_GROUP

Each top level component group should create a package. Those components that are not part of a group will also create their own package. This is the default if CPACK_COMPONENTS_GROUPING is not set. It is usually the most appropriate arrangement, but for some UI installers, it hides components that projects may prefer to be shown.

IGNORE

Each component creates its own package, irrespective of any component groups. This setting can be more suitable for some UI installers to ensure that no components are hidden unless explicitly configured to be so.

Two more variables also affect how generators interpret components and groups. If `CPACK_MONOLITHIC_INSTALL` is set to true, components and their groups are completely disabled, and all components are installed and bundled into a single package. This is a fairly brutal switch, so test the results carefully on all relevant platforms, paying special attention to look out for any unexpected files. For legacy reasons, each generator also has its own setting for whether components are supported by default. This setting can be overridden on a per-generator basis by the `CPACK_<GENNAME>_COMPONENT_INSTALL` variable, which can be set to true or false as needed.

When performing a component-based install, projects are not required to include all components in the final package(s). The set of components that will be included are controlled by the `CPACK_COMPONENTS_ALL` variable, which must be set before the call to `include(CPack)`. When not set, `cpack` packages all components, but the project can explicitly set this variable to only list the components it wants packaged. For example, if a project wanted to control whether documentation and code samples should be packaged, it could be achieved like so:

```
if(NOT MYPROJ_PACKAGE_HELP)
    set(CPACK_COMPONENTS_ALL
        MyProj_Runtime
        MyProj_Development
    )
endif()

include(CPack)
```

Rather than explicitly listing all the components to be packaged, a project may want to install all but a few specific components. The full set of components is available in the read-only pseudo-property `COMPONENTS`, which can only be retrieved via the `get_cmake_property()` command. The project can start with that list of components and then remove the unwanted entries.

```
if(NOT MYPROJ_PACKAGE_HELP)
    get_cmake_property(CPACK_COMPONENTS_ALL COMPONENTS)
    list(REMOVE_ITEM CPACK_COMPONENTS_ALL
        MyProj_Samples
        MyProj_ApiDocs
    )
endif()

include(CPack)
```

The selection of which set of components to install and how the components should be handled may seem a little complex at first. In practice, the main area that causes difficulty is understanding how each package generator handles the different values of `CPACK_COMPONENTS_GROUPING`. [Chapter 37, *Package Generators*](#) and its subsections explain the behavior of

each generator type, but some quick experiments on a test project can often be just as instructional for coming to terms with the effects of the various settings.

36.3. Multi Configuration Packages

CPack is primarily geared towards producing packages for a single build configuration. In most cases, packages are created for the Release build type, but for things like SDK projects, it may be desirable to include Debug and Release libraries, especially for multi-configuration generators.

There are two main approaches to creating a multi-configuration package. The first method can be adapted to work for both single and multi-configuration generators and has been available in CMake for a long time. It is more complex to set up, but it also supports other interesting scenarios. The second method only supports multi-configuration generators and is only available with CMake 3.16 or later, but it is very straightforward to set up and use.

36.3.1. Multiple Build Directories

CPack provides the advanced variable `CPACK_INSTALL_CMAKE_PROJECTS` which can be used to incorporate multiple build trees into the one packaging run. It is expected to hold one or more quadruples, where each quadruple consists of:

- The build directory.
- The project name. Historically, some package generators may have used this during package generation, but current CMake versions now only use it in some log output.
- The component or component set to install. The special value ALL means to install the components listed in the CPACK_COMPONENTS_ALL variable. If any other value is given, cpack will look for a variable of the name CPACK_COMPONENTS_<uppercaseValue>. If such a variable exists and is not empty, it will be treated as a list of component names to install. If no such non-empty variable exists, the value is used directly as the name of a component to install. For example, if the component to install was called Runtime, then a variable CPACK_COMPONENTS_RUNTIME could specify a list of components to install. If no such variable is defined, the Runtime component would be installed.
- The relative location within the package to install to. The only safe value for this is a single forward slash (/), due to the way different package generators use it.

The project can define sets of quadruples, one for the Release build and one for the Debug build. The build directory for the Release build can simply be CMAKE_BINARY_DIR, but for the Debug build, a second separate build directory needs to have been created and built.

The Debug quadruple would only need to add those components that are different between the two build configurations. But whether using the default ALL component or using specific components, special care needs to be exercised to ensure installed files don't unexpectedly overwrite each other. Listing the Release component last will ensure that any files that have the same name and install location will end up with the Release version when packaged.

```
set(CPACK_COMPONENTS_DEBUG_COMPS
    MyProj_Runtime
    MyProj_Development
)
unset(CPACK_INSTALL_CMAKE_PROJECTS)

if(MYPROJ_DEBUG_BUILD_DIR)
    list(APPEND CPACK_INSTALL_CMAKE_PROJECTS
        ${MYPROJ_DEBUG_BUILD_DIR}
        ${CMAKE_PROJECT_NAME}
        debug_comps
    /
)
endif()

list(APPEND CPACK_INSTALL_CMAKE_PROJECTS
    ${CMAKE_BINARY_DIR} ${CMAKE_PROJECT_NAME} ALL /
)
include(CPack)
```

When using multi-configuration generators like Xcode, Visual Studio, or Ninja Multi-Config, the MYPROJ_DEBUG_BUILD_DIR directory in the above example needs to be configured to

support only the Debug build type rather than the usual default set. This is the only way to force it to install Debug build outputs. When running `cmake` in that Debug build directory, explicitly set the `CMAKE_CONFIGURATION_TYPES` cache variable to Debug to get the necessary arrangement.

While it is possible to use just the one build directory for multi-configuration generators, the techniques to do so are more fragile and complex. In contrast, the above technique works for all build and package generator types. Furthermore, it can be extended to incorporate builds for different architectures, or even completely separate projects, into one unified package.

36.3.2. Pass Multiple Configurations To `cpack`

The `cpack` tool provides a `-C` command line option which can be used to specify the configuration to package. This option only has a useful meaning for multi-configuration generators. From CMake 3.16, more than one configuration can be given to that option as a semicolon-separated list. `cpack` will then add all the listed configurations to the package.

This functionality is only available when invoking `cpack` directly. It is not available using the package build target because a build is inherently a single configuration. It should be noted that this means the user is responsible for ensuring that all configurations listed have already been built before

invoking `cpack`. A typical example of the steps required looks like this:

```
cd /path/to/build/directory
cmake --build . --config Debug
cmake --build . --config Release
cpack -C "Debug;Release"
```

A significant advantage of this method is its simplicity. No additional setup is required, and the steps are easily scripted. It is considerably less complex than the approach described in the previous section. When using a multi-configuration generator and CMake 3.16 or later, this should generally be the preferred approach.

36.4. Recommended Practices

When configuring details for the various generators, a potentially large number of variables can influence the way contents are packaged. In many cases, the defaults are acceptable, but some details should always be set by the project. Projects should explicitly set all three of the `CPACK_PACKAGE_VERSION_MAJOR`, `CPACK_PACKAGE_VERSION_MINOR` and `CPACK_PACKAGE_VERSION_PATCH` variables, since the default version details are rarely suitable or might not always be reliable. The package name, description, and vendor details should also always be set. To ensure robust escaping of variable values in generated input files, always explicitly set `CPACK_VERBATIM_VARIABLES` to true.

In most cases, projects will want to avoid including a version number in the name of the default installation directory. A number of installers support updating an existing install in-place, so any version number in the directory name will be inappropriate after a product upgrade. Users may also prefer the directory name to stay the same across upgrades so that they can write wrapper scripts, launchers, etc. that work across versions. A more appropriate default installation directory can be obtained by setting `CPACK_PACKAGE_INSTALL_DIRECTORY` to `${CPACK_PACKAGE_NAME}` in most cases. Simple archive packages are an exception to this (see [Section 37.1, “Simple Archives”](#)).

When setting component details, prefer to use the commands defined by the relevant CMake modules rather than setting variables directly. Commands such as `cpack_add_component()`, `cpack_add_component_group()`, and so on use named arguments. These make setting various options more readable and easier to maintain. They are also more robust, since the commands will catch any error in argument names, whereas setting variables directly will silently go unnoticed if variable names are misspelled.

When defining component names, allow for the possibility that the project may be used as a child of some larger project hierarchy. Include the project name in the component name to prevent name clashes between projects. The component names shown to users in UI installers (i.e. their display names),

package file names, etc. can be set to something different, rather than relying on the component name used internally within the CMake project. In fact, setting custom display names and descriptions for components is encouraged, including providing localized values where the package format supports it.

Give consideration to whether end users should be able to install the product on a headless system. This directly impacts both the choice of package formats (see [Chapter 37, Package Generators](#)), and the way components are defined and used. For a headless system, a non-UI installation method must be available, and packages should not require UI-related dependencies. This means UI components need to be separated out from non-UI components. This is especially important for package formats like RPM and DEB where the package manager typically enforces inter-package dependencies.

If multi-architecture packages need to be produced from a single `cpack` invocation, use the `CPACK_INSTALL_CMAKE_PROJECTS` variable to incorporate components from multiple build trees. This method can also be used to create debug-and-release packages, regardless of the CMake version or CMake generator used. If using CMake 3.16 or later with a multi-configuration generator, a simpler way to produce a multi-configuration package is to invoke the `cpack` tool directly and specify the configurations to be packaged with the `-C` command-line option.

With either method, always list the Release components last in case both Debug and Release configurations install artifacts to the same file name and directory. Ideally this should not occur, but for cases where it may make sense to do so, the Release artifact is likely to be the preferred one.

37. PACKAGE GENERATORS

CPack can generate a variety of package formats, each falling into one of the following categories:

Simple archives

Archives can be in a variety of formats, such as zip, tarball, bz2 and so on. They are the most basic of all the package formats, since they are just an archive of files that the user is expected to unpack somewhere on their file system. They are the most widely supported of all the package formats. They are also the easiest to work with when the end user wants to have multiple different versions of a project available or installed simultaneously.

UI installers

These tend to have deep integration with the target platform, providing features like adding and removing components once installed, integration with desktop menus, and so on. They typically present the user with some means of selecting which components to install and are usually very intuitive, so novice users tend to prefer them.

CMake supports NSIS, Inno Setup, and WIX installers on Windows, DragNDrop (DMG), and productbuild on Mac, and the Qt Installer Framework (IFW) on Windows, Mac, and Linux. On Mac, some older installer types are still supported, but they should be considered deprecated and are only mentioned briefly in the sections that follow.

Non-UI packages

These are aimed at a specific package manager. RPM and DEB are very popular on Linux, with FreeBSD and Cygwin packages also being supported for their respective platforms.

Niche and product-specific packages

CMake 3.12 added initial support for the NuGet package format for .NET. CMake 3.13 added a special External generator which doesn't produce packages itself, but instead creates a JSON file which some other process can consume to produce packages outside CPack.

Regardless of which package generators are used, the same `CPackConfig.cmake` file is processed. This doesn't generally present an issue, since generator-specific configuration is normally made possible through generator-specific variables where needed.

If certain logic needs to be added for only a particular generator and the existing variables offered by CMake and

CPack are insufficient, the `CPACK_PROJECT_CONFIG_FILE` variable can be set to the name of a file that will be included once for each package generator being invoked. Each time it is read, the `CPACK_GENERATOR` variable will hold the name of the generator being processed rather than the whole list of generators. This allows that file to override settings made in `CPackConfig.cmake` for only those specific generators that require it.

The full `cpack` run loosely follows the steps in the following pseudocode:

```
include(CPackConfig.cmake)
function(generate CPACK_GENERATOR)
    # CPACK_GENERATOR is a single generator local to this
    # function scope
    if(CPACK_PROJECT_CONFIG_FILE)
        include(${CPACK_PROJECT_CONFIG_FILE})
    endif()
    # ...invoke package generator
endfunction()

# Here CPACK_GENERATOR is the list of generators to be
# processed, as set by CPackConfig.cmake or on the cpack
# command line
foreach(generator IN LISTS CPACK_GENERATOR)
    generate(${generator})
endforeach()
```

An example where the above can be useful is to set `CPACK_PACKAGE_ICON` to a generator-specific value. Different generators expect this icon to be in different formats, so the file name needs to be generator-specific.

37.1. Simple Archives

CPack supports the creation of archives in various formats. The most widely supported are ZIP and TGZ, the former being common for Windows platforms, and the latter producing gzipped tarballs (.tar.gz or .tgz) that are supported essentially everywhere else. Other available archive formats include TBZ2 (.tar.bz2), TXZ (.tar.xz), TZ (.tar.Z), and 7Z (7zip archives, .7z). CMake 3.16 added support for tarballs using Zstandard compression with the TZST (.tar.zst) format. CMake 4.0 added the ability to create tarballs with no compression at all with the TAR (.tar) format. For maximum portability, ZIP and TGZ should generally be preferred, but other formats may produce smaller archives and may be suitable for platforms where those formats are commonly supported.

A self-extracting archive format is also supported by cpack. It can be requested using the generator name STGZ, which produces a Unix shell script with the archive embedded at the end of that script. This can be thought of as a form of console-based UI installer, but in practice it offers only very basic functionality. Users may prefer a simple archive that they can unpack themselves.

For legacy reasons, archive generators have components disabled by default. To enable component-based archive creation, CPACK_ARCHIVE_COMPONENT_INSTALL must be set to true.

The `CPACK_COMPONENTS_GROUPING` variable will then determine the set of archive files that will be generated.

When performing a non-component install, the final package file name can be controlled using the `CPACK_ARCHIVE_FILE_NAME` variable. For component-based installs, the name of each component's package is controlled by `CPACK_ARCHIVE_<COMP>_FILE_NAME`, where `<COMP>` is the uppercase component or group name. The appropriate archive extension will be appended to the specified file name (`.tar.gz`, `.zip`, etc.). CMake 3.25 and later allow the extension to be overridden with the `CPACK_ARCHIVE_FILE_EXTENSION` variable, but this should not normally be needed.

A common convention for archive files is to make the top level of the extracted directory structure be the same as the name of the archive file without the file extension (i.e. the same as `CPACK_PACKAGE_FILE_NAME`). For non-component installs, this is already the default behavior for the archive generators, but for multi-component packages, no top level directory is used by default. Projects can enforce a common top level directory for component archives by setting `CPACK_COMPONENT_INCLUDE_TOPLEVEL_DIRECTORY` to true. Since this variable is shared by all package generators, a generator-specific override would be the most appropriate way to do this:

CMakeLists.txt

```
set(CPACK_PROJECT_CONFIG_FILE  
    ${CMAKE_CURRENT_LIST_DIR}/cpackGeneratorOverrides.cmake  
)
```

cpackGeneratorOverrides.cmake

```
if(CPACK_GENERATOR MATCHES  
    "^(7Z|TBZ2|TGZ|TXZ|TZ|TZST|ZIP)$")  
    set(CPACK_COMPONENT_INCLUDE_TOPLEVEL_DIRECTORY YES)  
endif()
```

Developers should note that some archive formats, platforms, and file systems have limitations on the length of file names and paths. For example, POSIX.2 requires file names to be no more than 100 characters and paths to be no more than 255 characters for the extended tar interchange format. Older tar formats may restrict the entire path to no more than 100 characters. When unpacking an archive onto an eCryptFS file system, file names have an empirically derived limit of about 140 characters. Unpacking on Windows can have a 260 character path length limit, depending on certain settings and OS version. UTF-8 file names and paths further complicate the picture and may shorten the effective character limits even more. With these constraints in mind, projects should avoid using long paths and file names in their package contents. These restrictions are most evident with archive package types, but since other non-archive formats also use archives internally and deploy to systems with these restrictions, shorter paths and file names should be preferred in general.

37.2. Qt Installer Framework (IFW)

The IFW package generator offers the broadest platform support of all UI-based package formats provided by CPack. Installers can be built for Windows, Mac, and Linux from the same configuration details, making it a good choice when a project wants to have a consistent UI installer across all major desktop platforms. It also has easy-to-use localization of component and group display names and descriptions, as well as extensive customizability.

The defaults for the UI appearance and installer icons are often sufficient, but some projects may want to customize a few aspects to improve the branding, especially around the use of icons. The `CPACK_PACKAGE_ICON` variable is ignored for this generator, which relies instead on three separate IFW-specific variables to control the icons for different contexts:

- `CPACK_IFW_PACKAGE_ICON` (.ico for Windows, .icns for Mac, ignored for Linux)
- `CPACK_IFW_PACKAGE_WINDOW_ICON` (always .png)
- `CPACK_IFW_PACKAGE_LOGO` (preferably .png)

Unfortunately, these variables are not handled consistently between platforms, so it can be difficult to set them correctly. For simplicity, it may be preferable to set all three to the same image, albeit potentially in different formats and/or sizes.

Testing on each platform of interest is recommended to ensure the installer presents itself as expected. The following example shows how such a configuration may be specified:

```
# Define generic setup for all generator types...

# IFW-specific configuration
if(WIN32)
    set(CPACK_IFW_PACKAGE_ICON
        ${CMAKE_CURRENT_LIST_DIR}/Logo.ico
    )
elseif(APPLE)
    set(CPACK_IFW_PACKAGE_ICON
        ${CMAKE_CURRENT_LIST_DIR}/Logo.icns
    )
endif()
set(CPACK_IFW_PACKAGE_WINDOW_ICON
    ${CMAKE_CURRENT_LIST_DIR}/Logo.png
)
set(CPACK_IFW_PACKAGE_LOGO
    ${CMAKE_CURRENT_LIST_DIR}/Logo.png
)

include(CPack)
include(CPackIFW)
# Define components and component groups...
```

Component-based installation is enabled by default for the IFW generator. A single installer is always produced, but CPACK_COMPONENTS_GROUPING controls how much of the component hierarchy is shown to the user:

ALL_COMPONENTS_IN_ONE

No component hierarchy is shown, the default enabled components will always be installed.

ONE_PER_GROUP

Only the first level of groups is shown along with any components that do not belong to any groups. Subgroups and components under any group will be hidden.

IGNORE

All components that are not explicitly hidden will be shown, regardless of where they are in the group hierarchy. This is likely to be the option most projects will want to use.

Components and groups can be further configured beyond what the generic commands provide:

```
cpack_ifw_configure_component(componentName
    [NAME componentNameId]
    [DISPLAY_NAME displayName...]
    [DESCRIPTION description...]
    [VERSION <version>]
    [DEPENDS compId1 [compId2...]] ①
    [REPLACES compId3 [compId4...]]
    # Other options not shown
)
# The cpack_ifw_configure_component_group() command
# supports the same options
```

① DEPENDENCIES is also accepted, but prefer DEPENDS for consistency with other CMake commands.

The DISPLAY_NAME and DESCRIPTION of each component or group can be given alternative contents for different languages and locales. These two options accept a list of pairs, where the first value of a pair is the language or locale ID, and the second

value is the text for that language. The first value in the list can be given without a preceding language or locale ID. It will be used as the default text if none of the languages or locale IDs match the user's current setting at install time.

```
cpack_ifw_configure_component(MyProj_Docs
    DISPLAY_NAME Documentation
        de Dokumentation
        pl Dokumentacja
)
cpack_ifw_configure_component_group(MyProj_Colors
    DISPLAY_NAME en Colors
        en_AU Colours
    DESCRIPTION en "Available color palettes"
        en_AU "Available colour palettes"
)
```

The `VERSION` option allows per-component and per-group version numbers to be specified. This is used by online installers to determine whether an update is available (see further below). If `VERSION` is not given, it defaults to `CPACK_PACKAGE_VERSION`.

The `DEPENDS` option is analogous to the same option in `cpack_add_component()` except that the form of the `compId1...` entries is different. These need to follow the QtIFW style, which is a hierarchical string rather than a raw `componentName`. Each level of the grouped hierarchy is dot-separated, as demonstrated by the following example:

```
include(CPack)
include(CPackIFW)
```

```
cpack_add_component(foo GROUP groupA)
cpack_add_component(bar GROUP groupB)

cpack_add_component_group(groupA)
cpack_add_component_group(groupB)

cpack_ifw_configure_component(bar DEPENDS groupA.foo)
```

One can also append a version requirement to the DEPENDS value. This can be achieved by appending a separator (discussed shortly), an operator (one of =, <, <=, > or >=), and the version number. Technically, the QtIFW format allows the operator to be omitted, which should result in using a default operator of =. CMake 3.20 and earlier contains a bug which causes the version number to be dropped when no operator is given. Therefore, prefer to always specify an operator if including a version constraint on an IFW component dependency.

The separator between the package name and operator can be either a colon (:) or a hyphen (-). Colons are more readable and have the advantage that component and group names can contain hyphens. A colon can only be used as the separator if using CMake 3.21 or later and QtIFW 3.1 or later. If using older CMake or QtIFW versions, a hyphen must be used as the separator, and the component and group names cannot contain any hyphens.

```
# Colons as separators, supports hyphens in names
# NOTE: Requires CMake 3.21+ and QtIFW 3.1+.
```

```
cpack_ifw_configure_component(baz DEPENDS a-b-c:=7.8.2)
cpack_ifw_configure_component(baz DEPENDS old-thing:<3)
cpack_ifw_configure_component(baz DEPENDS newbie:>=6)

# Hyphens as separators, no hyphens in names
cpack_ifw_configure_component(baz DEPENDS exacto-=7.8.2)
cpack_ifw_configure_component(baz DEPENDS oldie-<3)
cpack_ifw_configure_component(baz DEPENDS newbie->=6)
```

The name used internally within the installer for a component can be overridden with the NAME option. This name would be used to identify the component in DEPENDS arguments, and also when checking if a newer version of a component is available.

A top level group name can be set with the CPACK_IFW_PACKAGE_GROUP variable. It is often set to a reverse domain name to ensure component names don't clash in large, multi-vendor installers. This top level group name must then be included when listing dependencies with the DEPENDS option, as the following modification of the earlier example shows:

```
set(CPACK_IFW_PACKAGE_GROUP com.examplecompany.product)

include(CPack)
include(CPackIFW)

cpack_add_component(foo GROUP groupA)
cpack_add_component(bar GROUP groupB)

cpack_add_component_group(groupA)
cpack_add_component_group(groupB)

cpack_ifw_configure_component(bar
    DEPENDS com.examplecompany.product.groupA.foo
)
```

`CPACK_IFW_PACKAGE_GROUP` is just one example of a large number of extra variables that can be set to provide IFW-specific configuration. Such variables should be set before `include(CPackIFW)` is called. They can be used to modify the appearance and behavior of the installer in a variety of ways. The `CPackIFW` module documentation provides a complete listing of all supported variables and their effects, many of which have analogous settings in the QtIFW product's native configuration settings. Most of those variables have sensible defaults and should be seen more as opportunities for customization rather than things that need to be set.

One exception to this is the variables relating to the name of the maintenance tool installed along with the rest of the product. This tool allows the user to modify the set of installed components, or remove the product completely. By default, the tool is given the name `maintenancetool`, but this gives no indication of what the tool relates to. On some platforms, the tool name can show up in desktop or application menus, and the default name can be confusing for users. Therefore, projects should provide a more specific name, which can be done like so:

```
set(CPACK_IFW_PACKAGE_MAINTENANCE_TOOL_NAME
    ${PROJECT_NAME}_MaintenanceTool
)
set(CPACK_IFW_PACKAGE_MAINTENANCE_TOOL_INI_FILE
    ${CPACK_IFW_PACKAGE_MAINTENANCE_TOOL_NAME}.ini
```

```
)  
include(CPackIFW)
```

The `.ini` file is used by the installer to maintain state information between invocations. Setting the name of the `.ini` file is optional, but making the name consistent with the installer itself is preferable. With the above settings, the user will see a name that relates to the project if the maintenance tool shows up in their desktop or applications menu.

A significant feature of the IFW generator is its ability to create online installers. Some or all components can be downloaded on demand instead of bundling them as part of the installer. This is particularly advantageous if some optional components are large. The IFW generator offers more advanced functionality than all the other CPack generators in this area. Two key differences are worth highlighting:

- The IFW generator is the only one to support more than one online repository. This opens up possibilities like components with restricted access, since the freely available and the restricted components can live in different repositories with different network access restrictions. Different repositories can also be used for different stability levels, such as stable, preview, and so on. It can also be useful if different components are provided by different vendors, or where some components have a different release schedule to others.

- Individual components can also be upgraded if newer versions are made available from the online repositories. This provides a very convenient upgrade path for end users. They only need to run the maintenance tool, which contacts the set of online repositories to determine the available components and their versions. Individual components can then be added, removed or upgraded as desired. Other package generators only allow adding or removing components for the version the installer was built for.

For other CPack generators, the UPLOAD_DIRECTORY keyword of the `cpack_configure_downloads()` command specifies where the downloadable packages will be created, but the IFW CPack generator ignores this option. Instead, it creates a directory called `repository` located multiple levels deep under the base `_CPack_Packages` directory. The user is expected to upload the contents of that whole `repository` directory to the download server at the URL corresponding to that repository.

As mentioned above, the IFW generator allows projects to specify additional repositories for the maintenance tool and installer. This is done using the `cpack_ifw_add_repository()` command:

```
cpack_ifw_add_repository(repoName
    URL baseUrl
    [DISPLAY_NAME displayName]
    [DISABLED]
    [USERNAME username]
```

```
[PASSWORD password]  
)
```

The `repoName` is an internal tracking name, and the `baseUrl` has a similar meaning as for `cpack_configure_downloads()`. The `DISPLAY_NAME` option should generally be used to give a meaningful name, otherwise the `baseUrl` is shown as the repository name, which tends to be less user-friendly. If the repository needs a username and password, they can be supplied, but keep in mind that the password will be stored unencrypted and should be considered insecure. The `DISABLED` keyword indicates that the repository should be disabled by default, but the user can enable it in the installer or maintenance tool's UI.

An example of a main repository for release packages and a secondary repository for preview packages (disabled by default) could be configured like this:

```
include(CPack)  
include(CPackIFW)  
  
cpack_configure_downloads(  
    https://example.com/packages/product/release  
    ALL  
)  
cpack_ifw_add_repository(secondRepo  
    DISPLAY_NAME  
    "Preview features"  
    URL  
    https://example.com/packages/product/preview  
    DISABLED  
)
```

Unfortunately, `cpack_configure_downloads()` does not support specifying a display name, so the URL will be shown instead of a more user-friendly name.

Starting with QtIFW 4.0, the generated installers support unattended command-line installs. No extra configuration is needed on the part of the project. The developer only has to ensure that QtIFW 4.0 or later is used to generate the installer. The ability to perform scripted installs on the command line can be an important feature for some users, so it is highly recommended to use QtIFW 4.0 or later, if possible.

CMake 3.23 added further capabilities requiring QtIFW 4.0 or later. The installer can run an executable at the end of installation. This is achieved by setting the `CPACK_IFW_PACKAGE_RUN_PROGRAM` variable to the location of the executable to run. This must point to the installed location, which is configurable by the user at install time. Therefore, the path should begin with one of the predefined variables supported by QtIFW, typically `@TargetDir@`. If arguments need to be passed to the executable, they can be specified as a list in the associated `CPACK_IFW_PACKAGE_RUN_PROGRAM_ARGUMENTS` variable. The user will be shown a checkbox on the last page of the installer where they can choose whether to run the executable or not. The message shown next to that checkbox can be

specified with the CPACK_IFW_PACKAGE_RUN_PROGRAM_DESCRIPTION variable.

```
set(CPACK_IFW_PACKAGE_RUN_PROGRAM
    "@TargetDir@/bin/LicenseApp"
)
set(CPACK_IFW_PACKAGE_RUN_PROGRAM_ARGUMENTS
    --check-update --post-install
)
set(CPACK_IFW_PACKAGE_RUN_PROGRAM_DESCRIPTION
    "Run application to check for an updated license"
)
```

Another QtIFW 4.0 feature supported with CMake 3.23 or later is the ability to provide a set of product images to be shown during installation. This feature is only useful when the installation may take a long time. As the installation proceeds, the installer will cycle through the provided images, showing them one at a time for about 10 seconds each. They are often used to highlight things like major new features, related products, and other marketing-related content. The product images are specified as a list of absolute paths in the CPACK_IFW_PACKAGE_PRODUCT_IMAGES variable. The images must be in .png format. With CMake 3.31 or later, CPACK_IFW_PACKAGE_PRODUCT_IMAGE_URLS can also be set to an associated list of URLs. If the user clicks on a product image during installation, the installer will open the URL associated with that image.

CMake 3.23 also added support for signing the installer application (only on macOS). The Apple code signing identity can be specified in the `CPACK_IFW_PACKAGE_SIGNING_IDENTITY` variable. Note that this is an application signing identity, not an Apple installer identity. From the point of view of macOS, QtIFW produces an ordinary application, not an installer. See [Section 37.7, “productbuild”](#) for producing a native macOS installer instead.

One drawback of the IFW package generator is that the installer produced has extra overhead compared to most other generator types. It includes the Qt support needed for the installer’s interface, networking, and so on. This can make the size of even a trivial installer 18Mb or more, compared to a few hundred kB for other generator types.

The above discussion only covers the main aspects of the IFW generator. There are considerably more capabilities available that allow projects to customize the installer and maintenance tool extensively. For many projects, the above functionality already enables the creation of flexible, robust, and cross-platform installers. If further tailoring is needed, the features presented will serve as a solid base on which to extend.

37.3. WIX

The WIX package generator produces `.msi` installers for Windows using the [WiX toolset](#). Compared to the IFW package

generator, it has a similar degree of UI customizability and offers the following advantages:

- Support for unattended command-line installs is mature. It is provided through an option to the `msiexec` tool.
- Installers are tightly integrated into Windows' Add/Remove functionality.
- The default appearance should be familiar to most users.

On the other hand, it has the following disadvantages compared to IFW:

- No simple, direct way of providing localized component names and descriptions.
- `CPACK_WIX_COMPONENT_INSTALL` and `CPACK_COMPONENTS_GROUPING` are both ignored (see below).
- No support for downloadable components.
- Multiple versions with the same upgrade GUID cannot be installed simultaneously (see below). Each install replaces the previous one, even if in a completely different directory.

By default, the WIX generator produces a component-based package which will always be presented in the UI as though `CPACK_COMPONENTS_GROUPING` had been set to `IGNORE`. If a component-based package is undesirable, `CPACK_MONOLITHIC_INSTALL` can be set to true, but then all defined

components are always installed. It is not possible to only include some components in a monolithic installer, and if `CPACK_COMPONENTS_ALL` is set, CMake will issue a warning and ignore `CPACK_COMPONENTS_ALL`.

A key part of a WIX installer is that it contains a product GUID and an upgrade GUID. If any other installed package has the same upgrade GUID, that other package will be upgraded rather than installing the new package as a separate product. If the upgrade GUIDs are the same but the product GUIDs are different, the upgrade is considered a major upgrade and the new installer will completely replace the old package. Where the product GUID is also the same, the new installer should be able to perform a minor upgrade as long as the installer reports a newer version number than the currently installed package. Service packs are an example where the same product GUID is maintained as the base version they apply to. Unless creating a fairly advanced installer or packaging strategy, projects will typically need to change the product GUID with each release. The constraints from Windows itself for keeping the same product GUID from one package to another are fairly stringent.

CPack provides support for setting the product and upgrade GUIDs. The `CPACK_WIX_PRODUCT_GUID` and `CPACK_WIX_UPGRADE_GUID` variables can be set before calling `include(CPack)` to control them manually, or they can be left unset to allow `cpack` to generate new values each time it is invoked. For the product

GUID, this automatic generation is likely to be the desired behavior, but the upgrade GUID should ideally never change for the life of the product. Projects should obtain a GUID and set `CPACK_WIX_UPGRADE_GUID` to that value, then ideally never change it again. This will ensure all future releases are able to upgrade older releases seamlessly. The actual GUID can be obtained by a variety of means, such as command line tools, web-based UUID generators, or even with CMake itself using the `string(UUID)` command. For some products, it may make sense for the upgrade GUID to change with each major release to allow an older major release to co-exist with a newer one, thereby facilitating the users' migration path.

One of the criteria around when a product GUID must change is if the name of the `.msi` file changes. Since the installer's file name would typically include some version details, this means each release would be considered a major upgrade. If the user installs the new version, it would completely replace any previously installed version. The new version can be installed to a different directory and the old one would be removed. It may be tempting to then use a default installation directory (controlled by `CPACK_PACKAGE_INSTALL_DIRECTORY`) that includes a version number, but users would likely prefer the default directory to stay the same across upgrades. The default directory should ideally only change if the upgrade GUID changes, since that is the identifier that provides the continuity from one version to another.

When installing a new package and another package with the same upgrade GUID is already installed, a check is made between the versions. Only if the new package is of a later version will the upgrade be allowed to proceed. Only the first three version number components are considered in this test, so versions 2.7.4.3 and 2.7.4.9 would be considered the same version from an upgrade perspective. Projects intending to use the WIX generator should therefore avoid using more than three version number components. If allowing CPACK_PACKAGE_VERSION to be automatically set from the individual CPACK_PACKAGE_VERSION_xxx version parts, this will already be enforced.

Most of the UI defaults are acceptable for a basic WIX package. Projects may want to provide a product icon to use in place of the generic MSI installer icon for improved branding in the Add/Remove area, but the defaults are otherwise generally acceptable. The following example shows a basic configuration of a WIX installer.

```
# Define generic setup for all generator types...

# WIX-specific configuration
set(CPACK_WIX_PRODUCT_ICON
    ${CMAKE_CURRENT_LIST_DIR}/Logo.ico
)
set(CPACK_WIX_UPGRADE_GUID
    XXXXXXXX-XXXX-XXXX-XXXX-XXXXXXXXXXXX
)
```

```
include(CPack)
# Define components and component groups...
```

The WIX generator will use some basic heuristics to decide what architecture to build the installer for. With CMake 3.24 or later, this can be explicitly specified with the CPACK_WIX_ARCHITECTURE variable. This will be required if building an installer for platforms other than x86 or x64 (64-bit Intel-based chips), with arm64 being a common example where this is needed.

With CMake 3.28 and earlier, the WIX generator has a bug which affects the handling of start menu entries and registration of the uninstaller. The installer always installs the package for all users, and it requires administrator privileges. But the start menu entries and uninstaller are only made available to the user performing the install, which is inconsistent. CMake 3.29 fixed this behavior such that the start menu entries are available to all users, and the uninstaller is properly registered with the system. A new CPACK_WIX_INSTALL_SCOPE variable defines what type of installation is permitted, but only the perMachine value is currently supported. A perUser value is reserved for implementation in a future version of CMake.

CMake 3.29.0 to 3.29.4 made perMachine the default install scope, but it was later found to break updating existing installations made with an earlier version of cpack. Therefore, 3.29.5

restored the old (inconsistent) default behavior. CMake 3.31.0 made `perMachine` the default again, this time subject to policy CMP0172 so that projects can choose when to update to the new default.

Note also that installations made from packages where `CPACK_WIX_INSTALL_SCOPE` was *not* set (including packages made with CMake 3.28 and earlier) cannot be updated with a package where `CPACK_WIX_INSTALL_SCOPE` *was* set. Projects transitioning to using `CPACK_WIX_INSTALL_SCOPE` will need to warn users to manually uninstall earlier versions before installing a newer version with `CPACK_WIX_INSTALL_SCOPE` set.

CMake 3.30 added support for WIX 4, which is selected by setting `CPACK_WIX_VERSION` to 4. The user is responsible for ensuring the requested WIX version is installed. When `CPACK_WIX_VERSION` is set to 4, the `CPACK_WIX_INSTALL_SCOPE` default is always `perMachine`.

37.4. NSIS

The NSIS package generator produces installer executables for Windows using the [Nullsoft Scriptable Install System](#). It shares a number of similar characteristics with the IFW, WIX, and Inno Setup generators, including a degree of UI customizability and support for component hierarchies. Advantages of the NSIS generator include:

- Mature support for unattended command-line installs is provided directly by the installer executable.
- It is one of only two actively maintained CPack generators that support install types (Inno Setup being the other one).
- Pre-install, post-install, and pre-uninstall commands are directly supported, although these must be implemented as NSIS commands.
- It supports downloadable components.

The NSIS generator has a few drawbacks:

- `CPACK_NSIS_COMPONENT_INSTALL` and `CPACK_COMPONENTS_GROUPING` are both ignored. The NSIS generator has the same restrictions as the WIX generator in this regard.
- Once a product is installed, users cannot change the set of installed components without redoing the install.
- Only basic UI customization is supported, and there is no direct support for localization of any UI contents. These are limitations of CPack's generator, not of NSIS itself, which does offer some facilities via its own native scripting language.
- Although it is possible to install different versions to different locations, they share registry details, and so are not fully isolated from each other. Only one version will show up in the Add/Remove area of the Windows settings.

By default, these installers will only perform an upgrade of an existing product installation if the new package is installed to the same directory as the old one. Projects can set the CPACK_NSIS_ENABLE_UNINSTALL_BEFORE_INSTALL variable to true to force the installer to check the registry for an existing installation of the package first. This check does not rely on the install location, so it is a more reliable way to check for an existing installation to be upgraded. Therefore, setting this variable to true is recommended for most projects.

NSIS installers benefit from overriding the default appearance in a number of areas. The icons used for the installer, uninstaller, and in the Add/Remove area should be set, as the defaults are either of low quality or produce blank boxes. The name displayed for the product should also be explicitly set to avoid inappropriate default text supplied by CPack. The following example shows a basic configuration with overrides to avoid the defaults that most projects would find unsuitable.

```
# Define generic setup for all generator types...

# NSIS-specific configuration
set(CPACK_NSIS_MUI_ICON
    ${CMAKE_CURRENT_LIST_DIR}/InstallerIcon.ico      ①
)
set(CPACK_NSIS_MUI_UNICON
    ${CMAKE_CURRENT_LIST_DIR}/UninstallerIcon.ico    ②
)
set(CPACK_NSIS_INSTALLED_ICON_NAME bin/MainApp.exe) ③
set(CPACK_NSIS_DISPLAY_NAME      "My Project Suite") ④
set(CPACK_NSIS_PACKAGE_NAME     "My Project")        ⑤
set(CPACK_NSIS_ENABLE_UNINSTALL_BEFORE_INSTALL YES)
```

```
include(CPack)
# Define components and component groups...
```

- ① The icon used for the installer itself. Windows may overlay further content to indicate that the installer requires administrator privileges. Use an absolute path to ensure NSIS can find the icon when creating the installer.
- ② The icon used for the uninstaller that will be copied to the installation directory. Again, use an absolute path to the icon.
- ③ This controls the icon used for the product in the Add/Remove area. It must be a path to either an icon file (.ico) or an executable that has an embedded application icon of its own. The path should be to the *installed* location, relative to the base point of the install.
- ④ The name shown for the package in the Add/Remove area only.
- ⑤ The name used in many places in the installer's UI and also in the title bar during installation. The word Setup may be appended to it in some contexts.

CMake 3.17 added the CPACK_NSIS_WELCOME_TITLE and CPACK_NSIS_FINISH_TITLE variables, which override the default welcome and finishing titles, as well as CPACK_NSIS_MUI_HEADERIMAGE which overrides the default header image shown on each page of the installer. CMake 3.20 added support for the CPACK_NSIS_BRANDING_TEXT and CPACK_NSIS_BRANDING_TEXT_TRIM_POSITION variables, which can be used to replace the generic *Nullsoft Install System* message along the bottom of the installer pages. With CMake 3.22 and later, the licensing page normally shown during installation can be disabled by setting CPACK_NSIS_IGNORE_LICENSE_PAGE to true.

CMake 3.17 also added support for the CPACK_NSIS_UNINSTALL_NAME variable, which can be used to

change the name of the uninstaller from its generic default. This can improve the usability of the uninstaller by making its relationship to the package more obvious. The uninstaller will be more identifiable in a list of running processes and when the user is switching between running applications. Given these advantages, it is recommended projects always set this variable.

An important change that also occurred in CMake 3.17 was the minimum NSIS version was raised to 3.0 (previously it was 2.09). The CMake 3.17.0 release did not check the NSIS version and would fail with a NSIS parsing error if the NSIS version was not 3.0 or later. From CMake 3.17.1, the updated minimum NSIS version is properly checked and reported.

With CMake 3.18 or later, installers can be made DPI-aware by setting `CPACK_NSIS_MANIFEST_DPI_AWARE` to true. Note that icon handling and some NSIS plugins might not yield acceptable results in all cases, so it is advisable to test the installer at different DPI settings if enabling this option.

37.5. Inno Setup

This is the newest CPack generator, available since CMake 3.27. It is similar to the NSIS generator, producing a standalone Windows installer as an executable. Use `INNOSETUP` as the generator name in the `CPACK_GENERATOR` variable or the `cpack -G` command-line option. Notable advantages of the Inno Setup generator are very similar to those for NSIS:

- Support for unattended command-line installs is provided directly by the installer executable.
- It is one of only two actively maintained CPack generators that support install types (NSIS being the other one).
- It supports downloadable components.

The drawbacks are also mostly similar to those for NSIS:

- Like NSIS and WIX, the `CPACK_INNOSETUP_COMPONENT_INSTALL` and `CPACK_COMPONENTS_GROUPING` variables are both ignored.
- No direct support is provided for modifying an existing installation of the package through the Windows Add/Remove Program area. This is a limitation of the CPack generator, not Inno Setup. An uninstaller is provided though, and the installer can be re-run to add previously skipped components, but not to selectively remove installed components.
- Dependencies between components are ignored.

One unique feature of this generator is that it provides direct controls for disabling the readme and license pages of the installer. This is done using the `CPACK_INNOSETUP_IGNORE_README_PAGE` and `CPACK_INNOSETUP_IGNORE_LICENSE_PAGE` variables, respectively. When these variables are defined and set to true, they override the more generic `CPACK_RESOURCE_FILE_README` and

`CPACK_RESOURCE_FILE_LICENSE` variables. The license page is particularly relevant, since it must be disabled for a fully unattended, scripted install to be possible. Projects should ideally set `CPACK_INNOSETUP_IGNORE_LICENSE_PAGE` to true, and if a license page must be shown, do so when the installed application is run rather than during installation.

Being quite new, this generator lacks functionality in a number of areas. A couple of mechanisms are provided for accessing some Inno Setup features directly, which can be used to work around some limitations of the CPack generator implementation. Inno Setup itself has a fairly rich set of configuration options, and values from the [Setup] section can be manipulated using `CPACK_INNOSETUP_SETUP_xxxx` variables, where `xxxx` is the name of the setup option (case-sensitive). The example further below uses this to specify the icon for the uninstaller, which is achieved by modifying the `UninstallDisplayIcon` setting. It also sets the `PrivilegesRequiredOverridesAllowed` setting to allow non-administrator installs.

For more complex scenarios, whole scripts can be included automatically at the top of the Inno Setup input file generated by `cpack`. These are specified through the `CPACK_INNOSETUP_EXTRA_SCRIPTS` variable, which can contain a list of files specified with absolute paths. This is likely to be the preferred mechanism for projects to inject custom logic. For

even more advanced scenarios involving low-level Pascal code, CPACK_INNOSETUP_EXTRA_CODE is also available, but that is really only intended for those who are very familiar with Inno Setup.

The following example shows some relevant settings when using the Inno Setup generator, including how to set various icon types.

```
# Define generic setup for all generator types...

# INNOSETUP-specific configuration
set(CPACK_INNOSETUP_USE_MODERN_WIZARD Yes)
set(CPACK_INNOSETUP_SETUP_PrivilegesRequiredOverridesAllowed
    dialog ①
)
set(CPACK_INNOSETUP_SETUP_UninstallDisplayIcon
    ${CMAKE_CURRENT_LIST_DIR}/Uninstaller.ico ②
)
set(CPACK_INNOSETUP_ICON_FILE
    ${CMAKE_CURRENT_LIST_DIR}/InstallerApp.ico ③
)
set(CPACK_PACKAGE_ICON
    ${CMAKE_CURRENT_LIST_DIR}/Wizard.bmp ④
)

include(CPack)
# Define components and component groups...
```

① The installer will show a pop-up dialog asking if the package should be installed for all users, or just the current user.

② The icon shown in the Windows Add/Remove Programs area, and also for the uninstaller executable in the Windows File Explorer. This should be a file in .ico format, or an executable from which to extract an icon. The Inno Setup documentation states this should normally be a path based on a directory constant, such as {app} (which specifies the base install location). If specifying a .ico file, make sure that file is installed as part of the package.

- ③ This icon is used as the installer's icon when switching between applications. It is also shown in the installer's menu bar. This should be an absolute path to a file on the build machine, which must be in .ico format.
- ④ When the modern wizard is enabled (CPACK_INNOSETUP_USE_MODERN_WIZARD is set to true), the installer shows an icon in the top right of each wizard page. The default icon is often suitable, but projects can override it if they want to apply their own branding. It must be an absolute path on the build machine to a file in .bmp format.

As for the WIX generator, some basic heuristics are used to decide what architecture to build the installer for. The project can specify the architecture directly with the CPACK_INNOSETUP_ARCHITECTURE variable. Again, this will be required if building an installer for platforms other than x86 or x64 (64-bit Intel-based chips), with arm64 being a common example where this is needed.

37.6. DragNDrop

On macOS, products are commonly distributed as .dmg files. These act like disk images and can contain anything from a single application through to a whole suite of applications, documentation links, and so on. A symlink to the /Applications area is frequently provided as part of the image so that users can easily drag applications onto it to install them, hence the name DragNDrop for this generator type. Configuration variables specific to this generator type use DMG in their name rather than DRAGNDROP, but note that cpack will only recognize DragNDrop as the name of the generator itself.

The .dmg format is closer to an archive than a UI installer. Components are used to control whether one or multiple .dmg files are created and what each .dmg file contains, but there is no install-time UI to choose components. The user is expected to open the .dmg file(s) and drag the contents to the desired location to install them. CPACK_COMPONENTS_ALL controls which components are installed, and the CPACK_COMPONENTS_GROUPING variable controls how those components are distributed between .dmg file(s) as follows:

ALL_COMPONENTS_IN_ONE

All components will be included in a single .dmg file.

ONE_PER_GROUP

Each top level component group and each component not in a group will be put in its own separate .dmg file.

IGNORE

Each component will be put in its own separate .dmg file and all component groups will be ignored.

When using CMake 3.17 or later, the file name for each component's .dmg file can be specified using variables of the form CPACK_DMG_<component>_FILE_NAME if required (only relevant for the ONE_PER_GROUP or IGNORE cases).

This package generator type typically requires little customization beyond the defaults. The size and layout of the

Finder window displayed when the disk image is opened can be controlled by providing a custom `.DS_Store` file. The project will need to either prepare such a file manually using an example folder containing the same things as the final disk image, or it can be created programmatically in AppleScript. The `CPACK_DMG_DS_STORE` variable can be used to name a pre-prepared `.DS_Store` file or `CPACK_DMG_DS_STORE_SETUP_SCRIPT` can point to an AppleScript file to be run at package generation time. For either case, a background image can be set with the `CPACK_DMG_BACKGROUND_IMAGE` variable if desired, but leaving the background at the blank default is relatively common. For cases where the disk image should not provide a symlink to the `/Applications` folder, the project should set `CPACK_DMG_DISABLE_APPLICATIONS_SYMLINK` to true.

An icon can be specified for the disk image by setting `CPACK_PACKAGE_ICON` to an icon in `.icns` format. This icon is only used to represent the `.dmg` file when mounted, not for the `.dmg` file itself. The specified icon may show up in the Finder title bar or certain Finder views, but it is otherwise not a prominently displayed icon.

[Section 36.1, “Packaging Basics”](#) outlines how `CPACK_RESOURCE_FILE_LICENSE` can be used to add a license file to installers. For the DragNDrop generator, the file’s contents are shown in a license dialog presented to the user when they open the DMG image. The command CMake uses internally to add the

license file to the DMG image was deprecated by macOS 12.0, and will be removed altogether in a future macOS version. Thus, CMake will eventually lose the ability to provide that license dialog. CMake 3.23 added a separate `CPACK_DMG_SLA_USE_RESOURCE_FILE_LICENSE` variable which controls whether to consider `CPACK_RESOURCE_FILE_LICENSE` for just the DragNDrop generator. This allows the project to leave `CPACK_RESOURCE_FILE_LICENSE` set for other CPack generators, but avoid using the deprecated tool for the DragNDrop generator. `CPACK_DMG_SLA_USE_RESOURCE_FILE_LICENSE` defaults to true when using CMake 3.23 with a project that sets `CPACK_RESOURCE_FILE_LICENSE`. This preserves the old behavior and adds the license dialog to the DMG image. With CMake 3.24 or later, the default value for `CPACK_DMG_SLA_USE_RESOURCE_FILE_LICENSE` is controlled by policy `CMP0133`. The OLD policy behavior continues to default the variable to true, whereas the NEW policy behavior defaults it to false. Projects that set `CPACK_RESOURCE_FILE_LICENSE` should be updated to either set `CPACK_DMG_SLA_USE_RESOURCE_FILE_LICENSE` to false, or to set policy `CMP0133` to NEW. A different mechanism for handling license acceptance by the user will then need to be found (e.g. presenting an acceptance dialog the first time the user runs the application).

Limited language localization is provided through the `CPACK_DMG_SLA_LANGUAGES` and `CPACK_DMG_SLA_DIR` variables. These can be used to provide specific phrases used during the license

agreement phase of opening the disk image, and to provide a localized version of the license agreement. See the DragNDrop generator's documentation for how these two variables are used and the requirements around the language files that need to be provided. As mentioned above, projects should transition away from using these and find a different license acceptance mechanism.

CMake 3.21 added the ability to specify the file system format used for the .dmg image. The CPACK_DMG_FILESYSTEM variable can be set to any value that the hdiutil -fs option supports, but the most typical values are either APFS or HFS+. If this variable is not set, the default is HFS+. Note that APFS file systems are only officially supported on macOS 10.13 or later.

The Bundle generator type is related to the DragNDrop generator. It uses the same set of DMG variables, plus some of its own. The Bundle generator was originally intended for producing a single app bundle, potentially for submission to the Apple App Store. These days, such app bundles are better prepared during the build itself using CMake's Xcode generator, as this more closely follows the process expected by Apple. See [Chapter 25, *Apple Features*](#) for the recommended way of preparing such app bundles rather than using the CPack Bundle generator type.

37.7. productbuild

An alternative to the DragNDrop generator is productbuild. It produces a .pkg package for use with the macOS Installer app. CPACK_MONOLITHIC_INSTALL should not be set to true with this generator, as doing so can produce broken installers. Installer types are not supported, and there is very little ability to customize the UI, although the defaults are typically sufficient anyway.

Component handling with this generator has some quirks. Due to long-standing bugs in the generator's implementation, projects should always define at least one component by calling `cpack_add_component()` after the `include(CPack)` call. Failing to do so can result in a package containing no files. Other workarounds also exist, but this is the simplest and most robust. CPACK_COMPONENTS_GROUPING is ignored, and the installer will always replicate the whole component and component grouping hierarchy. The installer will respect any REQUIRED, HIDDEN, or DISABLED directives given to `cpack_add_component()`.

Packages created using CMake 3.22 or earlier are unable to be installed to the user's home directory. CMake 3.23 added a number of variables which provide more flexibility around allowable install locations:

CPACK_PRODUCTBUILD_DOMAINS

Setting this variable to true enables customizing where the package may be installed to. The permitted install

destinations are then controlled by the other CPACK_PRODUCTBUILD_DOMAINS_... variables below. When enabled, it allows CPack to avoid using deprecated methods internally and results in a more flexible installer. This will almost always be desirable. If this variable is not set, CMake 3.28 and older default to the domains feature being disabled. CMake 3.29 and later enable the domains feature by default, subject to policy CMP0161. Projects should generally either set CPACK_PRODUCTBUILD_DOMAINS to true, or ensure policy CMP0161 uses the NEW behavior.

CPACK_PRODUCTBUILD_DOMAINS_ANYWHERE

Setting this to true allows the package to be installed to any drive. It defaults to true, and projects should usually leave this at the default setting. It only has an effect if CPACK_PRODUCTBUILD_DOMAINS is set to true.

CPACK_PRODUCTBUILD_DOMAINS_USER

Setting this to true allows the package to be installed to a user's home directory. Such an installation does not require administrative access, since it runs as the user's account rather than as root. Note that a consequence of this is that the installer is not permitted to write to any location outside the user's home directory. This is especially relevant for pre- and post-flight scripts. CPACK_PRODUCTBUILD_DOMAINS_USER defaults to false, but if the package supports a user home directory installation, it would be desirable to set it to true.

`CPACK_PRODUCTBUILD_DOMAINS_USER` only has an effect if `CPACK_PRODUCTBUILD_DOMAINS` is set to true.

`CPACK_PRODUCTBUILD_DOMAINS_ROOT`

If this is set to true (the default), the package can be installed to the system drive. The only reason to set it to false is if the package only supports installation to a user's home directory, which would be unusual. It only has an effect if `CPACK_PRODUCTBUILD_DOMAINS` is set to true.

The productbuild generator supports signing the installer package. This is achieved by setting `CPACK_PRODUCTBUILD_IDENTITY_NAME` to the signing details. `CPACK_PRODUCTBUILD_KEYCHAIN_PATH` can also be set, if required. Often just specifying the default identity is enough, which can be done like so:

```
set(CPACK_PRODUCTBUILD_IDENTITY_NAME
    "Developer ID Installer"
)
include(CPack)
```

The productbuild generator theoretically supports downloadable components, but when productbuild processes the input files created by the generator, it still ends up embedding the component packages. The result is a fully offline installer, the same as if no components were designated as downloadable.

Upgrades are handled by replacing the previous contents of an existing install. Like for NSIS installers, the set of installed components cannot be modified without reinstalling the product. It is also not typically possible to install multiple versions simultaneously to different directories.

Installers produced by the productbuild generator are relocatable by default. When the package is installed on an end user's machine, if the OS knows of an app bundle with the same name as one of the apps provided by the package, the installer will overwrite that existing app no matter where it is on the file system. The app will not be installed to the default /Applications area in these cases, which usually means it also won't show up in places where the user expects it to.

The above situation commonly arises for developers on the machine they are using to build and test packages. The app bundle produced by the build is known to the OS, so when installing the package, the build tree's app bundle is used as the install location for that app instead of the expected location in /Applications. There will also be another copy of the app in the _CPack_Packages staging directory of the build tree which can yield similar behavior. To properly test the installer, all copies of the app bundles being installed would need to be removed from the developer's machine first before running the installer.

One workaround to the above relocation problem is to mark components as not relocatable. This prevents the installer from

selecting the location of an existing app bundle. The trade-off is that it also prevents the user from moving app bundles around, should they so wish. To make a component non-relocatable, a custom plist file needs to be provided for each component. This is achieved by using the PLIST option with the `cpack_add_component()` command:

```
cpack_add_component(MyProj_Runtime  
... # Other options  
PLIST runtime.plist  
)
```

The plist file should be obtained by using the `--analyze` option with the `pkgbuild` command and updating that file as needed. Verbose output of a `cpack` command for the project can also be helpful:

```
cpack -G productbuild -V
```

Example of a typical plist file:

```
<?xml version="1.0" encoding="UTF-8"?>  
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN"  
      "http://www.apple.com/DTDs/PropertyList-1.0.dtd">  
<plist version="1.0">  
<array>  
  <dict>  
    <key>BundleHasStrictIdentifier</key>  
    <true/>  
    <key>BundleIsRelocatable</key>  
    <true/>  
    <key>BundleIsVersionChecked</key>  
    <true/>  
    <key>BundleOverwriteAction</key>
```

```
<string>upgrade</string>
<key>RootRelativeBundlePath</key>
<string>Applications/MyApp.app</string>
</dict>
</array>
</plist>
```

Change the `BundleIsRelocatable` dictionary item to `false` to prevent the OS from relocating the app on install. There will be one `<dict></dict>` section for each app bundle in the component.

The `productbuild` generator should be considered a replacement for the older and no longer supported `PackageMaker` generator. Apple no longer provides the `PackageMaker` app, so developers using newer versions of macOS must use `productbuild` instead. The `PackageMaker` generator was officially deprecated in CMake 3.17 and was removed completely in CMake 3.24.

37.8. RPM

On Linux systems, RPM is one of the two dominant package management formats. RPM packages do not have UI features of their own, they are essentially just archives with a fairly extensive set of metadata and some scripting features. The system's package manager uses these to manage dependencies between packages, provide information to the user, trigger pre/post install and uninstall scripts, and so on.

Since the package itself has no UI features, there is no customization needed in that area, but the RPM generator provides extensive customizability of the metadata through a large number of variables. Many of these variables do not need to be explicitly set, since the majority of the defaults are appropriate for projects that don't need to do anything complex. For packages that do not need to invoke pre/post install or uninstall scripts, and for which inter-package dependencies can be automatically determined by the underlying package creation tool, the amount of customization is similar to that of other package generators.

The RPM generator supports component installs, but components are disabled by default. When components are disabled, only a single .rpm is produced and the behavior is as though CPACK_MONOLITHIC_INSTALL was set to true. All components are included in the package in such cases. If components are enabled, then CPACK_COMPONENTS_GROUPING has its usual meaning and multiple .rpm files will be created. Components are enabled by setting CPACK_RPM_COMPONENT_INSTALL to true, and the set of installed components is controlled by CPACK_COMPONENTS_ALL as usual.

```
# Define generic setup for all generator types...
set(CPACK_COMPONENTS_GROUPING ONE_PER_GROUP)

# RPM-specific configuration
set(CPACK_RPM_COMPONENT_INSTALL YES)
```

```
include(CPack)
# Define components and component groups...
```

The component or group names might not be suitable for use as package names. These package names can be set on a per-component basis with CPACK_RPM_<COMP>_PACKAGE_NAME, where <COMP> is the uppercase component name. When creating a package with components disabled, the single monolithic package name can be overridden by setting CPACK_RPM_PACKAGE_NAME instead.

```
add_executable(sometool ...)
install(TARGETS sometool ... COMPONENT MyProjUtils)

set(CPACK_RPM_MYPROJUTILS_PACKAGE_NAME myproj-tools)
include(CPack)
```

The name of the .rpm files can also be customized, and it is likely that projects will want to do so. The name of each component's .rpm file is controlled by the CPACK_RPM_<COMP>_FILE_NAME variable, or just CPACK_RPM_FILE_NAME for non-component packaging. The default value follows this pattern:

```
<CPACK_PACKAGE_FILE_NAME>[-<component>].rpm
```

The <component> part is the original component name (i.e. no change in upper/lowercase). One drawback to this default file name is that it does not include any version or architecture details, but such information would normally be required (or at

least desirable). It is generally preferable to instruct `cpack` to let the underlying package creation tool select a better default package name, which can be done by setting `CPACK_RPM_<COMP>_FILE_NAME` to the special string `RPM-DEFAULT`. Examples of typical file names produced by this arrangement are given below.

The `RPM-DEFAULT` package file name will automatically include the architecture. If the architecture needs to be explicitly specified, such as to mark a package as `noarch` to indicate it is not architecture-specific, the per-component `CPACK_RPM_<COMP>_PACKAGE_ARCHITECTURE` variable can be set to the required value. Alternatively, `CPACK_RPM_PACKAGE_ARCHITECTURE` can be set to act as the default if no component-specific override is set (it is also used for monolithic packages). The default value for the architecture is computed by `cpack` as the output of `uname -m`, but if building a 32-bit package on a 64-bit host, this would be wrong. The project would need to explicitly set the architecture value in that case.

RPM files are required to have version information. The RPM generator will use `CPACK_PACKAGE_VERSION` by default, but a RPM-specific version number can also be set using `CPACK_RPM_PACKAGE_VERSION` if required (but the need for this should be rare). Note that it is not currently possible to specify

per-component versions. The CPack RPM generator is currently limited to using the same version for all components.

In addition to the package version, RPM packages also have a separate release number, which is specified using `CPACK_RPM_PACKAGE_RELEASE`. This release number is the release of the package itself, not of the product, so the package version would normally remain constant if the release number is increased (e.g. to fix a packaging issue). If the package version changes, the release number is usually reset back to 1, which is the default value if `CPACK_RPM_PACKAGE_RELEASE` is not specified.

An optional epoch can also be specified by `CPACK_RPM_PACKAGE_EPOCH`. Its use may be more common on some systems or repositories than others. The full version has the format `E:X.Y.Z-R`, where `E` is the epoch and must be a number, if provided. When no epoch is set, the full version has the format `X.Y.Z-R`. Unless it is known that an epoch value is required, projects should generally leave the epoch unset.

Unless the project explicitly overrides `CPACK_PACKAGE_VERSION` and `CPACK_RPM_PACKAGE_ARCHITECTURE`, their values won't be available within `CMakeLists.txt` files. The defaults for these variables are only computed when `cpack` processes the input file, not when `CMake` runs. This means it is a lot more work to robustly set the package file name directly rather than using

RPM-DEFAULT. The following example shows how to make use of the RPM-DEFAULT feature:

```
# Optional, default of 1 is often okay
set(CPACK_RPM_PACKAGE_RELEASE 5)

if(CMAKE_SIZEOF_VOID_P EQUAL 4)
    set(CPACK_RPM_PACKAGE_ARCHITECTURE i686)
endif()

set(CPACK_RPM_MYPROJUTILS_PACKAGE_NAME myproj-tools)
set(CPACK_RPM_MYPROJUTILS_FILE_NAME      RPM-DEFAULT)
include(CPack)
```

For the above, assuming CPACK_PACKAGE_VERSION evaluates to a string of the form X.Y.Z, the example would typically lead to package file names like:

```
myproj-tools-X.Y.Z-5.i686.rpm
myproj-tools-X.Y.Z-5.x86_64.rpm
```

As discussed in the previous chapter, the default base install point is unlikely to be desirable on Linux systems, and this extends to the creation of RPM packages. In fact, for all but Windows systems, a more appropriate base point should generally be set for packaging too by explicitly setting the CPACK_PACKAGING_INSTALL_PREFIX variable. Extending the example from [Section 35.1.2, “Base Install Location”](#), the project may want to do something like the following:

```
if(NOT WIN32 AND
    CMAKE_SOURCE_DIR STREQUAL CMAKE_CURRENT_SOURCE_DIR)
```

```
set(CMAKE_INSTALL_PREFIX
    "/opt/mycompany.com/${PROJECT_NAME}"
)
set(CPACK_PACKAGING_INSTALL_PREFIX
    ${CMAKE_INSTALL_PREFIX}
)
endif()
```

A feature unique to RPM packages is that they can include relocation paths. Packages can specify one or more path prefixes which the user can then choose to relocate to another part of their file system at install time. To support this feature, the CPACK_RPM_PACKAGE_RELOCATABLE variable must be set to true. The CPACK_RPM_RELOCATION_PATHS variable can then contain a list of path prefixes that the user will be allowed to relocate. If using this feature, developers should consult the RPM generator's documentation to understand how relative paths are treated, and the various default fall backs that apply to both of these variables. Note also that if the project is included as part of a Linux distribution, the distribution maintainers will likely need to override both the install prefix variables and the relocation directories, so prefer to keep things simple.

The RPM package creation tool, `rpmbuild`, would normally be expected to strip debug symbols from binaries before adding them to the package. The rationale is that the size of release binaries should be minimized, and they would normally hide implementation details and not provide debugging facilities. Normally, stripping is controlled by the CPACK_STRIP_FILES

variable, which determines whether stripping is performed as part of the staged install during packaging. But in the case of the RPM generator, `rpmbuild` will often perform its own stripping by default. Therefore, even if `CPACK_STRIP_FILES` is false or unset, stripping may still occur. The underlying problem is that `rpmbuild` typically has a post-staging install section which strips binaries and performs other tasks before creating the final `.rpm` package. Traditionally, the workaround offered by `cpack` is to override that behavior by setting the `CPACK_RPM_SPEC_INSTALL_POST` variable, usually to something like `/bin/true`. That approach is deprecated in favor of using `CPACK_RPM_SPEC_MORE_DEFINE` instead:

```
# Prevent stripping and other post-install steps during
# package creation
set(CPACK_RPM_SPEC_MORE_DEFINE
    "%define __spec_install_post /bin/true"
)
```

While the above technique for preventing stripping works, it also discards all the other operations that would normally be applied (e.g. automatic byte code compilation for python files, architecture-specific post-processing). A potentially better alternative is to allow stripping of the binaries in the `.rpm` and produce a separate debuginfo package. Initial support for producing debuginfo packages was added in CMake 3.7, and it was further improved in 3.8 and 3.9. To enable this feature, all that is usually required is to set either

`CPACK_RPM_DEBUGINFO_PACKAGE` or the component-specific equivalent `CPACK_RPM_<COMP>_DEBUGINFO_PACKAGE` to true. The debuginfo packages produced will contain source files as well as the debug information. The sources are taken from `CMAKE_SOURCE_DIR` and `CMAKE_BINARY_DIR` by default, but this can be overridden with the `CPACK_BUILD_SOURCE_DIRS` variable. Parts of the source directory hierarchy can be excluded using the `CPACK_RPM_DEBUGINFO_EXCLUDE_DIRS` and `CPACK_RPM_DEBUGINFO_EXCLUDE_DIRS_ADDITION` variables, although projects probably only want to set the latter. The former is typically used to exclude system directories and has an appropriate default value. Distribution maintainers may want to override `CPACK_RPM_DEBUGINFO_EXCLUDE_DIRS` independently of what the project would set in `CPACK_RPM_DEBUGINFO_EXCLUDE_DIRS_ADDITION`, hence the use of two separate variables.

When producing debuginfo packages, errors like the following may sometimes be encountered:

```
CPackRPM: source dir path '/path/to/source/dir' is shorter
than debuginfo sources dir path
'/usr/src/debug/SomeProject-X.Y.Z-Linux/src_0'! Source dir
path must be longer than debuginfo sources dir path. Set
CPACK_RPM_BUILD_SOURCE_DIRS_PREFIX variable to a shorter
value or make source dir path longer. Required for
debuginfo packaging. See documentation of
CPACK_RPM_DEBUGINFO_PACKAGE variable for details.
```

Due to the way paths are rewritten as part of the debuginfo processing, the path to the source tree needs to be longer than the intended installed location of the sources. Note that this may impact continuous integration systems where the location of the source tree is typically fixed. This need for a longer path length may be in conflict with other constraints where the path length may need to be minimized, so consider carefully whether such constraints may apply to the project.

Source RPMs can also be produced by the RPM generator. These are similar to the debuginfo packages, but they only contain the sources and no debugging information. They are produced in the same way as source packages for other package generators. The RPM generator's documentation includes basic instructions showing how to build a binary RPM from the source RPM, which may be a useful verification step.

```
# Create source RPM
cpack -G RPM --config CPackSourceConfig.cmake

# Verify that a binary RPM can be produced from it
mkdir -p build_dir/BUILD      \
       build_dir/BUILDROOT \
       build_dir/RPMS     \
       build_dir/SOURCES \
       build_dir/SPECS   \
       build_dir/SRPMS
rpmbuild --define "_topdir build_dir"    \
          --rebuild <source-RPM-filename>
```

The RPM generator supports many more variables than the ones discussed above. Details about what the packages provide or require can be specified, or the package creation tool can be directed to automatically compute them. If the package replaces or conflicts with other packages, this can also be specified. Scripts to be run before or after package installation and uninstallation can be given, or if complete control is needed, the project can provide its own custom .spec file template instead of using the default one provided by cpack (although this should be avoided if possible, since it negates much of the functionality already provided by cpack).

37.9. DEB

The DEB format is the other dominant package format for Linux systems. Both DEB and RPM share many similar characteristics. DEB packages are also basically just archives with associated metadata, which the system's package manager uses to enforce dependencies, trigger scripts, etc.

One difference between DEB and RPM is that the preparation of DEB packages does not require a special tool, unlike RPM packages which do. This allows DEB packages to be created on systems that do not themselves use the DEB format. This means it is possible to produce both RPM and DEB packages on RPM-based systems, such as RedHat, SuSE, etc. The main caveat to this is that when creating DEB packages on non-DEB systems,

tools such as `dpkg-shlibdeps` are not available, so things like automatic dependencies cannot be computed.

Components are handled in a very similar way to RPM and have analogous configuration variables. Components are enabled by setting `CPACK_DEB_COMPONENT_INSTALL` to true (this variable does not follow the naming used for all other DEB-specific variables, which have a name prefixed by `CPACK_DEBIAN_` rather than `CPACK_DEB_`). Package names have analogous `CPACK_DEBIAN_PACKAGE_NAME` and `CPACK_DEBIAN_<COMP>_PACKAGE_NAME` variables, while file names are controlled by `CPACK_DEBIAN_FILE_NAME` and `CPACK_DEBIAN_<COMP>_FILE_NAME`. The same file naming issues apply to DEB as for RPM, except the special value `DEB-DEFAULT` should be used instead of `RPM-DEFAULT`. If providing any other value, the file name must end in `.deb` or `.ipk`. Versioning for DEB is also handled in a very similar way to RPM, as is specifying an architecture. Equivalent DEB variables are provided, with `DEBIAN` replacing `RPM` in the variable names.

The DEB package generator has fewer variables to influence how dependencies are handled compared to RPM. If packaging is being performed on a DEB-based host where the `dpkg-shlibdeps` tool is available, the shared library dependencies can be automatically computed by setting `CPACK_DEBIAN_PACKAGE_SHLIBDEPS`, or the component-specific `CPACK_DEBIAN_<COMP>_PACKAGE_SHLIBDEPS` variables to true.

Manually specified dependencies can be provided through the CPACK_DEBIAN_PACKAGE_DEPENDS and CPACK_DEBIAN_<COMP>_PACKAGE_DEPENDS variables and will be merged with the automatically determined ones if both manual and automatic dependencies are used. Note, however, that if a component-specific dependency variable is set, the non-component variable is not used for that component. If automatic dependency computation is enabled, it populates the component-specific variables, so if the project sets only CPACK_DEBIAN_PACKAGE_DEPENDS, it will be ignored for those components where automatic dependencies are populated. Therefore, it may be more robust to always populate CPACK_DEBIAN_<COMP>_PACKAGE_DEPENDS rather than CPACK_DEBIAN_PACKAGE_DEPENDS when enabling automatic dependencies. Projects should also set CPACK_DEBIAN_ENABLE_COMPONENT_DEPENDS to true if inter-component dependencies are specified via the DEPENDS option to cpack_add_component(). Doing so will then enforce those dependencies in the generated component packages.

Related to the above, each package can also specify the shared libraries it requires. On platforms that provide the readelf tool, these library dependencies can be determined automatically by setting CPACK_DEBIAN_PACKAGE_GENERATE_SHLIBS to true. The readelf tool is then used to determine the shared libraries each shared object needs, and that information is added to the package. The CPACK_DEBIAN_PACKAGE_GENERATE_SHLIBS_POLICY

variable controls whether exact (=) or minimum (>=) requirements are enforced.

The DEB generator's documentation details a number of other DEB-specific variables not mentioned above. In particular, some variables can be used to specify what the package(s) require, provide, replace and so on. Some DEB-specific metadata items can also be set, such as maintainer details, package group or category, etc. Developers should consult the DEB generator's documentation for the full set of supported variables.

37.10. FreeBSD

The FreeBSD package generator was added in CMake 3.10. It does not support components and always produces a single .pkg file. Some FreeBSD-specific variables can be set to specify basic package metadata, with a few falling back to DEB- or RPM-specific variables. Much of the package configuration can be specified by the generic CPACK_... variables rather than generator-specific variables, so configuration of this generator can be fairly basic. Project developers are advised to consult the FreeBSD generator's documentation for available features and limitations.

37.11. Cygwin

An even more basic package generator is that for Cygwin. It is essentially just a wrapper around a BZip2 archive and offers next to no configuration beyond the generic variables. Projects may wish to consider using one of the simple archive formats instead.

37.12. NuGet

The options supported by the NuGet generator follow a similar pattern to the other generators already discussed. Support for the NuGet package format first became available with CMake 3.12. CMake 3.20 expanded the set of available configuration variables further, providing generator-specific control of package icons, license files, and the locale. See the generator's documentation for the full list of supported options.

37.13. External

The External generator was added in CMake 3.13 and is very different to all the other package generators. This particular generator writes out a JSON file containing package metadata, component details, and other CPack information, but it does not produce a package itself. It can install the files that would normally be packaged into a temporary staging area if requested. Other tools are expected to consume the JSON file and staged install area to produce packages using their own methods. The main goal of this generator is to present the details accumulated by CPack in a way that platforms and

distributions can easily use within their own policy and technical constraints. Instead of having to delegate the entire package creation process to CPack, systems can read the description CPack provides and optionally use the staged install area and feed these into their own existing methods. As such, this generator has a fairly narrow audience and is only likely to be relevant for distribution maintainers, system integrators, etc. The interested reader should consult the latest CMake documentation for a detailed description of the JSON format and supported customization options.

37.14. Recommended Practices

One of the first decisions to be made regarding packaging is which package formats the project will provide for its releases. A good starting point is to consider providing at least one simple archive format and one native format for each target platform. The archive format is convenient when end users want to install multiple versions of the product simultaneously, since they can then just unpack the release archives to different directories. As long as the packages are fully relocatable, this is a simple and effective strategy. For the broadest compatibility, ZIP archives are recommended for Windows and TGZ for Unix-based systems.

Different non-archive formats are appropriate depending on the target platform. If a UI installer is appropriate for all

platforms, then consider using the IFW generator for a consistent end user experience regardless of platform. These installers also offer the greatest customizability, localization, and options for downloadable components. If more native installers are preferred, then the choices will depend on what the project considers more important. For Windows, either WIX or NSIS may be appropriate, and the capabilities are fairly similar. The Inno Setup generator may also be suitable once it matures. For Mac, a multi-component project may prefer the productbuild generator for a cleaner installation experience, but the DragNDrop generator is more likely to be preferred by end users for non-component projects due to its greater simplicity and flexibility. On Linux, consider providing both RPM and DEB packages for the broadest adoption by end users if not using the IFW generator for cross-platform consistency.

RPM and DEB packages should prefer to set package file names to RPM-DEFAULT and DEB-DEFAULT respectively. This ensures that package file names follow the common naming conventions. It is also a much simpler way of incorporating the package version and architecture details into the package file names. Do not rely on the default RPM or DEB package file names provided by CPack, since they omit the version and architecture details.

If debug information should be retained for release packages when using the RPM generator, consider using the debuginfo

functionality rather than preventing the stripping step of package creation. Preventing stripping requires disabling other potentially desirable aspects of package generation, and it requires exposing debug details as part of the release package. The debuginfo functionality allows a proper release package to be provided, with debugging details captured in a separate package that can be distributed or not to end users. The DEB generator also supports creating debuginfo packages when using CMake 3.13 or later.

Explore and understand the UI customization options provided by each UI installer the project wants to support. Defining appropriate product icons is highly recommended to ensure a professional look and feel. Be aware that different generators may use the same icon-related variables in different ways and have different expectations. Therefore, be sure to test the way each icon is displayed for each package type.

Projects should also always provide their own readme, welcome, and license details rather than relying on the default ones provided by CPack. The placeholder text provided by CPack is not suitable for production packages. Alternatively, where the generator supports it, disable the readme, welcome and license details if they are not needed. The DragNDrop generator is a special case. Projects should transition away from attaching license details to the DMG image. A future macOS version will remove the deprecated tools CMake relies on to

provide that feature. Projects should set CPACK_DMG_SLA_USE_RESOURCE_FILE_LICENSE to false and find an alternative way of handling user license acceptance for the DragNDrop generator (e.g. a modal dialog shown the first time the application is run).

38. EXTERNALPROJECT

For any project of modest complexity, it is likely to rely on one or more external dependencies. These could be commonly available toolkits such as zlib, OpenSSL, Boost, etc. Dependencies might be private projects by the same organization, or content to be used as resources, test data and so on.

In some scenarios, a project may be able to call `find_package()` to specify things it needs (see [Section 34.4, “Finding Packages”](#)), but leave the developer to take care of providing those packages. This keeps the project simple, at the expense of placing more of a burden on the developer. In other scenarios, the project may want or need to support providing its own dependencies directly. This chapter and the next focus on such use cases.

CMake provides a few choices for how to bring external content into a build. At a fairly raw level, the `file(DOWNLOAD)` command can be used to retrieve a specific file, either during the configure stage or as part of processing a CMake file in script mode (i.e. `cmake -P`). While this has its uses, it is usually well

short of the level of functionality needed to incorporate whole projects. For downloading and building an entire dependency, the traditional approach in CMake has been to use the ExternalProject module. This has been a part of CMake for a long time and has a variety of uses apart from simply doing a download and build. The FetchContent module, discussed in the next chapter, builds on top of ExternalProject.

38.1. High Level Overview

The ExternalProject module's main purpose is to enable downloading and building external projects that cannot be easily made part of the main project directly. The external project is added as its own separate sub-build, effectively isolated from the main project and treated more or less as a black box. This means it can be used to build projects for a different architecture, different build settings or even to build a project with a build system other than CMake. It can also be used to handle a project that defines targets or install components that clash with those of the main project or its dependencies.

ExternalProject works by defining a set of build targets in the main project that represent the distinct steps of obtaining and building the external project. These are then collected under a single CMake target which represents the whole sequence. Timestamps are used to keep track of which steps have already

been performed and do not need to be repeated unless relevant details change. The default set of steps are as follows:

Download

Various methods can be used to obtain the external project's source. These include downloading an archive from a URL and unpacking it automatically, or cloning/checking out from a source code repository such as git, subversion, mercurial or CVS. Alternatively, projects can define their own custom commands if none of the supported download options are appropriate.

Update

For source code repository download methods, an existing download can be efficiently brought up-to-date to account for things like changes to which commit to check out. Custom commands can be provided to override the default update behavior if necessary.

Patch

Once the source code has been downloaded and updated, a patch can be applied. A custom command has to be provided for the patch step to do anything. This should generally only be done for archive downloads. The behavior is difficult to make robust for any of the other source repository download methods.

Configure

If the external project uses CMake as its build system, this step executes `cmake` on the downloaded source. Some information is passed through from the main build to make configuring external CMake projects fairly seamless. For non-CMake external projects, a custom command can be provided to run the equivalent steps, such as running a `configure` script with appropriate options.

Build

By default, if CMake was used to configure the build, the configured external project is built with the same build tool as the main project. Custom commands can be provided for the build step to use a different build tool or to perform some other task.

Install

The external project can be installed to a local directory, typically to somewhere within the main project's build tree. The main project then knows where to expect the external project's build artifacts to be and can incorporate them into its own build. The default behavior depends on whether the `configure` step assumed a CMake build was being invoked.

Test

The external project may come with its own set of tests, which the main project might or might not wish to run. The `ExternalProject` module provides flexibility in whether to run a test step (by default it doesn't) and whether it should

come before or after the install step. If the test step is enabled, a default test target will be assumed to exist in the external project, but custom commands can be specified to provide full control over what the test step does.

The module allows other custom steps to be defined and inserted into any point in the above workflow, but the default set of steps are typically sufficient for most projects. The details for the default steps are all set by the main function provided by the module, `ExternalProject_Add()`. This function accepts many options, all of which are detailed in the module's documentation. Only a selection of the more commonly used ones and some typical scenarios are discussed in this chapter.

The simplest use case involves downloading a source archive from a URL and building it as a CMake project. The minimal information needed to achieve this is just the URL, which is provided like so:

```
include(ExternalProject)
ExternalProject_Add(SomeExtProj
    URL https://example.com/releases/myproj_1.2.3.tar.gz
)
```

The first argument to the function is always the name of a build target to be created in the main project. This target will be used to refer to the external project's whole build process. By default, it is added to the main project's `all` target, but this can be disabled by adding the usual `EXCLUDE_FROM_ALL` option, which

has the same effect as it does for commands like `add_executable()`, `add_custom_target()`, etc. In the above example, building the `SomeExtProj` target will result in the following being performed during the build stage of the main project:

- Download the tarball and unpack it.
- Run `cmake` with default options based on the main build.
- Invoke the same build tool as the main project for the default target.
- Build the external project's `install` target.

This is just one common scenario. The `ExternalProject` module supports much more than the above workflow.

38.2. Directory Layout

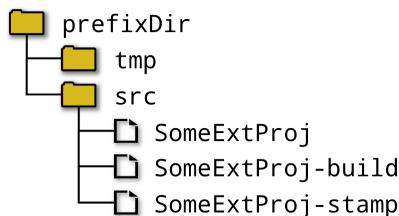
The various steps all use a separate set of directories created in the build directory to hold the sources, build outputs, timestamps and other temporary files associated with the external project's build. The structure of these directories depends on a few different factors and the module documentation provides a detailed explanation of how the directory structure is chosen. For the most part, projects won't typically need to know much about the directory structure, unless it needs to directly refer to things within it. An

awareness of the directory structure is therefore useful, but not always necessary.

The directory structure is perhaps most easily introduced by showing how the main project can control the structure rather than relying on the defaults. The base location of the directories can be set using the `PREFIX` option.

```
ExternalProject_Add(SomeExtProj
    PREFIX prefixDir
    URL      https://example.com/releases/myproj_1.2.3.tar.gz
)
```

When used this way, the directory layout will be based under `prefixDir`, which should generally be provided as an absolute path and would normally be somewhere within the main project's build area. The default relative directory layout created under this location is shown below. The unpacked archive will be in `prefixDir/src/SomeExtProj` and the CMake build will use `prefixDir/src/SomeExtProj-build` as its build directory.



The `EP_PREFIX` and `EP_BASE` directory properties can be set to influence the above layout. See the `ExternalProject` documentation for details. The prefix and these directory

properties only provide coarse control over the directory structure. For those cases where it is needed, `ExternalProject_Add()` allows some or all of the individual directories to be set directly:

```
ExternalProject_Add(SomeExtProj
    DOWNLOAD_DIR downloadDir
    SOURCE_DIR sourceDir
    BINARY_DIR binaryDir
    INSTALL_DIR installDir
    TMP_DIR tmpDir
    STAMP_DIR stampDir
    URL https://example.com/releases/myproj_1.2.3.tar.gz
)
```

In practice, the `TMP_DIR` and `STAMP_DIR` would rarely be used, but the others are more relevant to the main project and are sometimes provided. The default install location will be up to the external project, which will typically be a system-wide location. Therefore, it is very common for `INSTALL_DIR` to be specified to facilitate collecting all the final artifacts of external projects in a more appropriate place. This would typically be somewhere under the build directory. Further steps are required to make the external projects use the specified `INSTALL_DIR`, as later examples will show.

Another useful technique is to provide `SOURCE_DIR` and give a location of an existing directory that has already been populated. When used this way, no download method needs to be given, in which case the command will use the existing

contents of the specified source directory. This can be a very convenient way of building a part of the main project's source tree for a different platform. For example:

```
ExternalProject_Add(Firmware
    SOURCE_DIR
        ${CMAKE_CURRENT_LIST_DIR}/Firmware
    INSTALL_DIR
        ${CMAKE_CURRENT_BINARY_DIR}/Firmware-artifacts
    #... other options to configure differently
)
```

38.3. Built-in Steps

For the vast majority of cases, projects will generally find the built-in steps provided by `ExternalProject_Add()` to be sufficient. They provide a rich set of capabilities that cover many common use cases. For those they do not cover directly, custom steps and step relationships can be defined (these are as discussed in [Section 38.4, “Step Management”](#) and [Section 38.5, “Miscellaneous Features”](#)).

38.3.1. Archive Downloads

Archive download methods are identified by their use of the URL keyword. `ExternalProject` has considerably more downloading support than just a basic URL to download though. For archives, it supports the main project giving a hash of the file to be downloaded. This not only has the obvious advantage of verifying the downloaded contents, it also allows the module to

check a file it might have downloaded previously and avoid re-downloading it again if it knows it already has one with the correct hash. The hash value can be for any algorithm that the `file()` command supports, but it is typically either MD5 or SHA1. The hash is given with the `URL_HASH` option, as in the following example:

```
ExternalProject_Add(SomeAutotoolsProj
    URL      someUrl
    URL_HASH MD5=b4a78fe5c9f2ef73cd3a6b07e79f2283
    #... other options
)
```

Specifying a hash is strongly recommended. CMake will issue a warning if the `URL` option is used without an accompanying `URL_HASH` option. As a special case to maintain backward compatibility with older CMake versions, the `URL_MD5` option can be used to provide a MD5 hash, but projects should avoid it in favor of the more flexible `URL_HASH` option.

It is also possible to specify more than one URL and let the project try each in turn until one succeeds. This can be useful when the available servers to connect to might change depending on the network connection, VPN settings, etc., or to try local servers before potentially slower remote servers. This feature cannot be used with `file://` urls.

```
set(archive someproj-1.2.3.tar.gz)
```

```
ExternalProject_Add(SomeProj
```

```
URL      https://mirror.example.com/releases/${archive}  
          https://somewhereelse.com/artifacts/${archive}  
URL_HASH MD5=b4a78fe5c9f2ef73cd3a6b07e79f2283  
#... other options  
)
```

When downloading archives, the archive format is detected based on the file contents after download. The archive is then unpacked automatically. The automatic unpacking can be disabled if needed and various aspects of how the download itself is configured can be controlled. See the module documentation for details on the relevant options for these less common scenarios.

Archive-based URL download methods can be susceptible to an important timestamp-related problem. When archive contents are unpacked with CMake 3.23 or earlier, the files and directories are given timestamps that match those in the archive. These timestamps can be arbitrarily far back in the past. When the URL is changed for an existing build, ExternalProject correctly detects this and re-downloads and unpacks the archive from the new URL. But the build step might then incorrectly decide that some things don't need to be recompiled, since the timestamps of the source from the new archive are still older than the compiler outputs built with the previous archive's contents.

CMake 3.24 introduced policy `CMP0135` to address this problem. When that policy is set to `NEW`, the contents of an unpacked

archive will have their timestamps set to the time of extraction, not the timestamps from the archive. This ensures the build step sees inputs as being newer than things built from them, triggering recompilation as expected. Projects are strongly encouraged to ensure CMP0135 is set to NEW where possible to use the more robust behavior. This can be done with or without requiring CMake 3.24 as a minimum version.

```
# Require at least CMake 3.24, policy always set to NEW
cmake_minimum_required(VERSION 3.24)
```

```
ExternalProject_Add(SomeExtProj URL ...)
```

```
# Use NEW policy if available
if(POLICY CMP0135)
    cmake_policy(SET CMP0135 NEW)
endif()
```

```
ExternalProject_Add(SomeExtProj URL ...)
```

The timestamp behavior can also be specified directly as part of the call to ExternalProject_Add() with the DOWNLOAD_EXTRACT_TIMESTAMP option:

```
# Override policy for just one call
if(CMAKE_VERSION VERSION_GREATER 3.24)
    set(timestampOpt DOWNLOAD_EXTRACT_TIMESTAMP NO)
else()
    set(timestampOpt "")
endif()
```

```
ExternalProject_Add(SomeExtProj URL ... ${timestampOpt})
```

38.3.2. Repository Download Methods

Downloaded contents don't have to be from an archive, the module can also work directly with source code repositories for git, subversion, mercurial or CVS. Each of these require the repository to be named with a <REPOTYPE>_REPOSITORY option and then other repository specific options may also be given.

```
ExternalProject_Add(MyProj
    GIT_REPOSITORY git@example.com/git/myproj.git
    GIT_TAG        3a281711d1243351190bdee50a40d81694aa630a
)
```

The above example shows the typical information needed to clone a git repository and checkout a particular commit. If the GIT_TAG option is omitted, the latest commit on the master branch will be used. The name of a tag or branch can also be given with GIT_TAG instead of a commit hash. While GIT_TAG does support these different choices, it should be noted that only a commit hash is truly unambiguous. With git, the commit referenced by a branch or tag name can move over time, so using them does not guarantee a repeatable build. Similarly, omitting GIT_TAG altogether is the same as giving master, so it too won't always point at the same commit. A future CMake release is likely to make omitting the GIT_TAG an error when using the GIT_REPOSITORY method.

There is another reason to only use commit hashes with GIT_TAG. Because a tag or branch can change over time,

`ExternalProject_Add()` may need to contact the remote end every time CMake is run, even if it already has the named tag or branch locally. CMake cannot be sure that the tag or branch hasn't moved without fetching from the remote. This round trip every time CMake is re-run can be expensive, especially if the project is using many external projects. As a special case, if a tag is requested and that tag is already checked out, it will be assumed that the tag hasn't moved and no fetch will be performed. This trade-off between performance and robustness is typically safe for most projects where tags never move once created, but it does open an avenue for a non-reproducible build. If a commit hash is used instead, `ExternalProject_Add()` knows robustly whether it already has the commit locally without needing to contact the remote.

Other options can be used to customize the git behavior, including specifying a different default remote name, control of git submodules, shallow clones and arbitrary git config options. Consult the module documentation for further details.

Checking out from a subversion repository is fairly similar to git:

```
ExternalProject_Add(MyProj
    SVN_REPOSITORY svn+ssh@example.com/svn/myproj/trunk
    SVN_REVISION -r31227
)
```

The SVN_REVISION option specifies a svn command line option that is expected to specify the commit to check out. This will frequently be a global revision number specified with the -r option as shown above, but could technically be any valid command line option. If SVN_REVISION is omitted, the latest revision is used, but projects should strive to always provide this option to ensure that the build is repeatable. A few other security-related subversion options are also supported by ExternalProject_Add(), such as for authenticating with the repository and specifying certificate trust settings. Consult the ExternalProject module documentation for details on these less frequently used options.

In comparison, the support for Mercurial and CVS is very basic. In the case of Mercurial, only the repository and tag can be specified, while for CVS, the module is also required:

```
ExternalProject_Add(MyProjHg
    HG_REPOSITORY https://example.com/hg/myproj
    HG_TAG        dd2ce38a6b8a
)
ExternalProject_Add(MyProjCVS
    CVS_REPOSITORY https://example.com/cvs/myproj
    CVS_MODULE    someModule
    CVS_TAG      -rsomeTag
)
```

The CVS_TAG option is analogous to the SVN_REVISION option in that it is placed on the cvs command line directly, so it must

include any required command option prefix, such as shown above.

38.3.3. Configuration Step

By default, the configure step assumes the external project also uses CMake as its build system. Support is provided for passing custom options to its `cmake` command line to influence its configuration. The most direct way to achieve this is using the `CMAKE_ARGS` option, which should be followed by the arguments to be passed to the external project's `cmake` command. The earlier example from [Section 35.1, “Directory Layout”](#) can be extended to use a toolchain file, configure a release build, and use the nominated install directory like so:

```
set(toolchainFile
    ${CMAKE_CURRENT_LIST_DIR}/fwtoolchain.cmake
)
ExternalProject_Add(Firmware
    SOURCE_DIR
        ${CMAKE_CURRENT_LIST_DIR}/Firmware
    INSTALL_DIR
        ${CMAKE_CURRENT_BINARY_DIR}/Firmware-artifacts
    CMAKE_ARGS
        -D CMAKE_TOOLCHAIN_FILE=${toolchainFile}
        -D CMAKE_BUILD_TYPE=Release
        -D CMAKE_INSTALL_PREFIX=<INSTALL_DIR>    # See below
)
```

The above example uses a *placeholder* for the install directory passed as the value for `CMAKE_INSTALL_PREFIX`. A placeholder is just the option name for a particular directory surrounded by

angle brackets. The most commonly used placeholders are <SOURCE_DIR>, <BINARY_DIR> and <INSTALL_DIR>. <DOWNLOAD_DIR> is also available with CMake 3.11 or later. The full list of placeholders is given in the ExternalProject module documentation.

If more than a couple of CMake options need to be set, the length of the generated cmake command line could become a problem. An alternative is to specify cache variables to be defined using CMAKE_CACHE_ARGS rather than defining them via CMAKE_ARGS. These arguments are expected to be in the form -Dvariable:TYPE=value and will be converted to a file containing commands of the form set(variable value CACHE TYPE "" FORCE). This file is then passed to the cmake command line with a -C option. The effect is the same as if the variables had been set directly on the cmake command line via -D options.

```
set(toolchainFile
${CMAKE_CURRENT_LIST_DIR}/fwtoolchain.cmake
)
ExternalProject_Add(Firmware
SOURCE_DIR
${CMAKE_CURRENT_LIST_DIR}/Firmware
INSTALL_DIR
${CMAKE_CURRENT_BINARY_DIR}/Firmware-artifacts
CMAKE_CACHE_ARGS
-DCMAKE_TOOLCHAIN_FILE:FILEPATH=${toolchainFile}
-DCMAKE_BUILD_TYPE:STRING=Release
-DCMAKE_INSTALL_PREFIX:PATH=<INSTALL_DIR>
)
```

There are other options which can be used to change the CMake generator and a few other less common aspects of how CMake is invoked, but these are less frequently used. Consult the module documentation for further details.

If the external project does not use CMake as its build system, the `CONFIGURE_COMMAND` option can be given to provide an alternative custom command to be executed instead of running `cmake`. For example, many projects provide a `configure` script, which could be set up like so:

```
ExternalProject_Add(SomeAutotoolsProj
    URL           someUrl
    CONFIGURE_COMMAND <SOURCE_DIR>/configure
    ...
)
```

The `configure` command is run in the build directory, but the `configure` script will be in the source directory. Rather than explicitly having to define the directory layout to be used for the external project, the above demonstrates an alternative strategy whereby the default structure is used, but the command's placeholder support provides the location of the source directory.

38.3.4. Build Step

If the `CONFIGURE_COMMAND` option is not used, the project is assumed to be a CMake build and the external project's build step will use the same build tool as the main project. For such

cases, the default behavior of the build step is suitable and no special handling is needed. When `CONFIGURE_COMMAND` is provided, the default build tool is assumed to be `make` and the default build command is to invoke `make` without any explicit target. If a non-default target should be built instead or a build tool other than `make` is needed, a custom build command must be provided. For example:

```
find_program(MAKE_EXECUTABLE NAMES nmake gmake make)
ExternalProject_Add(SomeAutotoolsProj
    URL             someUrl
    CONFIGURE_COMMAND <SOURCE_DIR>/configure
    BUILD_COMMAND    ${MAKE_EXECUTABLE} specialTool
)
```

The custom build command could do anything, it doesn't have to be a known build tool. It can even be set to an empty string to effectively bypass the build step.

38.3.5. Install Step

Predictably, the same pattern continues for the install step too. For CMake projects, the main project's build tool will be invoked to build a target called `install` by default, whereas for non-CMake projects, the default command is `make install`. The `INSTALL_COMMAND` option can be used to provide a custom install command, or it can be set to an empty string to disable the install step altogether. This is often done when the main project can use the results of the build step without needing any further install.

```
ExternalProject_Add(SomeAutotoolsProj
    URL someUrl
    CONFIGURE_COMMAND <SOURCE_DIR>/configure
    BUILD_COMMAND ${MAKE_EXECUTABLE} specialTool
    INSTALL_COMMAND "" # Disables the install step
)
```

Care should be taken to handle the install step properly. If the external project uses CMake as its build system, the destination of the default install rule is controlled by the `CMAKE_INSTALL_PREFIX` cache variable. If this variable is not set, the default location will be used, which typically results in the external project being installed to a system-wide location, which is not usually the desired outcome (certainly not if the project is being built within a continuous integration system). Similarly, if the external project uses a build system other than CMake, the default install command will be `make install`, which again will likely try to install to a system-wide location. For the CMake case, setting the cache variable via `CMAKE_ARGS` as shown in the earlier example addresses the situation. For a Makefile based project, something like the following is usually appropriate:

```
ExternalProject_Add(otherProj
    URL ...
    INSTALL_DIR
        ${CMAKE_CURRENT_BINARY_DIR}/otherProj-install
    CONFIGURE_COMMAND
        <SOURCE_DIR>/configure
    INSTALL_COMMAND
        ${MAKE_EXECUTABLE} DESTDIR=<INSTALL_DIR> install
)
```

The `INSTALL_DIR` option doesn't do anything other than define a value for the `<INSTALL_DIR>` placeholder. It is up to the caller to use the `<INSTALL_DIR>` placeholder to pass that information through to wherever it is needed. Projects should use `INSTALL_DIR` to define the location and then use the `<INSTALL_DIR>` placeholder rather than embedding the path directly in options like `INSTALL_COMMAND`. This ensures that the location can be queried later if required, as covered in [Section 38.5, “Miscellaneous Features”](#) further below.

38.3.6. Test Step

The test step is handled slightly differently and does nothing by default. To enable it, one of the test-specific options must be given, such as `TEST_BEFORE_INSTALL YES` or `TEST_AFTER_INSTALL YES`. Once enabled, the pattern is the same as for the build and install steps, with the appropriate build tool invoking the test target by default, but `TEST_COMMAND` can be given to provide alternative behavior.

38.4. Step Management

Sometimes it can be useful or even necessary to refer to one of the steps in the `ExternalProject` sequence, such as to add a dependency on another CMake target that provides an input to a particular step. The `STEP_TARGETS` option can be given to `ExternalProject_Add()` to tell it to create CMake targets for the

specified set of steps. These targets have names of the form `mainName-step`, where `mainName` is the target name given as the first argument to `ExternalProject_Add()` and `step` is the step the target represents. For example, the following would result in targets named `MyProj-configure` and `MyProj-install` being defined:

```
ExternalProject_Add(MyProj
    GIT_REPOSITORY git@example.com/git/myproj.git
    GIT_TAG        3a281711d1243351190bdee50a40d81694aa630a
    STEP_TARGETS   configure install
)
```

Adding dependencies for these step targets requires a little more care. To make a step target depend on some other CMake target, the project should use the `ExternalProject_Add_StepDependencies()` function provided by the module rather than calling `add_dependencies()`. This ensures that things like the step timestamps are handled correctly. The form of that command is as follows:

```
ExternalProject_Add_StepDependencies(
    mainName step otherTarget1...
)
```

The following example shows how to use this function to make the `configure` step of the previous example depend on an executable built by the main project:

```
add_executable(PreConfigure ...)
ExternalProject_Add_StepDependencies(
```

```
    MyProj configure PreConfigure  
)  
|
```

To make an ordinary CMake target depend on a step target, `add_dependencies()` is fine:

```
add_executable(PostInstall ...)  
add_dependencies(PostInstall MyProj-install)
```

If a particular step of one external project needs to depend on a step of a different external project, `ExternalProject_Add_StepDependencies()` must once again be used:

```
ExternalProject_Add(Earlier  
    STEP_TARGETS build  
    ...  
)  
ExternalProject_Add(Later  
    STEP_TARGETS build  
    ...  
)  
ExternalProject_Add_StepDependencies(  
    Later build Earlier-build  
)
```

The above arrangement can be useful if `Earlier` defines tests that are time-consuming to run, but in a parallel build the `Later` project doesn't need to wait for those tests, only for `Earlier` to be built.

When the same set of step targets need to be defined for multiple external projects, rather than repeating them each

time, they can be made the default by setting the EP_STEP_TARGETS directory property instead.

```
set_property(DIRECTORY PROPERTY EP_STEP_TARGETS build)
ExternalProject_Add(Earlier ...)
ExternalProject_Add(Later ...)
ExternalProject_Add_StepDependencies(
    Later build Earlier-build
)
```

For many projects though, such granularity of dependencies offers only limited gains and the complexity may not be worth it. The whole external project can be made dependent on another target by using the DEPENDS option with ExternalProject_Add(), which is much simpler:

```
add_executable(PreConfigure ...)
ExternalProject_Add(MyProj
    DEPENDS PreConfigure
    ...
)
```

The DEPENDS option takes care of ensuring all the step dependencies are handled correctly, just as ExternalProject_Add_StepDependencies() does when setting up more granular dependencies.

Projects are not limited to only the default steps, they can create their own custom steps and insert them into the step workflow with whatever dependency relationships they require. The ExternalProject_Add_Step() function provides this capability:

```
ExternalProject_Add_Step(mainName step
    [COMMAND           command [args...] ]
    [COMMENT           comment]
    [WORKING_DIRECTORY dir]
    [DEPENDS           filesWeDependOn...]
    [DEPENDEES         stepsWeDependOn...]
    [DEPENDERS         stepsDependOnUs...]
    [BYPRODUCTS        byproducts...]
    [INDEPENDENT      bool] # CMake 3.19 or later
    [ALWAYS            bool]
    [EXCLUDE_FROM_MAIN bool]
    [LOG               bool]
    [USES_TERMINAL    bool]
)
```

COMMAND is used to define the action to take when the step is executed. It is analogous to the custom command that can be specified for each of the default steps. COMMENT can be supplied to provide a custom message when executing the step, but as noted back in [Section 20.1, “Custom Targets”](#), such comments are not always shown. Therefore, consider them helpful, but not essential. The WORKING_DIRECTORY option has the same meaning as for an add_custom_target() command.

Comprehensive dependency details can be provided with the custom step. If the command depends on a specific file or set of files, they should be listed with the DEPENDS option. For files generated as part of the build, they must be generated by custom commands created in the same directory scope. The DEPENDEES and DEPENDERS options define where this custom step sits in the step workflow of the external project. Care must be

taken to fully specify all direct dependencies. Otherwise, the custom step will potentially execute out of sequence. The `BYPRODUCTS` option should also be used if the custom step produces a file that something else in the external project or main project depends on. Without this, the Ninja generators will likely complain about a missing build rule.

CMake 3.19 added support for the `INDEPENDENT` keyword, which must be followed by a boolean true or false value. Where the step does not depend on anything outside the external project, it can be specified as independent. It may still depend on other steps within the `mainName` external project, as long as those other steps are also considered independent. For example, the `update` step depends on the `download` step, but both are created as independent because they don't rely on any targets from other parts of the build. Specifying a step to be independent can improve parallelism and may avoid unnecessarily re-executing the step when unrelated external dependencies change. If the `INDEPENDENT` option is given a value of false or is not present, the step target will depend on everything that the `mainName` target depends on. The reader is referred to the policy `CMP0114` documentation, which discusses the use, limitations and relevant historical notes around this functionality in considerable depth.

A custom step can be made to always appear out of date by setting the `ALWAYS` option to true. Projects should generally only

do this if no other step depends on it, since anything depending on it would then also be always considered out of date. This may lead to builds doing more work than they need to. If the custom step is intended to only be built on demand, then setting both `ALWAYS` and `EXCLUDE_FROM_MAIN` to true is usually the desired combination. The remaining options `LOG` and `USES_TERMINAL` are discussed in the next section.

All the default steps are created by calls to `ExternalProject_Add_Step()` internally from within `ExternalProject_Add()`. Projects must not try to redefine them, which means custom steps cannot be named `mkdir`, `download`, `update`, `skip-update`, `patch`, `configure`, `build`, `install` or `test`.

The actions and inter-step dependencies are defined by `ExternalProject_Add_Step()`, but in order for a target to be created for a custom step, the `ExternalProject_Add_StepTargets()` function must be called as well. This function is also called internally by `ExternalProject_Add()` to create targets for steps listed in its `STEP_TARGETS` option or set via the `EP_STEP_TARGETS` directory property.

```
ExternalProject_Add_StepTargets(  
    mainName [NO_DEPENDS] steps...  
)
```

The `NO_DEPENDS` option is rarely desirable and is not recommended for most scenarios. It is deprecated since CMake 3.19 and is not available if policy `CMP0114` is set to `NEW`. See the discussion of this option in the module documentation for further details.

The following example demonstrates how to define a package custom step which depends on the build step, but is only executed when explicitly requested:

```
ExternalProject_Add_Step(MyProj package
    COMMAND      ${CMAKE_COMMAND}
                --build <BINARY_DIR>
                --target package
    DEPENDES     build
    ALWAYS       YES
    EXCLUDE_FROM_MAIN YES
)
ExternalProject_Add_StepTargets(MyProj package)
```

38.5. Miscellaneous Features

For any of the default or custom steps, a custom command can be specified. For `ExternalProject_Add()`, the relevant options are those that end with `_COMMAND`, while for `ExternalProject_Add_Step()` it is the `COMMAND` option that provides the custom command to execute. Both of these functions allow more than one command to be given by appending further `COMMAND` options that immediately follow the first. Each command is then executed in order for that step.

```

ExternalProject_Add(MyProj
    CONFIGURE_COMMAND
        ${CMAKE_COMMAND} -E echo "Starting configure"
    COMMAND ./configure
    COMMAND ${CMAKE_COMMAND} -E echo "Configure completed"

    BUILD_COMMAND
        ${CMAKE_COMMAND} -E echo "Starting build"
    COMMAND ${MAKE_EXECUTABLE} MySpecialTarget
    COMMAND ${CMAKE_COMMAND} -E echo "Build completed"
)
ExternalProject_Add_Step(MyProj package
    COMMAND ${CMAKE_COMMAND} -E echo "Starting packaging"
    COMMAND ${CMAKE_COMMAND}
        --build <BINARY_DIR>
        --target package
    COMMAND ${CMAKE_COMMAND} -E echo "Packaging completed"
    DEPENDEES      build
    ALWAYS         YES
    EXCLUDE_FROM_MAIN YES
)
ExternalProject_Add_StepTargets(MyProj package)

```

Commands can also be given access to the terminal. This can be important for things like repository access which may require the user to enter a password for a private key, etc. While this is not applicable to continuous integration builds, it is sometimes useful for developers in their day-to-day activities. Access to the terminal is controlled on a per-step basis with `ExternalProject_Add()` options of the form `USES_TERMINAL_<STEP>`, where `<STEP>` is the step name in uppercase, and the value given for the option is a true or false constant. For custom steps, the `USES_TERMINAL` option for the `ExternalProject_Add_Step()` command has the same effect. If using a git or subversion

repository for the download, it may be desirable to give the download and update steps access to the terminal.

```
ExternalProject_Add(MyProj
    GIT_REPOSITORY git@example.com/git/myproj.git
    GIT_TAG        3a281711d1243351190bdee50a40d81694aa630a
    USES_TERMINAL_DOWNLOAD YES
    USES_TERMINAL_UPDATE YES
)
```

Steps should only be given access to the terminal if it is needed. The effect of doing so is mostly relevant for the Ninja generators, where the custom step will be placed into the console job pool. All targets allocated to the console pool are forced to run serially and the output of any tasks running in other job pools in parallel is buffered until the current console job completes. Be especially careful not to give the build step access to the terminal unless absolutely necessary, since it has the potential to have a significant negative impact on the overall build performance of the project. [Section 26.3.2, “Ninja Generators”](#) discusses further aspects of Ninja job pools in general.

In some cases, it can be useful to capture the output from individual steps to file rather than have it go to the terminal. This is especially useful where there is a large amount of output that will only be of interest if there is an error or other unexpected problem. To redirect a step’s output to file, set the LOG_<STEP> option in ExternalProject_Add() or the LOG option in

`ExternalProject_Add_Step()` to a true value. The terminal output will then only show a short message indicating whether the step was successful and where the log files can be found.

Prior to CMake 3.14, log files were always created in the timestamp directory (i.e. `STAMP_DIR`), which isn't always the most intuitive location. With CMake 3.14 and later, the log file directory can be specified with the `LOG_DIR` keyword. If a relative path is given, it will be treated as being relative to `CMAKE_CURRENT_BINARY_DIR`. The `LOG_MERGED_STDOUTERR` option was also added in CMake 3.14 and when it is set to true, the `stdout` and `stderr` streams will be merged into a single log file for each step with `LOG_<STEP>` also set to true.

```
ExternalProject_Add(MyProj
    GIT_REPOSITORY git@example.com/git/myproj.git
    GIT_TAG        3a281711d1243351190bdee50a40d81694aa630a
    LOG_BUILD      YES
    LOG_TEST       YES

    # The following require CMake 3.14 or later
    LOG_DIR         logs
    LOG_MERGED_STDOUTERR YES
)
```

A project may want to know the value of an `ExternalProject_Add()` option. Placeholders such as `<SOURCE_DIR>` cover many of the common scenarios where values are needed within the call to `ExternalProject_Add()`, but for other cases the `ExternalProject_Get_Property()` command is useful:

```
ExternalProject_Get_Property(mainName propertyName...)
```

Its syntax differs significantly from other property retrieval commands like `get_property()`. No output variable name is given, instead a variable matching the name of the property to be retrieved is created. This allows multiple properties to be retrieved in one call.

```
ExternalProject_Get_Property(MyProj SOURCE_DIR LOG_BUILD)
set(msg "MyProj source will be in ${SOURCE_DIR}")
if(LOG_BUILD)
    string(APPEND msg
        " and its build output will be redirected to files"
    )
endif()
message(STATUS "${msg}")
```

38.6. Common Issues

The `ExternalProject` module is both powerful and effective when used correctly, but it can also sometimes lead to problems that can be difficult to trace. One of the most common problems encountered is when trying to set up multiple external projects where one project wants to be able to use build outputs from another. This generally requires the main project to do two things:

- Specify the dependency relationships between the two projects.

- Give the depender project the information it needs to find the dependee.

The first point is easy enough to establish by creating a dependency for the configure step of the depender on the main target of the dependee. The second point requires understanding how the depender wants to know about the location of the dependee. For example, if it uses `find_package()`, `find_library()`, etc. to locate the dependee, then setting its `CMAKE_PREFIX_PATH` may be sufficient. The following example demonstrates this technique, building both `zlib` and `libpng` as external projects and installing them to the same directory. Since `libpng` requires `zlib`, giving it the common install area for `CMAKE_PREFIX_PATH` allows it to find `zlib`. The example ensures `zlib` is installed before `libpng` runs its configure step, which is when `libpng` will use `CMAKE_PREFIX_PATH`.

```

set(installDir ${CMAKE_CURRENT_BINARY_DIR}/install)

include(ExternalProject)
ExternalProject_Add(zlib
    INSTALL_DIR ${installDir}
    URL         https://zlib.net/zlib-1.2.11.tar.gz
    URL_HASH    SHA256=c3e5e9fdd5 # Shortened for space
    CMAKE_ARGS  -DCMAKE_INSTALL_PREFIX:PATH=<INSTALL_DIR>
)
set(pngHost ftp://ftp-osl.osuosl.org)
set(pngPath pub/libpng/src/libpng16/libpng-1.6.34.tar.gz)
ExternalProject_Add(libpng
    INSTALL_DIR ${installDir}
    URL         ${pngHost}/${pngPath}
    URL_HASH    MD5=03fbc5134830240104e96d3cda648e71
)

```

```
CMAKE_ARGS -DCMAKE_INSTALL_PREFIX:PATH=<INSTALL_DIR>
            -DCMAKE_PREFIX_PATH:PATH=<INSTALL_DIR>
)
ExternalProject_Add_StepDependencies(libpng configure zlib)
```

Another dependency-related issue that can arise when using the Ninja generators is Ninja complaining that it doesn't know how to build a particular file that an external project is supposed to be supplying. The following example demonstrates such a situation.

```
ExternalProject_Add(MyProj
    # Options to download and build a library "someLib"...
)
ExternalProject_Get_Property(MyProj INSTALL_DIR)

add_library(MyProj::someLib STATIC IMPORTED)
set_target_properties(MyProj::someLib PROPERTIES
    # Platform-specific due to hard-coded library location
    # and file name
    IMPORTED_LOCATION ${INSTALL_DIR}/lib/libsomeLib.a
)
add_dependencies(MyProj::someLib MyProj)
```

The Ninja generators will try to find `libsomeLib.a` at the expected location, but it won't yet exist before the `MyProj` external project is built for the first time. Ninja will then halt with an error saying it doesn't know how to build the missing dependency. Other generators may be more relaxed in their dependency checking and not complain, but that should not be considered confirmation of correctly specified dependencies.

A solution to the above is to list `libsomeLib.a` as a byproduct of the external project. With CMake 3.2 and later, `ExternalProject_Add()` supports a `BUILD_BYPRODUCTS` keyword. CMake 3.26 added support for an `INSTALL_BYPRODUCTS` keyword as well. Both keywords work in the same way, but apply to different steps in the external project workflow. If the install step of the external project produces the file referred to by the `IMPORTED_LOCATION` (`libsomeLib.a` in the above example), use `INSTALL_BYPRODUCTS` in the call to `ExternalProject_Add()`. If the `IMPORTED_LOCATION` refers to a file generated by the build step of the external project, use `BUILD_BYPRODUCTS` instead. Once the byproducts have been listed using one of these two keywords, Ninja will have all the information it needs to satisfy its dependencies.

```
# CMake 3.26 or later required
ExternalProject_Add(MyProj
    INSTALL_BYPRODUCTS <INSTALL_DIR>/lib/libsomeLib.a
    ...
)
```

```
# Only requires CMake 3.2 or later
ExternalProject_Add(MyProj
    BINARY_DIR ${CMAKE_CURRENT_BINARY_DIR}/MyProj-build
    BUILD_BYPRODUCTS <BINRAY_DIR>/lib/libsomeLib.a
    ...
)
```

If CMake 3.25 or earlier must be supported, but the install step produces the file being referenced, `BUILD_BYPRODUCTS` can be

used in place of `INSTALL_BYPRODUCTS` in typical scenarios. While not technically correct, it works as long as the imported target depends on the whole external project workflow. This is what the `add_dependencies()` call in the preceding example is doing. If more granular step management is used, the more accurate constraint is that the imported target must depend on the external project's install step.

```
ExternalProject_Add(MyProj
    STEP_TARGETS build install
    BUILD_BYPRODUCTS <INSTALL_DIR>/lib/libsomeLib.a
    ...
)
add_dependencies(MyProj::someLib MyProj-install)
```

Dependency issues like those discussed above are an example of the problems that arise when mixing `ExternalProject` with targets defined in the main project. This is difficult to do robustly and usually involves having to manually specify platform-specific details that CMake normally handles on the project's behalf (e.g. library names and locations). Projects should consider whether a superbuild arrangement would be more appropriate and not try to create build targets of their own when using `ExternalProject`.

Dependency problems can also arise in other situations. In an earlier example, `ExternalProject` was used to build firmware artifacts with a different toolchain to the main build:

```

set(toolchainFile
    ${CMAKE_CURRENT_LIST_DIR}/fwtoolchain.cmake
)
ExternalProject_Add(Firmware
    SOURCE_DIR
        ${CMAKE_CURRENT_LIST_DIR}/Firmware
    INSTALL_DIR
        ${CMAKE_CURRENT_BINARY_DIR}/Firmware-artifacts
    CMAKE_ARGS
        -D CMAKE_TOOLCHAIN_FILE=${toolchainFile}
        -D CMAKE_BUILD_TYPE=Release
        -D CMAKE_INSTALL_PREFIX=<INSTALL_DIR>
)

```

The above would build successfully and all would appear to be in order. If the developer then went and made a change to the sources in the Firmware source directory, the main project would not rebuild the firmware targets. This is because ExternalProject uses timestamps to record successful completion of the steps, so unless something changes in the way the dependencies are computed, the main project thinks the Firmware project is still up-to-date. This can be addressed by forcing the Firmware build target to always be considered out of date using the BUILD_ALWAYS option:

```

set(toolchainFile
    ${CMAKE_CURRENT_LIST_DIR}/fwtoolchain.cmake
)
ExternalProject_Add(Firmware
    SOURCE_DIR
        ${CMAKE_CURRENT_LIST_DIR}/Firmware
    INSTALL_DIR
        ${CMAKE_CURRENT_BINARY_DIR}/Firmware-artifacts
    CMAKE_ARGS

```

```
-D CMAKE_TOOLCHAIN_FILE=${toolchainFile}  
-D CMAKE_BUILD_TYPE=Release  
-D CMAKE_INSTALL_PREFIX=<INSTALL_DIR>  
BUILD_ALWAYS YES  
)
```

This will result in the `Firmware` project's build tool being invoked every time the main project is built. If nothing has changed in the `Firmware` project, its build step will do no actual work. But if there has been a change, then anything that has become out of date will be rebuilt as expected. The main drawback to setting `BUILD_ALWAYS` to true is that it effectively makes the main external project target always appear out of date to the main build, so the main build will never be a true no-op, even when nothing actually needs rebuilding.

38.7. ExternalData

Another module called `ExternalData` provides an alternative way of managing files to be downloaded at build time. The focus of this module is on downloading test data when a particular target representing that data is built. In some ways, it is similar to how `ExternalProject` works, but the way the two modules define the content to be downloaded is considerably different. The `ExternalProject` module allows the download details to be explicitly defined and it supports a variety of methods. The `ExternalData` module takes a different approach, expecting individual files to be available under one of a set of project-defined base URL locations, with paths and file names

encoded using a particular hashing method. The actual file is represented in the project's source tree by a placeholder file of the same name, except with the name of a hashing algorithm appended as a file name suffix. The module provides a function to translate string arguments of a special form into their final downloaded location and name, along with a wrapper around the `add_test()` function to make it easier to pass these resolved locations to test commands.

In practice, the steps involved in setting up the necessary support for `ExternalData` tend to make it less attractive. The server from which the data is to be downloaded has to use a defined structure and treat every file separately. Every time a new file is added or an existing file is updated, it has to be manually hashed and uploaded to a path and file name that matches that hash. If the file is large but has only a small difference to the previous iteration, the file still has to be fully copied. In comparison, the `ExternalProject` module can achieve the same thing with one of its repository-based download methods, but the steps involved are easy and familiar for most developers. These methods also typically handle small changes in large textual files efficiently.

One reason to consider using `ExternalData` is its support for a file series rather than just an individual file. This is more of a niche scenario that typically arises for tests that process a sequence of files. Even then, one could potentially implement

similar functionality with `ExternalProject` and a `foreach()` loop, which may still be simpler to set up than the fairly rigid structure `ExternalData` requires. If the project has tests that are heavily focused on time series data or other similarly sequential data sets, then it may be worth at least evaluating whether `ExternalData` offers a preferable way to obtain that data on demand at build time. Consult the module's documentation for reference details, or for a more practical introduction, the [article](#) on this topic available from the same site as this book may be helpful.

38.8. Recommended Practices

`ExternalProject` provides one way to incorporate external content into a parent project. It can be well-suited to bringing in external projects that are mature, have good packaging and provide well-defined config files that `find_package()` can use to import the relevant targets. It also has the advantage that external dependencies are only downloaded if the build needs them. Furthermore, the downloading can be done in parallel with other build tasks. `ExternalProject` can be less convenient when developers need to work across multiple projects and make changes, especially if any modest amount of refactoring is involved.

Since `ExternalProject` has been part of CMake for a long time, there is also an established body of material available for it

online. Despite this, it is common to see developers struggle with getting it set up robustly. A particularly common weakness is hard-coding paths and file names of libraries in platform-specific ways, usually as a result of blending ExternalProject with other targets in the main project instead of a classical superbuild arrangement (see [Section 43.1, “Superbuild Structure”](#)). Give careful thought to the maturity and quality of packaging of the external dependencies and whether the main project can use a superbuild arrangement before choosing to make use of ExternalProject. Prefer not to use it if the main project cannot be converted to a superbuild arrangement. Also avoid ExternalProject if users might want to provide the external package themselves, such as through a package manager (see [Chapter 41, Dependency Providers](#)) or building it directly from sources. FetchContent (covered in the next chapter) or plain `find_package()` commands may be a better alternative in many cases.

If download details are being defined for a git repository, prefer to set `GIT_TAG` to the commit hash rather than a branch or tag name. This is more efficient, since it avoids making any network connection if the local clone already has that commit.

If the project wants to download test data on demand, check whether the ExternalData module is an appropriate choice. The ExternalProject module may be simpler to use and is likely to be better understood by most developers, but in specific cases

such as working with file sequences, `ExternalData` could potentially be simpler. If in doubt, prefer `ExternalProject` for its easier interface and potentially more efficient handling of small changes to large data sets.

39. FETCHCONTENT

The `FetchContent` module was added in CMake 3.11, with significant improvements added in CMake 3.14, 3.24, and 3.30. While it is closely related to `ExternalProject`, it has some fundamental differences. These differences strongly impact the way `FetchContent` is used and the scenarios it addresses.

39.1. Comparison With ExternalProject

Some strengths of `ExternalProject` are also its weaknesses. It allows external project builds to be completely isolated from the main project. This means it can use a different toolchain, target a different platform, use a different build type, or even an entirely different build system. The cost of these benefits is that the main project knows nothing about what the external project produces. That information has to be provided to the main build manually if anything in the main build needs to refer to the external project's outputs. This is the sort of thing that CMake is meant to do on the project's behalf, so it can be a backward step to use `ExternalProject` in this way.

For external projects that do use CMake as their build system, the flexibility to build them with different settings to the main project is often unnecessary. In fact, the more common case is that the external project should be built with the same settings as the main project. This is not all that easy to do using ExternalProject. Often a much more convenient arrangement would be to add it to the main build directly using add_subdirectory() as though it was part of the main project's own sources. This cannot be done with the traditional use of ExternalProject because the source isn't downloaded until build time. Projects may use alternative strategies such as git submodules to overcome this, but they are not without their own drawbacks too.

The FetchContent module was added to solve problems like those mentioned above, and more. It uses ExternalProject internally to download and update the external content, but it does this during the configure stage. All the same download methods are supported for FetchContent as for ExternalProject, including custom commands.

Because FetchContent downloads the external content during the configure stage, the external project's sources are available much earlier than with ExternalProject. This is the most fundamental difference between the two modules. With the content available during the configure stage, it is possible to bring the external project's sources directly into the main build.

`FetchContent` does this automatically by default by calling `add_subdirectory()` internally if the external project has a `CMakeLists.txt` file (for the basic usage at least, see next section). This means all the external project's targets, functions, etc. are all visible to the main project. There is no need to manually tell the main build where to find the built artifacts from the external project, because they are part of the same build. This also potentially makes installing things provided by the external project easier too. The same compiler flags and toolchain are also used consistently throughout the project without any extra handling.

Files downloaded at configure time can be used for a variety of purposes, not just adding sources to the build for compilation. For example, [Section 39.7, “Other Uses For `FetchContent`”](#) discusses providing CMake modules and toolchain files to the main build.

39.2. Basic Usage

`FetchContent` has a number of capabilities. This section introduces the most common use case, and later sections expand the discussion to include more recently added features.

Bringing in a dependency with `FetchContent` is always a two-step process. The canonical pattern is demonstrated by the following example:

```
include(FetchContent)

FetchContent_Declare(googletest
    GIT_REPOSITORY https://github.com/google/googletest.git
    GIT_TAG        ec44c6c1675c25b9827aacd08c02433cccde7780
)
# This command requires CMake 3.14 or later
FetchContent_MakeAvailable(googletest)
```

First, details about *how* to obtain the dependency are given using `FetchContent_Declare()`. The first argument is the name of the dependency. The rest of the arguments are mostly anything that `ExternalProject_Add()` supports, except those arguments that relate to `configure`, `build`, `install`, or `test` steps. In practice, the only options typically given are those that define a download method, such as the git details in the example above. A `SYSTEM` keyword may also be present when using CMake 3.25 or later, and `EXCLUDE_FROM_ALL` with CMake 3.28 or later (see further below).

FetchContent follows a "first to declare, wins" philosophy. If `FetchContent_Declare()` has not been called previously anywhere in the build for the same dependency, it saves the provided details for later. The details are discarded if there has been a previous call that already saved details for the specified dependency. The reasoning behind this behavior is discussed in [Section 39.3, “Resolving Dependencies”](#). Importantly, this command does not perform any download or content population.

The second step is to call `FetchContent_MakeAvailable()`, which ensures the dependency is populated by the time it returns. This is effectively the *when* part of obtaining a dependency. `FetchContent_MakeAvailable()` accepts a list of dependencies, not just a single dependency. In simple terms, the following pseudocode is executed for each argument passed to the command:

```
if the dependency is not yet populated:  
    populate it using the saved details  
    if the populated content has a CMakeLists.txt file:  
        call add_subdirectory() on the populated content
```

With CMake 3.25 or later, if the `SYSTEM` keyword was included in the call to `FetchContent_Declare()`, the `SYSTEM` keyword will be added to the `add_subdirectory()` call made by `FetchContent_MakeAvailable()`. Unless the dependency is logically directly part of the main project rather than something provided by a third party, this will be desirable. Therefore, adding the `SYSTEM` keyword is usually recommended unless the project needs to support CMake 3.24 or earlier. See [Section 16.8.2, “System Header Search Paths”](#) for further discussion of this topic.

Similarly, with CMake 3.28 or later, including the `EXCLUDE_FROM_ALL` keyword in the call to `FetchContent_Declare()` will result in `EXCLUDE_FROM_ALL` being added to the `add_subdirectory()` call made by `FetchContent_MakeAvailable()`.

This option is not recommended if the dependency produces any executables, as the developer may expect those to be available after building the default `all` target. Libraries from dependencies are less of an issue because they are always built if something else being built depends on them, even if `EXCLUDE_FROM_ALL` was given.

If a dependency is populated but there is no `CMakeLists.txt` file at the top of its source tree, `add_subdirectory()` will not be called. This is not considered an error. It allows the command to be used to populate arbitrary projects which may only contain a collection of files to be used as resources, scripts, toolchain files, etc. With CMake 3.18 or later, the `SOURCE_SUBDIR` option can be given with `FetchContent_Declare()` to specify an alternative location to search for a `CMakeLists.txt` file instead of the top of the dependency's source tree.

In practice, `FetchContent_MakeAvailable()` does much more than the pseudocode above. It also provides integration with `find_package()` and dependency providers, both of which can fulfill the request to make the dependency available in very different ways. These more complex cases are discussed in detail in [Section 39.5, “Integration With `find_package\(\)`”](#) and [Chapter 41, *Dependency Providers*](#).



FetchContent_MakeAvailable() was only added in CMake 3.14. When using earlier CMake versions, the above pattern had to be implemented manually like so:

```
FetchContent_GetProperties(foo)
if(NOT foo_POPULATED)
    FetchContent_Populate(foo)
    add_subdirectory(${foo_SOURCE_DIR} ${foo_BINARY_DIR})
endif()
```

Projects should no longer use this pattern. Calling FetchContent_Populate() in the above way is officially deprecated as of CMake 3.30. Projects should call FetchContent_MakeAvailable() instead, which provides a much richer set of features.

39.3. Resolving Dependencies

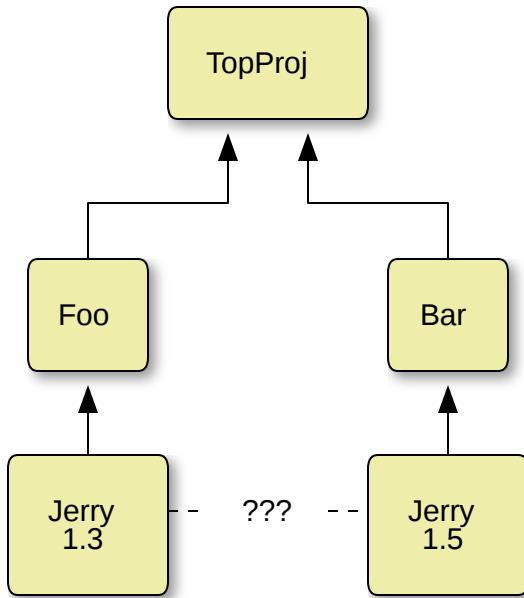
Separating the declaration of how to obtain a dependency from the command that actually populates it is a critical aspect of how FetchContent works. To understand why this is necessary, and more importantly, how to take full advantage of it, one needs to consider how dependencies are resolved in less trivial projects.

Consider a project that depends on a set of external packages, and where those packages in turn share some common dependencies. It would be undesirable to download and build those common dependencies multiple times. It would also typically be undesirable to have different parts of the build using different versions of the same dependency. Such

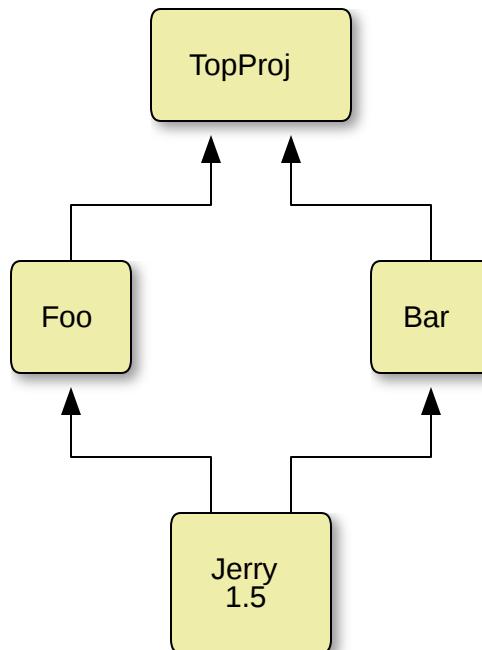
inconsistencies invite undefined behavior at run time, if the project is even able to build at all.

FetchContent handles this situation by only populating a particular dependency once for the whole CMake configure run. Later calls that ask for that dependency to be populated will re-use the same one that was populated by the first call. Furthermore, it uses the details from the first call to provide them for a dependency, and it ignores all later calls for the same dependency. Together, this "first setter wins" and "only populate once" approach means that a parent project can override dependency details of external child projects.

The following example highlights the way the FetchContent module allows a top level project to override the details set by the lower level dependencies. Consider a top level project TopProj which depends on external projects Foo and Bar. Both Foo and Bar in turn both depend on another external project, Jerry, but they each want slightly different versions of it.



Only one copy of `Jerry` should be downloaded and built, which `Foo` and `Bar` would then use. When these projects are combined into one build, the selected version of `Jerry` has to override the version normally used by `Foo` or `Bar`, or possibly even both. The top level project is responsible for ensuring that a valid version is selected such that `Foo` and `Bar` can build against it. This example assumes that while `Foo` uses version 1.3 when built on its own, it can safely use a later version. The desired arrangement and an example that implements it looks like this:



TopProj CMakeLists.txt

```
# Declare the direct dependencies
include(FetchContent)
FetchContent_Declare(foo GIT_REPOSITORY ... GIT_TAG ...)
FetchContent_Declare(bar GIT_REPOSITORY ... GIT_TAG ...)

# Override the Jerry dependency to force our preference
FetchContent_Declare(jerry
    URL      https://example.com/releases/jerry-1.5.tar.gz
    URL_HASH ...
)
# Populate the direct dependencies but leave Jerry
# to be populated by foo
FetchContent_MakeAvailable(foo bar)
```

Foo CMakeLists.txt

```
include(FetchContent)
FetchContent_Declare(jerry
```

```
    URL      https://example.com/releases/jerry-1.3.tar.gz
    URL_HASH ...
)
FetchContent_MakeAvailable(jerry)
```

The `CMakeLists.txt` file for Bar would be identical to that of Foo, except the URL would specify `jerry-1.5.tar.gz` instead of `jerry-1.3.tar.gz`. The above skeleton example allows Foo and Bar to be built as standalone projects on their own, or they can be incorporated into another project like TopProj and still have the required flexibility to resolve the common dependencies.

If TopProj wanted to completely take over the way Jerry is populated and added to the main build, it could do so by listing jerry before the other dependencies in the call to `FetchContent_MakeAvailable()`.

```
include(FetchContent)
FetchContent_Declare(foo  GIT_REPOSITORY ... GIT_TAG ...)
FetchContent_Declare(bar  GIT_REPOSITORY ... GIT_TAG ...)
FetchContent_Declare(jerry URL ... URL_HASH ...)

# Because jerry is first in the list, it will be populated
# here rather than by either foo or bar.
FetchContent_MakeAvailable(jerry foo bar)
```

This might be useful if foo or bar had used the old population pattern instead of calling `FetchContent_MakeAvailable(jerry)`.

39.4. Avoiding Sub-builds For Population

With CMake 3.29 and earlier, `FetchContent_MakeAvailable()` was implemented by creating a separate sub-build off to the side. Nothing is actually built in the sub-build, it is just re-using the way CMake works to wrap a carefully crafted call to `ExternalProject_Add()` to perform the download, update, and patch steps. On some platforms, each sub-build can consume a non-trivial amount of time, even when a dependency has already been populated by a previous run. For projects with a large number of dependencies, the time taken for these sub-builds can be prohibitive.

CMake 3.30 can drastically improve performance by avoiding the separate sub-build. It can perform all required operations directly within the main project, but this new behavior is only enabled if the `CMP0168` policy setting allows it. The policy exists to support projects that may be using some highly questionable practices that rely on implementation details of the sub-build. No project should be using such features, and it is highly unlikely any of the project's dependencies would be using the questionable practices either.

Given the above, it will usually be desirable to force the `CMP0168` policy to default to `NEW` across the whole build. This can be achieved by setting the `CMAKE_POLICY_DEFAULT_CMP0168` variable to `NEW` in the top level `CMakeLists.txt` before any dependencies are pulled in.

```
cmake_minimum_required(VERSION 3.24)
project(MyProj)

set(CMAKE_POLICY_DEFAULT_CMP0168 NEW)

# All dependencies added using FetchContent from this point
# onward will use the new, more efficient implementation.
```

Setting `CMAKE_POLICY_DEFAULT_CMP0168` as shown above has the advantage that it doesn't raise the minimum CMake version of the project. If the developer is using CMake 3.29 or older, it will continue to use the old method of a separate sub-build for population. But if the developer uses CMake 3.30 or later, the more efficient population method that avoids a sub-build will be used.

39.5. Integration With `find_package()`

The behavior described in [Section 39.2, “Basic Usage”](#) is powerful, but it isn't the only way a dependency can be provided to the main build. CMake has a long history of providing dependencies using `find_package()`, whereas `FetchContent` only became available starting with CMake 3.11. And it isn't always clear which method is better for providing a particular dependency. The better approach may depend on how the main project will be used.

For example, if the project will be packaged up to be part of a Linux distribution, the distribution maintainers will almost certainly prefer `find_package()`. The distribution is expected to

provide all dependencies, and their packaging workflow is very likely to be built around `find_package()`. On the other hand, a company may prefer `FetchContent` so that they can fully control where dependencies are obtained from, apply patches to the sources, control how the dependencies are built, and so on.

Developers too may have different preferences to project maintainers. A common example would be a developer working on a new feature in a dependency project, and at the same time, testing out that feature with their main project. That workflow is directly supported by `FetchContent` (see [Section 39.6, “Developer Overrides”](#)), but is more difficult if using `find_package()`.

With CMake 3.24 or later, features are available which enable projects to support both methods. This section focuses on features for *consuming* dependencies. The integration is driven predominantly from the `FetchContent` side. [Chapter 40, *Making Projects Consumable*](#) focuses on what projects should do so that *other projects* can more easily consume them as a dependency. That chapter details the conditions which must be satisfied for a dependency to support the integration features discussed here.

39.5.1. Try `find_package()` Before `FetchContent`

The integration features are most directly enabled by the `FIND_PACKAGE_ARGS` keyword of the `FetchContent_Declare()`

command:

```
FetchContent_Declare(somedep
    ...other options...
    # If present, the following keyword and its arguments
    # must be the last
    FIND_PACKAGE_ARGS [args...]
)
```

When the `FIND_PACKAGE_ARGS` keyword is given, it indicates that the dependency can be fulfilled using `find_package()`. Not every dependency will be able to support this. Certain constraints must be satisfied in order for it to work robustly, as discussed in [Chapter 40, *Making Projects Consumable*](#).

When the `FIND_PACKAGE_ARGS` keyword is present, the `FetchContent_MakeAvailable()` command will try calling `find_package()` first, unless disabled by conditions discussed further below. The name of the dependency is automatically used as the first argument to the `find_package()` call, followed by any arguments that were provided after the `FIND_PACKAGE_ARGS` keyword. If that `find_package()` call fails to find a package, `FetchContent_MakeAvailable()` falls back to populating the dependency using the saved details from the `FetchContent_Declare()` call (i.e. the behavior as discussed in [Section 39.2, “Basic Usage”](#)).

One common use case this enables is to look for and use a pre-built version of a dependency before falling back to building it

from sources. It is an ideal solution where a project wants to support the developer using a package manager to provide dependencies, but without requiring them to do so. See [Chapter 41, Dependency Providers](#) for a deeper discussion of this topic.

The following example from the official FetchContent documentation shows calls with and without extra arguments following the FIND_PACKAGE_ARGS keyword:

```
FetchContent_Declare(googletest
    GIT_REPOSITORY https://github.com/google/googletest.git
    GIT_TAG        703bd9caab50b139428cea1aaff9974ebee5742e
    FIND_PACKAGE_ARGS NAMES GTest
)
FetchContent_Declare(Catch2
    GIT_REPOSITORY https://github.com/catchorg/Catch2.git
    GIT_TAG        605a34765aa5d5ecbf476b4598a862ada971b0cc
    FIND_PACKAGE_ARGS
)

# This will try calling find_package() first for
# both dependencies
FetchContent_MakeAvailable(googletest Catch2)
```

The additional NAMES GTest arguments for the googletest dependency show how to account for a dependency name used with FetchContent that might not match the name typically used with `find_package()` ([Section 39.5.3, “Redirections Directory”](#) discusses additional steps needed to fully handle this scenario). For Catch2, no additional arguments are needed, but the FIND_PACKAGE_ARGS keyword is still required to enable the `find_package()` integration for that dependency. The

`find_package()` calls `constructed` internally by `FetchContent_MakeAvailable()` would essentially be:

```
find_package(googlemock QUIET NAMES GTest)
find_package(Catch2 QUIET)
```

The `QUIET` keyword is inserted automatically if not already included as one of the arguments following `FIND_PACKAGE_ARGS`. This is to limit messages from unsuccessful `find_package()` calls, which could be misleading given that the package *would* subsequently be provided by the build-from-source fallback implementation.

If the internally generated `find_package()` call fails to find the dependency and `FetchContent_MakeAvailable()` populates it from the saved details instead, hooks are automatically set up to force any future call to `find_package()` for that dependency to re-use the populated content. As a result, the same dependency is re-used for the remainder of the CMake configure run. The method used to achieve this is discussed in [Section 39.5.3, “Redirections Directory”](#).

```
FetchContent_Declare(Catch2
    GIT_REPOSITORY https://github.com/catchorg/Catch2.git
    GIT_TAG        605a34765aa5d5ecbf476b4598a862ada971b0cc
    FIND_PACKAGE_ARGS
)

# This will try calling find_package() first
FetchContent_MakeAvailable(Catch2)
```

```
# Later on, possibly in another CMakeLists.txt file...
# If the above call populated Catch2 from sources, the
# following call will use that instead of finding one
# from somewhere else.
find_package(Catch2)
```

FetchContent also provides a `FETCHCONTENT_TRY_FIND_PACKAGE_MODE` variable which controls whether `FetchContent_MakeAvailable()` is allowed to call `find_package()` (unless overridden as discussed in [Section 39.6, “Developer Overrides”](#)). The variable affects the details saved by `FetchContent_Declare()`, so what matters is the variable’s value when `FetchContent_Declare()` is called, not when `FetchContent_MakeAvailable()` is called. If set, the variable may contain one of three values:

OPT_IN

This is the behavior as described above. `find_package()` will only be called if the `FIND_PACKAGE_ARGS` keyword was given to `FetchContent_Declare()`. If

`FETCHCONTENT_TRY_FIND_PACKAGE_MODE` is not set, this is also the default behavior.

NEVER

`FetchContent_MakeAvailable()` will not call `find_package()`. Any `FIND_PACKAGE_ARGS` given to `FetchContent_Declare()` will be ignored. This is essentially the behavior of CMake 3.23 and earlier.

ALWAYS

`find_package()` will be called by `FetchContent_MakeAvailable()` regardless of whether the `FetchContent_Declare()` call included a `FIND_PACKAGE_ARGS` keyword or not. If no `FIND_PACKAGE_ARGS` keyword was given, the behavior will be as though `FIND_PACKAGE_ARGS` had been provided with no additional arguments after it.

`FETCHCONTENT_TRY_FIND_PACKAGE_MODE` should not be set by the project, it is intended to be a developer control. Projects should use the keywords in `FetchContent_Declare()` calls instead.

In practice, `FETCHCONTENT_TRY_FIND_PACKAGE_MODE` should rarely be needed. One use case would be where Linux distribution or package manager maintainers might elect to set it to `ALWAYS` in their packaging scripts. This would route all `FetchContent_MakeAvailable()` requests through `find_package()`, which their existing infrastructure may be better equipped to handle. This won't always be appropriate, but it may work for a reasonable number of packages as a quick and simple technique.

39.5.2. Redirect `find_package()` To `FetchContent`

In some situations, a project may want to force `find_package()` to use a dependency built from sources as part of the project.

One such use case is where the project requires a specific patch that isn't in any public release, or where the project needs direct access to something from the dependency's sources that would not be available from an installed package. The OVERRIDE_FIND_PACKAGE keyword provides this capability.

```
FetchContent_Declare(somedep
    OVERRIDE_FIND_PACKAGE
    ... # other options as usual
)
```

If this is the first call to FetchContent_Declare() for the given dependency, any future call to find_package() for that dependency will automatically be redirected to call FetchContent_MakeAvailable() instead. If the find_package() call contains a NAMES keyword, redirection will occur if any of the specified names match the dependency name given to FetchContent_Declare().

```
FetchContent_Declare(Catch2
    GIT_REPOSITORY ...
    GIT_TAG ...
    OVERRIDE_FIND_PACKAGE
)
# This will be redirected to FetchContent_MakeAvailable()
find_package(Catch2)
```

Conceptually, the OVERRIDE_FIND_PACKAGE and FIND_PACKAGE_ARGS keywords invoke more or less opposite behaviors. The former redirects find_package() to use FetchContent_MakeAvailable().

The latter works the other way around and allows `FetchContent_MakeAvailable()` to try `find_package()`. Therefore, at most only one of the two keywords may be given in a call to `FetchContent_Declare()`.

39.5.3. Redirections Directory

Starting with CMake 3.24, every call to `find_package()` will first look for config package files in a special directory before searching anywhere else (unless intercepted by a dependency provider, see [Chapter 41, “Dependency Providers”](#)). The location of this special directory is given by the read-only `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` variable.

`FetchContent_MakeAvailable()` may write files to this directory, as might a project in some circumstances, as explained further below. The directory is automatically cleared at the start of every CMake run. Any contents from a previous run are *always* discarded. This ensures that no stale redirection files are left from earlier CMake invocations and only files created by the current run are used.

When a call to `FetchContent_MakeAvailable()` populates a dependency as described in [Section 39.2, “Basic Usage”](#), it checks to see if future calls to `find_package()` for that dependency should be redirected to use the populated content. It will set up that redirection if either of the following conditions are met:

- A `FIND_PACKAGE_ARGS` or `OVERRIDE_FIND_PACKAGE` keyword was given in the `FetchContent_Declare()` call.
- `FETCHCONTENT_TRY_FIND_PACKAGE_MODE` was set to `ALWAYS` at the time `FetchContent_Declare()` was called.

Once population has occurred, the behavior of `FIND_PACKAGE_ARGS` and `OVERRIDE_FIND_PACKAGE` is the same. Both will result in future `find_package()` calls for that dependency using the populated content.

`FetchContent_MakeAvailable()` sets up the redirection by generating a pair of `<lowercaseDepName>-config.cmake` and `<lowercaseDepName>-config-version.cmake` files in the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory. Because `find_package()` always looks there first, these files will always be found and used ahead of files in any other location.

The generated `<lowercaseDepName>-config.cmake` file is very minimal. The only thing it does is look for a couple of optional extra files in the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory:

- `<lowercaseDepName>-extra.cmake`
- `<depName>Extra.cmake`

If either file is present, it will be read using `include()`. CMake doesn't generate these "extra" files, they are intended as a customization point for dependency projects to create, if they

want to. They allow dependency projects to define things that would normally be available using `find_package()`, but which would otherwise not be available in the calling scope when the dependency is built from source. Targets and commands defined by the build-from-source method already have global visibility, so the only thing that would normally be defined in such files would be variables. Where possible, projects should prefer to provide information through targets and commands rather than through variables, so this mechanism would generally only be used to preserve backward compatibility. [Section 40.4, “Avoid Package Variables If Possible”](#) discusses this particular topic in more detail.

The generated `<lowercaseDepName>-config-version.cmake` file is also very simple. All it does is set the `PACKAGE_VERSION_COMPATIBLE` and `PACKAGE_VERSION_EXACT` variables to true (the latter will only be set with CMake 3.24.2 or later due to a bug in earlier versions). This has the effect of accepting any version requirement which may have been part of a `find_package()` call. It is assumed that the `FetchContent`-provided (typically built-from-source) dependency always satisfies any version requirements of consumers.

The "first to declare, wins" philosophy is also applied when `FetchContent_MakeAvailable()` looks to generate the `<lowercaseDepName>-config.cmake` and `<lowercaseDepName>-config-version.cmake` files. If a file already exists,

`FetchContent_MakeAvailable()` will not replace it. This gives the dependency a chance to provide the file first if it wants to. A dependency therefore always has control over how it is presented to consumers, just like it would if using an installed package.

The `<lowercaseDepName>-config.cmake` file would not typically be overridden. The `<lowercaseDepName>-extra.cmake` file mechanism already provides the necessary functionality to fully customize the behavior, so that file should be provided by a dependency project instead if additional things need to be set. On the other hand, a dependency may want to provide its own `<lowercaseDepName>-config-version.cmake` file to set the `PACKAGE_VERSION` variable. When overriding this file, it must obey the following requirements:

- The `PACKAGE_VERSION_COMPATIBLE` and `PACKAGE_VERSION_EXACT` variables *must* be set to true, regardless of what version was requested or is being provided.
- The `PACKAGE_VERSION_UNSUITABLE` variable *must not* be set to true, and ideally shouldn't be set at all.

These requirements mean a version file generated using `write_basic_package_version_file()` from the `CMakePackageConfigHelpers` module is not appropriate for overriding the default generated `<lowercaseDepName>-config-`

`version.cmake` file. For projects with a version number, the file contents should be no more than something like this:

```
set(PACKAGE_VERSION 1.2.3)
set(PACKAGE_VERSION_COMPATIBLE TRUE)
set(PACKAGE_VERSION_EXACT TRUE)
```

In some situations, a project may want to write a `*-config.cmake` file to the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory for a different but related dependency name. In [Section 39.5, “Integration With `find_package\(\)`”](#), an example was given where the `FIND_PACKAGE_ARGS` keyword was used to provide alternate names for `googletest`:

```
FetchContent_Declare(googletest
  GIT_REPOSITORY https://github.com/google/googletest.git
  GIT_TAG        703bd9caab50b139428cea1aaff9974ebee5742e
  FIND_PACKAGE_ARGS NAMES GTest
)
```

This ensures that a call like `find_package(googletest)` will be redirected to `FetchContent_MakeAvailable(googletest)`. However, because CMake provides a module called `FindGTest`, projects will typically (and rightfully) call `find_package(GTest)` instead. Therefore, additional steps are needed to redirect `find_package(GTest)` as well. The official documentation for `FetchContent` contains an example with the necessary logic to achieve this, shown here for reference:

```
FetchContent_Declare(googletest ...)
FetchContent_MakeAvailable(googletest)
```

```

if(NOT EXISTS ${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/gtest-config.cmake AND
    NOT EXISTS ${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/GTestConfig.cmake)
    file(WRITE ${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/gtest-config.cmake
[=]
include(CMakeFindDependencyMacro)
find_dependency(googletest)
]=)
endif()

if(NOT EXISTS ${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/gtest-config-version.cmake
AND
    NOT EXISTS ${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/GTestConfigVersion.cmake)
    file(WRITE ${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/gtest-config-version.cmake
[=]
include(${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/googletest-config-version.cmake
OPTIONAL)
if(NOT PACKAGE_VERSION_COMPATIBLE)
    include(${CMAKE_FIND_PACKAGE_REDIRECTS_DIR}/googletestConfigVersion.cmake
OPTIONAL)
endif()
]=)
endif()

```

By writing the `gtest-config.cmake` and `gtest-config-version.cmake` files to the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory, `find_package(GTest)` calls will be redirected. All the `gtest-config.cmake` file has to do is call `find_dependency(googletest)`, which is equivalent to `find_package(googletest)` but with some additional handling of arguments like `QUIET` and `REQUIRED` (see [Section 35.9.1, “Config Files For CMake Projects”](#)). The `gtest-config-version.cmake` file is also very simple. It only needs to include the equivalent `googletest-config-version.cmake` or

`googletestConfigVersion.cmake` file, if present in the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory. The names of variables set by these version files don't contain the package name, so they can be re-used for an alternative name for the same thing.

As shown in the example, these files should only be written if they don't already exist. This follows the "first to declare/define, wins" principle of `FetchContent`, which ensures a higher level project always has full control of its dependencies.

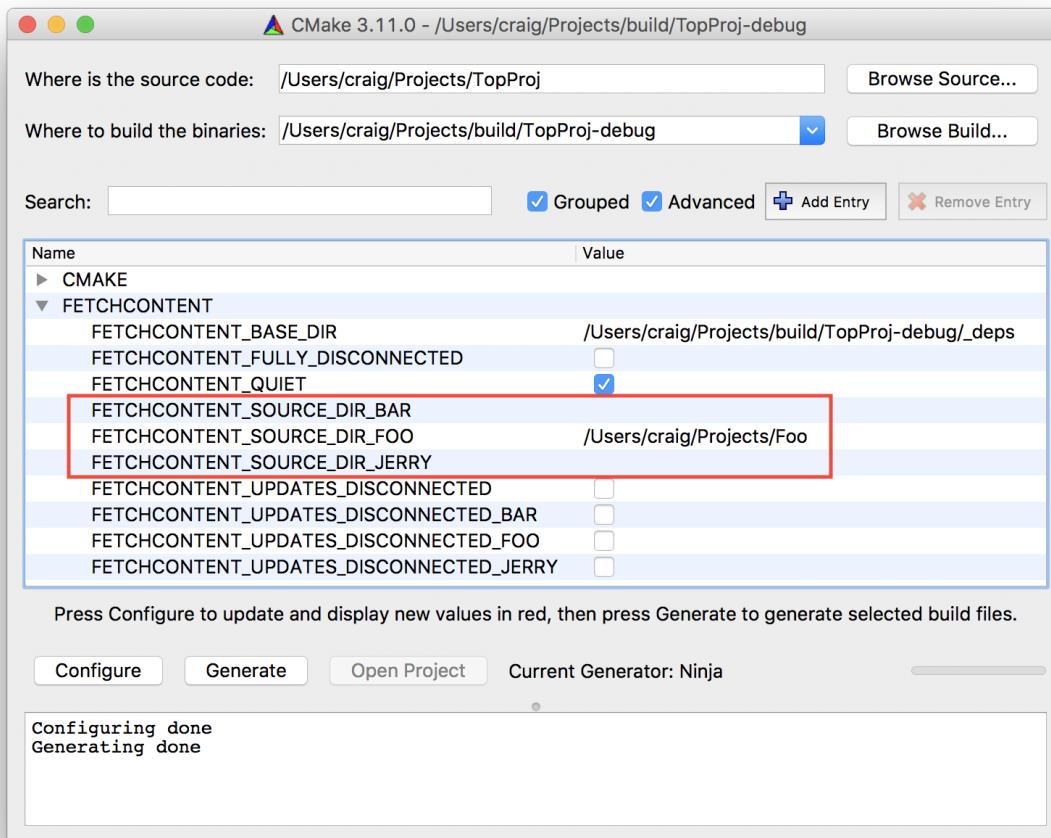
39.6. Developer Overrides

There may be occasions when a developer wants to work on multiple projects at once, making changes in both the main project and its dependencies or across multiple dependencies, etc. When changing parts of an external project, the developer will want to work with a local copy rather than having to update the remote location it is downloaded from or found at each time. The `FetchContent` module offers direct support for this developer workflow by allowing the source directory of any external dependency to be overridden with a CMake cache variable. These variables have names of the form `FETCHCONTENT_SOURCE_DIR_<DEPNAME>`, where `<DEPNAME>` is the dependency name in uppercase.

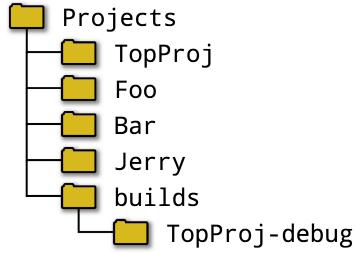
For the example scenario used earlier in [Section 39.3, “Resolving Dependencies”](#), consider a situation where the

developer wants to make a change to Foo and see how it affects the main TopProj project. They can create a separate clone of Foo outside the main project and then set `FETCHCONTENT_SOURCE_DIR_FOO` to that location. The TopProj project would use the source of that local copy and not modify it in any way, but it would still use the same build directory for it within its own TopProj build area. The only difference would be where the source comes from. By setting `FETCHCONTENT_SOURCE_DIR_FOO`, the developer would take over control of the content. They would be free to change anything in their local copy, make further commits, switch branches or whatever else may be needed, then rebuild the main TopProj project without having to change TopProj at all.

Because the relevant cache variables all share the same prefix, they are easy to find in the CMake GUI or `ccmake` tool. This in turn makes it trivial to see which projects are currently using a local copy instead of the default downloaded or found contents.



An arrangement that works well when using `FETCHCONTENT_SOURCE_DIR_<DEPNAME>` is to have a common directory under which the developer checks out the different projects they want to work with. The main project can then be pointed at these local checkouts when needed, but still use the default downloaded or found contents otherwise. Such an arrangement may look like this for the above example:



If the developer wanted to make some changes to Foo and test it with a build of TopProj, they could set `FETCHCONTENT_SOURCE_DIR_FOO` to `./Projects/Foo`, but all the build output from the Foo dependency would still be under `Projects/builds/TopProj-debug`. If `FETCHCONTENT_SOURCE_DIR_BAR` was left unset, then Bar would still be downloaded rather than using the local checkout in `Projects/Bar`. The developer could switch to that local checkout just as easily by setting `FETCHCONTENT_SOURCE_DIR_BAR` at any time.

A significant advantage of the `FETCHCONTENT_SOURCE_DIR_<DEPNAME>` approach is that it integrates well with IDE features like code refactoring tools, etc. The IDE sees the whole project, including its dependencies. As a result, when local checkouts of those dependencies are used, refactoring can be performed transparently across multiple projects just as easily as if they were all part of the same project. Even if local dependency checkouts are not used, the IDE has greater opportunity to build up a more complete code model for autocompletion, following symbols, and so on.

When a dependency has details declared via `FetchContent_Declare()` and either the `FIND_PACKAGE_ARGS` keyword was used or `FETCHCONTENT_TRY_FIND_PACKAGE_MODE` was set to `ALWAYS`, the `FETCHCONTENT_SOURCE_DIR_<DEPNAME>` variable also takes priority over `find_package()` calls for that dependency. If a dependency provider is registered (see [Chapter 41, Dependency Providers](#)), the provider will not see the request for a dependency that has the `FETCHCONTENT_SOURCE_DIR_<DEPNAME>` variable set. The assumption is that if the developer sets this variable, they expect it to override all other methods for fulfilling a dependency request, whatever the form.

39.7. Other Uses For FetchContent

FetchContent enables more than just downloading an external project's source code and building it as part of the main project. It is also a great way to re-use build logic and supporting functionality across multiple projects.

39.7.1. Sharing Toolchain Files

The following example takes advantage of the fact that the `FetchContent` module can be used even before the first `project()` call. This feature allows the module to provide toolchain files which the developer can then use for the main project.

```
cmake_minimum_required(VERSION 3.14)
```

```
include(FetchContent)
FetchContent_Declare(CompanyXToolchains
    GIT_REPOSITORY ...
    GIT_TAG      ...
    SOURCE_DIR    ${CMAKE_BINARY_DIR}/toolchains
)
FetchContent_MakeAvailable(CompanyXToolchains)

project(MyProj)
```

```
cmake -DCMAKE_TOOLCHAIN_FILE=toolchains/beta_cxx.cmake ...
```

In the above example, the directory into which the toolchains are downloaded is overridden using the `SOURCE_DIR` option. Assuming `CompanyXToolchains` is just a collection of toolchain files with no subdirectories, their location is both predictable and easy for developers to use. Where organizations work with very specific toolchains that are expected to always be installed to the same place (e.g. in a Docker container), this can be a very effective way to facilitate a whole team using common build setups. When combined with CMake presets (see [Chapter 42, Presets](#)), the entire setup can be fully automated. The technique could even be extended to download the toolchains themselves.

When using the above pattern, it may be desirable to be able to build the toolchains repository standalone. By adding some very simple source files, then compiling and linking them with each toolchain file, the correctness of the toolchain files can be verified. The main caveat is that the toolchain repository cannot call `project()` if it is being pulled in by a parent like in

the example above. The parent must be the first place where `project()` is called, and that must happen after the toolchains repository has been pulled in.

The following example of a toolchain repository's top level `CMakeLists.txt` file demonstrates how to safely support both scenarios discussed above:

```
cmake_minimum_required(VERSION 3.21)

# Only call project() for standalone builds
if(CMAKE_SOURCE_DIR STREQUAL CMAKE_CURRENT_SOURCE_DIR)
    project(CompanyXToolchains)
    # Add some smoke tests to verify the toolchain used
    add_subdirectory(src)
endif()
```

The `src/CMakeLists.txt` file is where `add_executable()` or `add_library()` calls would be made with the simple source files mentioned just above.

39.7.2. Sharing CMake Modules And Commands

Another use case is to collect commonly used CMake modules and commands in a central repository and re-use them across many projects. Multiple collections can be pulled in via this mechanism, which makes it relatively straightforward to incorporate useful CMake scripts from other projects without having to embed copies in the main project's own sources.

The following demonstrates an example where an external git repository is downloaded and its `cmake` subdirectory is added to the CMake module search path of the main project.

```
include(FetchContent)
FetchContent_Declare(JoeSmithUtils
    GIT_REPOSITORY ... GIT_TAG ...
)
FetchContent_MakeAvailable(JoeSmithUtils)

if(NOT "${joesmithutils_SOURCE_DIR}" STREQUAL "")
    list(APPEND CMAKE_MODULE_PATH
        ${joesmithutils_SOURCE_DIR}/cmake
    )
endif()
```

The above example relies on a specific behavior of the `FetchContent_MakeAvailable()` command. Unless it is redirected to provide the dependency using `find_package()`, it will normally define a set of variables in the calling scope. One of these variables is `<lowercaseDepName>_SOURCE_DIR`. When defined, this variable provides the location of the source directory of the populated content, even if it was populated by an earlier call rather than this one. The variable might also not be defined if the dependency request is fulfilled by a dependency provider (see [Chapter 41, Dependency Providers](#)), hence the need to test if the variable is set before using it.

A more flexible and arguably more robust alternative to the above arrangement is for the dependency to provide its own setup command. Consumers then call this after

`FetchContent_MakeAvailable()` instead of having to manually set things like `CMAKE_MODULE_PATH` using variables which might not be defined in all use cases. Using a setup command has the advantage that it should work for all methods that `FetchContent_MakeAvailable()` might use to obtain the dependency. The dependency needs to ensure the command is defined regardless of whether it is consumed via `find_package()` or if it is brought directly into the consumer's build as though via `add_subdirectory()`. In practice this means the dependency's `<lowercaseDepName>-config.cmake` file should define the command, as should the dependency's own `CMakeLists.txt` file. A dependency that implements this approach might be structured something like this:

cmake/joesmithutils-extra.cmake

```
function(JoeSmithUtilsSetup)
    # Only modify caller's scope once
    if(JoeSmithUtilsSetupDone)
        return()
    endif()

    set(CMAKE_MODULE_PATH
        ${CMAKE_MODULE_PATH}
        ${CMAKE_CURRENT_FUNCTION_LIST_DIR}
        PARENT_SCOPE
    )
    set(JoeSmithUtilsSetupDone TRUE PARENT_SCOPE)
endfunction()
```

JoeSmithUtils' CMakeLists.txt file

```
cmake_minimum_required(VERSION 3.14)
project(SomeDep)
```

```
include(cmake/joesmithutils-extra.cmake)
```

```
...
```

JoeSmithUtilsConfig.cmake

```
include(${CMAKE_CURRENT_LIST_DIR}/joesmithutils-extra.cmake)
# Usual contents to define targets, etc...
```

The project consuming the dependency would then do something like this:

```
include(FetchContent)
FetchContent_Declare(JoeSmithUtils ...)
FetchContent_MakeAvailable(JoeSmithUtils)
JoeSmithUtilsSetup()
```

39.8. Restrictions

For the most part, the `FetchContent` module comes with some strong advantages, but there are some restrictions to be aware of. The main limitation is that CMake target names must be unique across the whole set of projects being combined. If two external projects define a target with the same name, they cannot both be added via `add_subdirectory()`, which `FetchContent_MakeAvailable()` will typically call internally. This can be easily avoided if projects use project-specific target names, but this practice is not always followed, especially in older projects.

Another common problem is projects that assume they are the top level project. A frequently observed symptom of this is the

use of variables like `CMAKE_SOURCE_DIR` and `CMAKE_BINARY_DIR` where alternatives like `CMAKE_CURRENT_SOURCE_DIR` and `CMAKE_CURRENT_BINARY_DIR` would be more appropriate. Again, this is usually easy to fix, it is often just an awareness issue for the project maintainers.

[Chapter 40, *Making Projects Consumable*](#) presents a more comprehensive discussion of things projects can do to facilitate other projects consuming them as dependencies. It covers the broader discussion of how to make projects compatible with different ways of incorporating a project into another build, not just via `FetchContent`.

39.9. Recommended Practices

The `FetchContent` module is a good choice where other projects need to be added to the build in a way that allows them to be worked on at the same time. It affords developers the freedom to work across projects and temporarily switch to local checkouts, change branches, test with different release versions, and various other use cases in a seamless manner. It is also friendly to IDE tools, since the whole build appears as a single project. Code completion often provides greater insight and may be more reliable than if the projects had been loaded separately. Refactoring can also be performed across repositories much more robustly.

If adding dependencies to an existing mature project, `FetchContent` can be much less disruptive than `ExternalProject`, since it doesn't require any restructuring of the main project. It is also well-suited to incorporating external projects that are relatively immature and which don't yet have install components and packaging implemented. A further advantage of `FetchContent` is that it inherently results in using the same compiler and settings across the whole project hierarchy. If a minimum CMake version of 3.11 or higher is acceptable, consider whether `FetchContent` is a more convenient and natural fit for the project than `ExternalProject`. It is also strongly recommended to become familiar with tools like `ccache` for speeding up the build, as the benefits are especially pronounced when using `FetchContent`. See [Section 26.5, “Compiler Caches”](#) for a detailed discussion of how to set this up for various compilers.

Use `FetchContent_MakeAvailable()` to populate content. Avoid the older, more manual pattern of calling `FetchContent_GetProperties()` and `FetchContent_Populate()`, which has been officially deprecated since CMake 3.30. The `FetchContent_MakeAvailable()` command offers far more flexibility and choice for the developer, it is easier to use, and it provides a much richer set of functionality.

Always prefer to enable the more efficient `FetchContent_MakeAvailable()` implementation that avoids

separate sub-builds. Set `CMAKE_POLICY_DEFAULT_CMP0168` to `NEW` in the top level `CMakeLists.txt` file before any dependency is added. In the extremely unlikely scenario where a dependency uses one of the highly discouraged and questionable practices not supported by the `NEW` behavior (see [Section 39.4, “Avoiding Sub-builds For Population”](#)), add an earlier call to `FetchContent_Declare()` with more appropriate arguments to override the problematic one.

Just as for `ExternalProject`, if download details are being defined for a git repository, prefer to set `GIT_TAG` to the commit hash rather than a branch or tag name. This is more efficient, since it avoids making any network connection if the local clone already has that commit.

When adding a dependency using `FetchContent`, check if the dependency project can be treated the same way regardless of whether it is consumed as an installed binary package using `find_package()`, or it is being built from sources as described in [Section 39.2, “Basic Usage”](#). The requirements for being able to treat both the same are given in [Chapter 40, *Making Projects Consumable*](#). If a dependency can be consumed identically for both scenarios, add the `FIND_PACKAGE_ARGS` keyword to the `FetchContent_Declare()` call. This gives the developer the flexibility to choose how they want to obtain that dependency instead of being locked in to the project’s choice. It also allows the project to be mixed with other projects which might have

requested the same dependency with `find_package()` rather than `FetchContent`.

Avoid using the `OVERRIDE_FIND_PACKAGE` keyword with `FetchContent_Declare()` unless it is absolutely necessary. It reduces developer choice for how to obtain that dependency, or forces them to make their own earlier call to `FetchContent_Declare()` just to prevent the override. If the project making the call to `FetchContent_Declare()` is an open source project, `OVERRIDE_FIND_PACKAGE` is usually inappropriate. Prefer to give developers the freedom to provide the dependency through the method that best suits their needs.

Do not set `FETCHCONTENT_TRY_FIND_PACKAGE_MODE` in project code. It is intended as a developer control and should be left for the developer or driving script author to use as appropriate in their own situation. This variable is probably not of great use to developers apart from short-term experiments. It may be more useful to package manager maintainers with established infrastructure built around `find_package()`.

[Section 40.5, “Use Appropriate Methods To Obtain Dependencies”](#) also provides a condensed summary of recommendations covering much of the above, which may be a helpful reference.

40. MAKING PROJECTS CONSUMABLE

Projects should make as few assumptions as possible about how they will be consumed by other projects or packages. Consumers could use a variety of different methods, but most of them ultimately reduce down to one of the following two main scenarios:

- The project is installed as a binary package. Consumers would then use standard CMake methods like `find_package()` to use the project as a dependency in their own build.
- Consumers incorporate the project's sources directly into its own build, using standard CMake methods like `FetchContent` or `add_subdirectory()`. The consumer and the dependency project are both built together in a single, combined build.

Projects tend to have more difficulty with the second case above, since there are more opportunities for problems due to the shared global build state. However, some problems and their solutions span both scenarios.

Consumers also want to avoid having to treat a dependency differently based on how it was brought into the build. Ideally, they just want to say "I need X", and then they do everything the same regardless of how "X" was provided. In practice, this means a project should present the same things (targets, commands, etc.) to the consumer, regardless of which of the above two main approaches they use. It also means the project should ensure all of its own dependencies are satisfied too.

Projects can avoid most problems by following a few basic principles. This chapter collects and condenses a number of guidelines mentioned in earlier chapters and combines them with additional recommendations to demonstrate those principles.

40.1. Use Project-specific Names

When a consumer pulls in multiple dependencies, there are certain restrictions that may apply to the names of things the dependencies define. Perhaps the most relevant is that global targets must be unique. If dependencies are built from sources, their targets will be global. In certain cases, targets from binary packages may also need to be global. Therefore, projects should ensure that any targets they define have project-specific names to avoid clashing with other projects.

A recommended naming strategy was discussed in detail in [Section 35.3, “Installing Exports”](#). The main points of that discussion can be summarized as follows:

- In the project’s `CMakeLists.txt` files, use a `< projectName >_...` prefix on target names.
- Use the target’s `OUTPUT_NAME` property to specify a more appropriate name for a target’s built binary, if required. Ideally, this name would still be project-specific to minimize the chance of the binary’s name clashing with other projects’ binaries.
- When exporting targets as part of install logic, follow the strong convention of using `< projectName >::` as the export namespace.
- To avoid repeating the project name in the final exported target name, use the `EXPORT_NAME` target property to override the default exported target name.
- Define an `ALIAS` target in the project’s `CMakeLists.txt` files which matches the full exported name of the target. This allows consumers to link to this name and not care whether the project is provided as a binary package or built from source as part of the main build.

The following (slightly reduced) example from [Section 35.3, “Installing Exports”](#) demonstrates the above points:

```
add_library(MyProj_Algo SHARED ...)
add_library(MyProj::Algo ALIAS MyProj_Algo)

set_target_properties(MyProj_Algo PROPERTIES
    OUTPUT_NAME MyProjAlgo
    EXPORT_NAME Algo
)

install(TARGETS MyProj_Algo EXPORT MyProj ...)
install(EXPORT MyProj NAMESPACE MyProj:: ...)
```

If the project defines install components (see [Section 35.2, “Installing Project Targets”](#) and [Section 36.2, “Components”](#)), ideally its component names should also be project-specific. When the project is consumed in a build-from-source scenario, this should prevent its install components from being merged with install components from other projects. The consumer gains more precise control over how it manages the different install components of each of its individual dependencies without any overlap between them.

```
install(TARGETS MyProj_Algo
    RUNTIME COMPONENT MyProj_Runtime ...
    LIBRARY COMPONENT MyProj_Runtime
        NAMELINK_COMPONENT MyProj_Development ...
    ARCHIVE COMPONENT MyProj_Development
)
```

Test names are another place where name conflicts may need to be considered, although the consequences are usually less severe. [Section 40.2, “Don’t Assume A Top Level Build”](#) discusses why tests should typically only need to be enabled for the top

level project. But for situations where tests from dependencies may still be desirable, it is helpful if test names from dependencies are uniquely identifiable from those of other dependencies or the top level project. The `ctest` tool doesn't currently raise an error if there are duplicate test names between different directories. However, duplicate test names can be confusing for users, as they can't differentiate between them in the test results. Therefore, test names should be globally unique. A simple but effective way to achieve this is to prefix them with the project name followed by a dot. This format has the advantage that it may already be familiar and feel natural to developers accustomed to other languages and test frameworks.

```
add_test(NAME MyProj.Algo COMMAND test_Algo)
add_test(NAME MyProj.Core COMMAND test_Core)
```

Cache variables are yet another place where using project-specific names is advisable. This avoids unintended coupling of the behavior of two different projects that happen to use the same cache variable name. A recommended strategy is to prefix cache variable names with the project name in uppercase, followed by an underscore. When IDEs present variables to the user, some support grouping them by the prefix up to the first underscore, so this naming convention has the nice benefit of grouping all of a project's variables together in such IDEs. This makes them very easy for the developer to find, especially in large, complex projects.

```
# BAD: Name is generic, may clash with other projects.  
option(ENABLE_HUGE_TESTS "Build and run expensive tests")  
  
# GOOD: Name starts with project-specific prefix.  
option(MYPROJ_ENABLE_HUGE_TESTS "...")  
  
# COULD BE IMPROVED: Variable name doesn't start with the  
# project name, so project cache variables won't be  
# grouped in IDEs that support that feature.  
option(ENABLE_HUGE_MYPROJ_TESTS "...")
```

40.2. Don't Assume A Top Level Build

Many projects have never considered the use case of being absorbed into a larger parent build directly. For such projects, there are a few common problems that are often encountered. The first and perhaps most prevalent is the use of global path variables like `CMAKE_SOURCE_DIR` and `CMAKE_BINARY_DIR`. When the project is absorbed into a larger parent build, the relative location of the global path variables will change. The project might then no longer find things at the locations it expected. In general, avoid using `CMAKE_SOURCE_DIR` or `CMAKE_BINARY_DIR` unless a path truly needs to be relative to the top level of the source or build tree, even when absorbed into a larger parent build. Prefer instead to use directory-relative variables like `CMAKE_CURRENT_SOURCE_DIR` and `CMAKE_CURRENT_BINARY_DIR`, or project-relative variables like `PROJECT_SOURCE_DIR` and `PROJECT_BINARY_DIR`.

Another common problem is modifying variables that have the potential to affect the whole build, not just the project. A classic example is forcing the value of cache variables like `BUILD_SHARED_LIBS`, `BUILD_TESTING`, `CMAKE_BUILD_TYPE`, `CMAKE_MODULE_PATH` or `CMAKE_RUNTIME_OUTPUT_DIRECTORY`. Using the `FORCE` or `INTERNAL` keywords with the `set()` command on these variables prevents a parent project from overriding that choice. Quite often, these variables shouldn't be defined by the project as cache variables at all, and maybe shouldn't even be set by the project to begin with. For variables like `CMAKE_MODULE_PATH`, append to existing values rather than replace them.

Another variable-related problem is the way the initial value of cache variables are set. Policies `CMP0077` and `CMP0126` affect how a non-cache variable is interpreted when a cache variable of the same name is first initialized. As discussed in [Section 6.3.1, “Getting And Setting Cache Variables”](#), the `NEW` behavior of these policies minimize the opportunities for surprise. Where possible, projects should require CMake 3.21 or later and ensure policies `CMP0077` and `CMP0126` are set to `NEW`. This will prevent the project from discarding values set by parent projects as non-cache variables. Note that these policies can also result in no cache variable being defined if a non-cache variable of the same name already exists. Protect any logic that assumes a cache variable exists with an appropriate check:

```
if(DEFINED CACHE{TRAFFIC_LIGHT})
    set_property(CACHE TRAFFIC_LIGHT PROPERTY STRINGS)
```

```
    Red Orange Green  
)  
endif()
```

It is also worth mentioning a usability aspect that is often forgotten. Projects should provide good default behavior when brought in as part of a larger build. Two areas where this is often neglected are testing and packaging. Tests are much less likely to be of interest to the developer when a project is not the top level of the build, so they should be disabled by default when they are not the top level. It may be appropriate to provide a project-specific cache variable in this case, since the user may still want to enable the project's tests in some situations. And while install components may be useful to a parent project, only top level projects should call `include(CPack)` to configure packaging. The following example shows a pattern that provides good default behavior whether the project is the top level or not (see [Section 8.3, “Project-relative Variables”](#) for an expanded discussion of `PROJECT_IS_TOP_LEVEL` and alternatives).

```
# CMake 3.21 or later is required for PROJECT_IS_TOP_LEVEL  
  
option(MYPROJ_ENABLE_TESTING "..." ${PROJECT_IS_TOP_LEVEL})  
if(MYPROJ_ENABLE_TESTING)  
    add_subdirectory(tests)  
endif()  
  
if(PROJECT_IS_TOP_LEVEL)  
    add_subdirectory(packaging)  
else()  
    # Users are unlikely to be interested in testing this
```

```
# project, so don't show it in the basic options
mark_as_advanced(MYPROJ_ENABLE_TESTING)
endif()
```

40.3. Avoid Hard-coding Developer Choices

Some CMake features are intended for the developer or a script driving the build to use, not for the project. Sometimes, projects are tempted to use these features and hard-code specific behaviors instead of allowing the developer to choose. Some examples of this include:

- Hard-coding logic that forces the use of a specific package manager.
- Forcing compiler warnings to be treated as errors.
- Discarding previous contents of `CMAKE_MODULE_PATH` or `CMAKE_PREFIX_PATH` instead of appending to the existing values.
- Prepending to search paths instead of appending, causing those paths to always take precedence over values the developer or driving script might set.

The problem is not always that the project wants to set or do these things. The main issue is whether the developer, driving script, or even a parent project still has the ability to override that behavior, and how hard it is for them to do so. Avoid forcing non-essential choices on the consumer of the project.

40.4. Avoid Package Variables If Possible

Before CMake 3.0, packages and Find modules would typically provide information to consumers through variables like `foo_INCLUDE_DIRECTORIES`, `foo_LIBRARIES` and so on. In the post-3.0 era, such information should be provided through target properties instead (see [Section 10.4, “Target Properties”](#) and [Section 16.2, “Target Property Commands”](#)). Targets are more robust and convey usage requirements, whereas variables require the consumer to know and apply the variables appropriately where they are needed.

If a project needs to define such variables for backward compatibility reasons, consider supporting `find_package()` integration with `FetchContent_MakeAvailable()`. This involves writing a `<lowercaseDepName>-extras.cmake` file to the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory (see [Section 39.5.3, “Redirections Directory”](#)), setting each of the package variables. Without this file, consumers won’t be able to rely on having the variables available with all dependency methods.

Conversely, if a project doesn’t need to provide such variables to satisfy backward compatibility requirements, don’t add them. They do not help consumers, they only promote poor habits. Prefer to offer targets exclusively and record any information that needs to be conveyed as properties on those targets. This includes additional details like package version, a list of enabled features, etc. Even then, avoid providing details

"just in case". Good package APIs should be complete and minimal.

Providing commands to obtain information about a package is also sometimes an acceptable alternative to defining package variables. Commands have global visibility, so they don't have the scope concerns that variables can bring.

```
# GOOD: Information is available everywhere the target is
set_target_properties(MyThing PROPERTIES
    MYTHING_VERSION 1.2.3
    MYTHING_BACKEND CoolBeans
)

# GOOD: Commands are global, information always available
function(mything_get_info key outVar)
    # ...
endfunction()

# BAD: Variables will not be available to the consumer
#       without further help for some dependency methods
set(MYTHING_VERSION 1.2.3)
set(MYTHING_BACKEND CoolBeans)
```

As a special case, if a project normally provides a `<packageName>-config-version.cmake` file when installed, it can write a simplified version of that file to the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory when building from source, as detailed in [Section 39.5.3, “Redirections Directory”](#). Such files need be no more complicated than these three lines:

```
set(PACKAGE_VERSION 1.2.3)
set(PACKAGE_VERSION_COMPATIBLE TRUE)
set(PACKAGE_VERSION_EXACT TRUE)
```

By writing this file to the `CMAKE_FIND_PACKAGE_REDIRECTS_DIR` directory, any redirected `find_package()` call for that dependency will populate the usual set of `<PackageName>_VERSION...` variables for that package automatically (see the official `find_package()` documentation for the full list). Consumers frequently don't use this version information, but by providing it, a project ensures that the details are available for those few consumers that need it.

40.5. Use Appropriate Methods To Obtain Dependencies

Making a project consumable also means ensuring it consumes its own dependencies in an appropriate way. The following recommendations are mostly a condensed form of discussions that directly relate to this topic from other chapters, especially [Section 39.5, “Integration With `find_package\(\)`”](#) and [Chapter 41, *Dependency Providers*](#).

- If the project can use `find_package()` to obtain a dependency and doesn't need any functionality provided by `FetchContent`, prefer calling `find_package()`. Where it is not reasonable or desirable to put the responsibility for supplying a dependency on the developer, prefer using `FetchContent`. Internal company projects or patched dependencies are typical examples of the latter.

- Regardless of the approach used, aim to give every dependency an opportunity to be found using `find_package()`. This maximizes the chances it can be supplied by a third party package manager.
- If a project calls `FetchContent_Declare()`:
 - Add the `FIND_PACKAGE_ARGS` keyword if the dependency package meets the criteria for being consumed that way. If CMake versions earlier than 3.24 need to be supported, use a CMake version test to add it conditionally.
 - Reserve `OVERRIDE_FIND_PACKAGE` for meeting strict requirements in controlled environments (e.g. where dependencies must be built from source, or a particular patched version needs to be used).
 - Use the same dependency name as would be used for `find_package()`, including upper/lowercase.
- Avoid using the `<lowercaseDepName>_SOURCE_DIR` or `<lowercaseDepName>_BINARY_DIR` variables which may be provided by `FetchContent_MakeAvailable()`. They assume building from source, which precludes using `find_package()`.
- Don't use the manual `FetchContent` population pattern. Update projects to use `FetchContent_MakeAvailable()` instead.
- For open source projects, be prepared for `FETCHCONTENT_TRY_FIND_PACKAGE_MODE` being set to `ALWAYS` (package managers or Linux distributions may do that).

- Don't set or modify `FETCHCONTENT_TRY_FIND_PACKAGE_MODE` in the project.

40.6. Recommended Practices

Much of this chapter already provides a fairly comprehensive set of guidelines for ensuring a project is consumable by a broad range of methods. The following summarizes the main over-arching principles that underpin those recommendations:

- Use project-specific names for things that are visible outside the project.
- Always assume the project will some day be used as a child of some other parent project, so it won't always be the top level.
- Don't interfere with or block features that developers, driving scripts or parent projects should be able to control.
- Prefer to define only targets, target properties and commands for packages. Avoid setting package variables except to preserve backward compatibility.
- Enable `find_package()` integration for any call to `FetchContent_Declare()` where that dependency meets the requirements for doing so.

41. DEPENDENCY PROVIDERS

Projects have always had to specify the things they depend on, or the "what" part of the dependency picture. The "how" part of managing dependencies tends to be more challenging. Different developers or use cases may require dependencies to be provided by very different mechanisms for the same project. One developer may want to use package manager X to provide all dependencies, but another developer may want to choose a different package manager Y. A Linux distribution or package manager maintainer may want to completely take over all dependency provision altogether. Another developer might want to replace just one particular dependency with their own forked version that contains local changes. A company may want to provide some dependencies from an internal binary artifact system, but obtain other dependencies as built from source or from third party services. Yet another developer might want to avoid dealing with any of it and expect the project to provide a working out-of-the-box experience on its own.

CMake 3.24 added a number of features aimed at better supporting the variety of needs around dependency handling.

The integration between `find_package()` and `FetchContent` enables projects to provide more complete fallbacks for the "how" part of obtaining a dependency. Importantly, it does so without taking away the developer's ability to override that and provide the dependency in their own preferred way instead. The mechanics of that integration was discussed in [Section 39.5, "Integration With `find_package\(\)`"](#). This chapter focuses on the features available to the developer for controlling how dependency requests are fulfilled.

Two features added in CMake 3.24 give the developer full control of the project's dependencies:

- A dedicated, clearly-defined injection point for executing one-time setup logic in the top project.
- Dependency providers which can intercept `find_package()` and `FetchContent_MakeAvailable()` requests and choose how they should be fulfilled.

These two features work together. A dependency provider can only be registered at the top level injection point. Projects cannot change the provider later, ensuring the developer remains in control for the whole build.

41.1. Top Level Setup Injection Point

With CMake 3.24 or later, the developer can specify a list of files in a variable named `CMAKE_PROJECT_TOP_LEVEL_INCLUDES`. Those

files will be read by the very first `project()` command, and *only* by the very first `project()` command. The files will be read in the order provided, each one as though by an `include()` command.

The `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` files are included after any toolchain file has been read, but before any languages are enabled. Therefore, variables that describe the host or target platform will be set (e.g. `CMAKE_SYSTEM_NAME`), but not necessarily any variables related to specific languages.

Projects should never set, modify or use `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` directly. It is intended exclusively for the developer, who may use it to inject files that are specific to their host machine and personal needs. It might also be set by scripts that are driving the CMake configure step. In more controlled environments, such as within an organization, CMake presets might also set it as a convenience for the developer, which still gives the developer ultimate control.

A primary use case for `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` is to provide a place where dependency providers can register themselves and perform any provider-specific setup at the start of the project. Dependency providers should supply such a file, developers should not have to write it themselves. A developer should be able to pass the provider-supplied setup file directly

to CMake via `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` and not need to know anything more about how it works.



Since `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` is still relatively new, it may take some time for existing dependency providers to implement that support and provide an appropriate file. The reader is encouraged to check with their preferred dependency provider regarding availability of support for this feature.

Some package managers hijack the toolchain file as a way to hook into the CMake configuration process for things not related to the toolchain. This is not recommended, as it isn't what a toolchain file is meant for (see [Section 24.1, “Toolchain Files”](#)). It is also not particularly intuitive for developers, and it complicates the situation when the developer wants to use a real toolchain file. With CMake 3.24 or later, `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` should be the preferred mechanism if the dependency provider supports it. This allows the developer to cleanly separate how they define their toolchain from other services wanting to perform setup steps at the start of the project.

The setup files don't have to be related to managing dependencies, they can be used for other purposes too. Another use case for `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` is as a hook for IDEs. Such tools may take advantage of this feature by

prepend their own setup files to the list already specified by the developer. This may allow an IDE to define things like `cmake_language(DEFER)` calls to record information at the very end of the CMake run, or to add an IDE-specific build target that extends the project in some way.

41.2. Dependency Provider Implementation



This section is intended for those implementing their own dependency provider, or using the provider hooks for information-gathering purposes. These details are not needed to use a provider if it has supplied a setup file, as discussed above.

When a project calls `find_package()` or `FetchContent_MakeAvailable()`, that call can be intercepted by a dependency provider. These are implemented as a single CMake command, which will be called with the appropriate arguments for the request type. A provider is registered with the following command:

```
cmake_language(  
    SET_DEPENDENCY_PROVIDER commandName  
    SUPPORTED_METHODS methods...  
)
```

At most, only one dependency provider can be registered. Registering a new one will replace any previously registered provider. Importantly, the *only* time a provider can be

registered is while processing the CMAKE_PROJECT_TOP_LEVEL_INCLUDES files at the start of the project. Any attempt to register a provider outside that context will result in a fatal error.

The command named by commandName must already be defined. Typically, the command will be defined in the same file just before registering it with cmake_language(). Making the file self-contained simplifies re-using it between different projects.

For reasons explained in [Section 41.2.1, “Accepting find_package\(\) Requests”](#) further below, provider commands should almost always be macros, not functions. By convention, the command name should follow the pattern xxx_provide_dependency(), where xxx is some provider-specific string to prevent name clashes with other dependency providers.

The SUPPORTED_METHODS is a list that specifies which types of requests the provider accepts. Supported values for the methods are:

- FIND_PACKAGE
- FETCHCONTENT_MAKEAVAILABLE_SERIAL

A dependency provider is not required to accept all methods. Requests for any methods it does not accept will be passed through transparently to the default built-in implementation.

The request method is always passed as the first argument to the provider command, so if it does accept multiple methods, it can always tell what type of request each call is for.

```
cmake_minimum_required(VERSION 3.24)

macro(example_provide_dependency method)
    # ...
endmacro()

# Accepts find_package() only
cmake_language(
    SET_DEPENDENCY_PROVIDER example_provide_dependency
    SUPPORTED_METHODS
        FIND_PACKAGE
)
# Accept find_package() and FetchContent_MakeAvailable()
cmake_language(
    SET_DEPENDENCY_PROVIDER example_provide_dependency
    SUPPORTED_METHODS
        FIND_PACKAGE
        FETCHCONTENT_MAKEAVAILABLE_SERIAL
)
```

The general pattern for a provider implementation is that it must explicitly indicate if it fulfills the request given to it. When the provider returns, CMake checks a set of method-specific conditions, discussed in the sub-sections below. If the provider didn't fulfill the request, CMake forwards it to the default built-in implementation.

41.2.1. Accepting find_package() Requests

If a provider lists `FIND_PACKAGE` as one of the methods it accepts, all `find_package()` calls will be routed through the provider. The arguments passed to the provider's command will be the request method, followed by all the arguments originally given to the `find_package()` call. Since the first argument to `find_package()` is always the package name, it is customary to hard-code that as the second positional argument to the provider command for convenience (see example below).

If the provider fulfills the request, it has to set the same variables the built-in `find_package()` implementation expects to indicate success. That typically means, at a minimum, setting `<depName>_FOUND` to `true`. If the provider command doesn't do this, CMake will assume the request was not fulfilled and will try its own built-in implementation next.

The following example file is suitable for listing in the `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` variable. In this scenario, dependencies with names that start with `restricted_...` are intercepted and replaced with placeholder artifacts. These might be stubs, alternative algorithm implementations, placeholder resources and so on. This might be a way for a developer who is subject to security or export constraints to work on code without access to restricted packages. No changes need to be made to the project itself, since the provider contains all the logic and the developer injects the provider from outside the project.

setup_provider.cmake

```
cmake_minimum_required(VERSION 3.24)

function(get_artifact_placeholder)
    # ...
endfunction()

macro(mycomp_provide_dependency method depName)
    if("${depName}" MATCHES "^restricted_.*")
        # Assume this halts with an error if it fails
        get_artifact_placeholder(${depName} ${ARGN})
        set(${depName}_FOUND TRUE)
    endif()
endmacro()

cmake_language(
    SET_DEPENDENCY_PROVIDER mycomp_provide_dependency
    SUPPORTED_METHODS
    FIND_PACKAGE
)
```

The above example demonstrates how one can write a custom provider that handles a subset of dependencies differently to others. The `restricted_...` dependencies are explicitly handled and the provider indicates it fulfilled the request by setting `_${depName}_FOUND` to true. For all other dependencies, `_${depName}_FOUND` is not set and the request is left to be handled by CMake's normal built-in processing.

The example also demonstrates why provider commands should almost always be implemented as a macro rather than a function. Provider commands are expected to set variables like `_${depName}_FOUND` and often many others in the calling scope.

This will not be just for the direct dependency, but also for any further transitive dependencies that might get pulled in. A provider is unlikely to be able to robustly know all variables it would have to forward to the caller, so it is safer to make it a macro and operate directly in the caller's scope. The main caveat is that the provider shouldn't leak unnecessary variables. It should minimize the extra variables it defines for its own internal purposes and ensure they are removed before returning to the caller. Those extra variables should also all have provider-specific names to avoid clashing with project variables.

Another interesting feature of the example is that it only accepts the `FIND_PACKAGE` method. Because it doesn't list `FETCHCONTENT_MAKEAVAILABLE_SERIAL` as one of its accepted methods, it can assume it will never receive a call for anything but a `find_package()` request. That simplifies its implementation, since it doesn't have to switch behavior based on the request type and can ignore the `method` argument. CMake already guarantees it will only be called for the type of requests it said it could handle.

41.2.2. Accepting `FetchContent_MakeAvailable()` Requests

The `FETCHCONTENT_MAKEAVAILABLE_SERIAL` method indicates the provider accepts dependency requests from

`FetchContent_MakeAvailable()` one at a time. The arguments passed to the provider for such requests will be the method, followed by the associated `FetchContent_Declare()` arguments for the dependency, with some modifications. Since the first argument to `FetchContent_Declare()` is always the dependency name, it is again customary to hard-code that as the second positional argument of the provider command (see example below). For the arguments after the dependency name, if `find_package()` integration is not enabled for that dependency, any `FIND_PACKAGE_ARGS` will be stripped out. The `OVERRIDE_FIND_PACKAGE` keyword is also always stripped out. The `SOURCE_DIR` and `BINARY_DIR` keywords will always be present, even if the original call didn't have them (they will be passed in with their default values in that case).

If the provider fulfills the request, it must call `FetchContent_SetPopulated()` with appropriate details:

```
FetchContent_SetPopulated(  
    depName  
    [SOURCE_DIR srcDir]  
    [BINARY_DIR binDir]  
)
```

The built-in implementation always provides a `SOURCE_DIR` and `BINARY_DIR`, but a dependency provider is not required to do so. This gives the provider the freedom to provide the dependency in a way that might not include source or build directories. This would be the case if it was providing pre-built artifacts instead

of building the dependency from source, for example. Note that some projects may have been written to expect the source to be available. In such cases, a provider that doesn't satisfy that requirement should not be used.

The following example implements a provider that checks if a pre-built package is available from a custom location or service and uses it if available. If no such pre-built artifact is found, the provider leaves the request to be fulfilled by the default built-in implementation.

```
cmake_minimum_required(VERSION 3.24)

function(get_prebuilt_artifact)
    # ...
endfunction()

macro(prebuilt_provide_dependency method depName)
    get_prebuilt_artifact(${depName})
    RESULT_VAR havePrebuilt
    SOURCE_DIR_VAR sourceDir
    BINARY_DIR_VAR binaryDir
)

if(havePrebuilt)
    FetchContent_SetPopulated(${depName})
    SOURCE_DIR "${${sourceDir}}"
    BINARY_DIR "${${binaryDir}}"
)
endif()
endmacro()

cmake_language(
    SET_DEPENDENCY_PROVIDER prebuilt_provide_dependency
    SUPPORTED_METHODS
```

```
    FETCHCONTENT_MAKEAVAILABLE_SERIAL  
)
```

In the above example, the pre-built artifact might still provide a source and build directory. The pre-built artifact could be provided by a separate build the developer has been working with, for example. It is not an error for empty strings to be given as the SOURCE_DIR or BINARY_DIR values in a call to FetchContent_SetPopulated().

41.2.3. Accepting Multiple Request Methods

Providers supporting multiple methods can use the first argument to the provider command to differentiate between the request types. For the two methods currently supported by CMake, the second argument is always the name of the dependency, so it can be a positional argument too.

```
cmake_minimum_required(VERSION 3.24)  
  
macro(multimethod_provide_dependency method depName)  
    message(VERBOSE  
        "Provider for ${depName} using method ${method}"  
    )  
    if("${method}" STREQUAL "FIND_PACKAGE")  
        # find_package() implementation...  
    else()  
        # FETCHCONTENT_MAKEAVAILABLE_SERIAL  
        # FetchContent_MakeAvailable() implementation...  
    endif()  
endmacro()  
  
cmake_language(  
    SET_DEPENDENCY_PROVIDER multimethod_provide_dependency  
    SUPPORTED_METHODS
```

```
FIND_PACKAGE  
FETCHCONTENT_MAKEAVAILABLE_SERIAL  
)
```

41.2.4. Wrapping The Built-in Implementations

In certain situations, a provider might want to perform some action before or after a `find_package()` call, but not actually change how the built-in `find_package()` implementation works. For example, a package manager may want to prepare some files that the built-in implementation might use, or special case post-find handling may need to be applied for a few specific dependencies. For such situations, a provider can call the built-in implementation directly by adding the `BYPASS_PROVIDER` keyword to `find_package()`. This prevents CMake from re-routing the request back to the provider again, which would otherwise cause an infinite loop. Inside a provider command is the *only* place the `BYPASS_PROVIDER` keyword should ever be used in a `find_package()` call. Future versions of CMake may halt with an error if it detects use of the `BYPASS_PROVIDER` keyword outside a provider.

A similar thing can be done with `FetchContent_MakeAvailable()`. The `FetchContent_MakeAvailable()` implementation automatically detects if a call to the provider is already in progress for a dependency and will not re-route a nested call back to the provider again. Infinite loops are therefore avoided.

A provider can take advantage of this to call `FetchContent_MakeAvailable()` directly if it wants to keep the built-in implementation and just wrap it with pre- or post-call logic.

```
cmake_minimum_required(VERSION 3.24)

function(pre_provider depName)
    # ...
endfunction()

function(post_provider depName)
    # ...
endfunction()

macro(wrapper_provide_dependency method depName)
    pre_provider(${depName})

    if("${method}" STREQUAL "FIND_PACKAGE")
        find_package(${depName} ${ARGN} Bypass_Provider)
    else()
        # FETCHCONTENT_MAKEAVAILABLE_SERIAL
        FetchContent_MakeAvailable(${depName})
    endif()

    post_provider(${depName})
endmacro()

cmake_language(
    SET_DEPENDENCY_PROVIDER wrapper_provide_dependency
    SUPPORTED_METHODS
        FIND_PACKAGE
        FETCHCONTENT_MAKEAVAILABLE_SERIAL
)
```

41.2.5. Preserving Variable Values

Both `find_package()` and `FetchContent_MakeAvailable()` operate directly in the variable scope from which they are called. This means a provider command also operates in that scope, which it needs to do in order to pass back any relevant variables for the requested dependency and any of its sub-dependencies. As part of fulfilling nested dependencies, a provider command might also end up with nested calls in the same scope. This means any variable set in the provider's implementation could hold a different value after any place it calls `find_package()` or `FetchContent_MakeAvailable()`.

Note that macro arguments are not variables, so they are not susceptible to being changed by a call to `find_package()` or `FetchContent_MakeAvailable()`. The example in the previous section took advantage of this when it referred to `${depName}` in the call to `post_provider()`. The value of `${depName}` will be the same as when the provider was called. If the provider had been implemented as a function instead of a macro, this would not be the case.

Providers sometimes need to define variables within their implementation. If those variables need to be persisted across calls to `find_package()` or `FetchContent_MakeAvailable()`, they need to be explicitly saved and restored. One technique for achieving that is to use a provider-specific list variable like a stack. One can append values to that list before calling `find_package()` or `FetchContent_MakeAvailable()`, then pop those

values off in reverse order afterwards. This simple approach only works for single-valued variables. If the variables could hold lists, a more complex implementation would be required.

The following example logs the time taken to provide each dependency. The time shown will include all nested dependencies. See [Appendix C, Timer Dependency Provider](#) for the full implementation, including the `startTimer()` and `reportTimeSince()` commands.

```
cmake_minimum_required(VERSION 3.24)

macro(timer_provide_dependency method depName)
    startTimer(t0)
    list(APPEND providerVarStack "${t0}")

    if("${method}" STREQUAL "FIND_PACKAGE")
        find_package(${depName} ${ARGN} Bypass_Provider)
    else()
        # FETCHCONTENT_MAKEAVAILABLE_SERIAL
        FetchContent_MakeAvailable(${depName})
    endif()

    list(POP_BACK providerVarStack t0)
    reportTimeSince("Time for ${depName}" "${t0}")
endmacro()

cmake_language(
    SET_DEPENDENCY_PROVIDER timer_provide_dependency
    SUPPORTED_METHODS
        FIND_PACKAGE
        FETCHCONTENT_MAKEAVAILABLE_SERIAL
)
```

41.2.6. Delegating Providers

CMake only allows a single dependency provider to be registered at any point in time. Registering a second provider replaces the first. However, it is possible to define forwarding or composing providers which delegate to other providers internally. This might be desirable if there are clearly separated groups of dependencies with no overlap, where one set should be obtained with provider A and another set with provider B. Another example is where an off-the-shelf provider should supply all the dependencies, but the developer also wants to gather information about each dependency, so they need to wrap the off-the-shelf provider.

Forwarding arguments to providers that accept the `FETCHCONTENT_MAKEAVAILABLE_SERIAL` method requires special care. Some arguments for that request type could be empty strings, and these are interpreted differently to no value being provided at all. Therefore, empty strings must be retained, if present. Because all variables set by providers need to propagate up to the original caller making the dependency request, delegating providers *must* be implemented as macros, not functions. This has implications for forwarding the command arguments.

As discussed back in [Section 9.8.1, “Parsing Arguments Robustly”](#), naively forwarding `${ARGN}` would silently drop empty strings. To avoid that, a technique such as that presented at the end of [Section 9.8.2, “Forwarding Command Arguments”](#)

must be used. The main compromise involved is that list flattening of arguments cannot be avoided. This is because there is no way to obtain the original unflattened argument list of a macro. However, this shouldn't impact the arguments for either request method, so it is an acceptable compromise in this specific situation.

The following example demonstrates how to combine the time reporting wrapper in the previous section's example with an off-the-shelf provider supplying the dependencies.

```
# This provides cots_provide_dependency()
include(/path/to/commercialOffTheShelfProvider.cmake)

macro(wrapper_provide_dependency method depName)
    startTimer(t0)
    list(APPEND providerVarStack "${t0}")

    # Preserve empty strings, flattened lists are ok
    string(REPLACE
        ";" "]==>] [==[" args "[==[$ENV{ARGV}]]==]"
    )
    cmake_language(EVAL CODE
        "cots_provide_dependency(${args})"
    )

    list(POP_BACK providerVarStack t0)
    reportTimeSince("Time for ${depName}" "${t0}")
endmacro()
```

41.3. Recommended Practices

`CMAKE_PROJECT_TOP_LEVEL_INCLUDES` is the most appropriate code injection method for once-per-run setup logic controlled by the

developer. The `project()` command supports a number of other injection variables (see [Section 43.8, “Injecting Files Into Projects”](#)), but those should be reserved for cases where logic is needed for every `project()` call, or for one specific `project()` call at somewhere other than the top level.

Ensure every file given to `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` starts with its own `cmake_minimum_required()` call. This sets the expected policy behavior for that file instead of relying on the policy settings of the project the file is being injected into. This will also make the injected file more resilient and more reusable across multiple projects.

Avoid adding any provider-specific logic to a project. Expect all provider-specific code to be contained in a file injected using the `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` variable, which the developer ultimately controls. Prefer to use a provider-supplied setup file if one is available.

If implementing a dependency provider command, use a macro rather than a function. In most cases, providers must not introduce a new variable scope so that variables set by dependencies will propagate back out properly to the caller.

Be careful about handling arguments if forwarding them on to a delegated provider command. Always preserve empty strings, which means you must not naively forward arguments using a bare `${ARGN}`. Use appropriate bracket quoting of arguments in

conjunction with the `cmake_language(EVAL)` command to preserve empty values.

VI: PROJECT ORGANIZATION

As projects grow in size, so does the complexity of configuring, building, testing, and packaging for different scenarios. CMake presets help manage this complexity. They provide ready-to-use settings which can be shared across the development team, and used in automated workflows. An organized, well-defined set of presets reduces the learning curve for new developers, simplifies day-to-day tasks, and reduces errors associated with using inappropriate settings.

A project's ease of use also depends on an appropriate structure. What works for a small, simple project would often be a headache for a larger one. A cross-platform project will also have concerns that a single-platform project may not. Even the way a project brings in its dependencies and how it provides build artifacts for consumption by other projects can strongly affect the overall structure.

This part of the book discusses these more global, structural aspects of CMake projects. It builds on the knowledge gained from the earlier chapters of the book, showing how to structure

and define a project to be flexible, robust, and easier for developers to work with.

42. PRESETS

As a developer becomes more experienced with CMake, certain usage patterns and scenarios tend to be repeated. Some common examples include:

- A preferred way of placing and naming build directories relative to the source directory.
- A preference for a particular CMake generator on a given platform.
- Setting a certain combination of CMake cache variables to particular values for a given project.
- Re-using a toolchain file across projects, sometimes in conjunction with setting a few CMake cache variables or selecting a particular CMake generator.
- Automating a sequence of configure, build, test and packaging steps for continuous integration and release processes.

CMake 3.19 added a new feature called *presets* which allow scenarios like those above to be handled in a more reliable, automated, and convenient way. Presets can specify the build

directory, CMake generator, target architecture, host toolset, CMake variables, environment variables, and even vendor-specific content (e.g. for certain IDE tools). Later CMake versions extended presets further to support build, test, and packaging steps, and whole workflow descriptions.

The material in this chapter covers the more commonly used aspects of presets. They are best learned by experimenting with real world projects, trying out different ideas and exploring how the various capabilities can be used. Consult the presets manual in the CMake documentation for a comprehensive coverage of all the available features.

42.1. High Level Structure

CMake looks in the top source directory of a project for files named `CMakePresets.json` and `CMakeUserPresets.json`. Neither file is required to be present, but if the user tries to list or use presets, at least one of the files must exist. If both files are present, they will effectively be merged by reading the `CMakePresets.json` file first and then the `CMakeUserPresets.json` file. The two files have exactly the same format, but they serve different purposes:

`CMakePresets.json`

This file should only be provided by the project. It can be used to define presets for things like continuous integration jobs or cross-compilation setups using toolchains provided

as part of the project (see [Section 39.7, “Other Uses For FetchContent”](#) for one way this might be done). It should not refer to any paths or files outside the source or build directories, except perhaps well-known locations that would typically be present on most host systems. The preset file should be kept under version control, just like other parts of the project.

CMakeUserPresets.json

This file provides presets defined by the developer for use on their own machine. The file contents can refer to any file or path without restriction, since they only have to make sense for that user’s local machine. Projects should never provide a CMakeUserPresets.json file. It should ideally be excluded from source control. Developers may want to add this file name to their global git ignore configuration or other equivalent source control settings.

The CMake documentation includes a detailed explanation of the format of preset files. The following example shows the most important top level elements:

```
{  
    "version": 6,  
    "include": [...],  
    "configurePresets": [...],  
    "buildPresets": [...],  
    "testPresets": [...],  
    "packagePresets": [...],
```

```
"workflowPresets": [...]  
}
```

The `version` field specifies the JSON schema and must always be present.

Schema Version	CMake Version	Comments And Main Changes
		Required
1	3.19	First release, only supports <code>configurePresets</code> .
2	3.20	Adds support for <code>buildPresets</code> and <code>testPresets</code> .
3	3.21	Adds support for conditions and drops the constraint that the generator and build directory must be specified.
4	3.23	Adds support for <code>include</code> .
5	3.24	Minor additions.
6	3.25	Adds support for <code>packagePresets</code> and <code>workflowPresets</code> .
7	3.27	Adds support for <code>\$penv{}</code> macro expansion in <code>include</code> .
8	3.28	Minor addition (support for <code>\$schema</code> field).
9	3.30	All non-preset-specific macros can be used in <code>include</code> .
10	3.31	Adds support for <code>\$comment</code> and <code>graphviz</code> fields.

For large projects, especially those using a monorepo structure, it is common for the set of presets to grow quite large. Maintaining them all in a single `CMakePresets.json` file can

become difficult. Developers who create a lot of their own presets in the `CMakeUserPresets.json` file experience the same problem. With CMake 3.23 or later, the `include` array can be used to break up the set of presets into more manageable pieces. Each array item is the name of another presets file to read. Relative paths are treated as being relative to the directory of the file specifying the `include` array.

Files included from `CMakePresets.json` should always be provided by the project. This would typically mean the included files are in the project's source control repository, or potentially in a git submodule of the repository. Any paths outside the project are not under the project's control, so files included from such locations might not exist on every developer's machine. `CMakeUserPresets.json` can freely include files from anywhere, since it is specific to the user's machine and is under the user's control.

File inclusion can be nested to any level, but it would normally be no more than a few. It is not an error for a file to be included more than once, but there must not be any cycles among the included files. [Section 42.2.2, “Inheritance”](#) discusses additional requirements on included files.

42.2. Configure Presets

Configure presets apply to the configure phase of the developer workflow. They can be used when running CMake to set up a

build directory for a project. For a preset file to be useful, it needs to provide a `configurePresets` section containing an array of one or more presets. The following shows a fairly simple example:

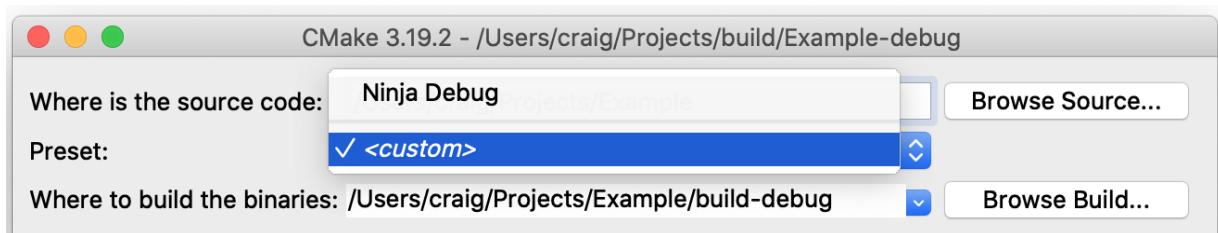
```
{  
  "version": 1,  
  "configurePresets": [  
    {  
      "name": "ninja",  
      "displayName": "Ninja Debug",  
      "generator": "Ninja",  
      "binaryDir": "build-debug",  
      "cacheVariables": { "CMAKE_BUILD_TYPE": "Debug" }  
    }  
  ]  
}
```

42.2.1. Essential Fields

Every preset must provide a `name`. It is a single word that serves as the unique name of the preset. A `displayName` is optional, but recommended. It is shown in GUI applications in combo boxes, etc. The `name` and `displayName` (if defined) of all available (non-hidden) configure presets can be obtained by running the following command from the top source directory of a project:

```
cmake --list-presets  
  
Available configure presets:  
  
"ninja" - Ninja Debug
```

The CMake GUI also shows the available configure presets for the currently selected source directory. Presets are listed by their `displayName`, falling back to the name if no `displayName` is provided. The `ccmake` tool does not support presets.



The name is used to select a configure preset on the `cmake` command line. When run from the top source directory of the project, the following would select the configure preset defined above:

```
cmake --preset ninja
```

With schema version 1 or 2, configure presets must also provide a `generator` and `binaryDir`, although these can be inherited (see further below). Schema version 3 allows the `generator` and `binaryDir` to be omitted, in which case they follow the same behavior as when presets are not used.

If the configure preset provides a `binaryDir` field (and also a `generator` field if it is a schema version 1 or 2 presets file), the `--preset=...` option is enough on its own to configure a build directory.

Any of the usual CMake options can still be provided on the `cmake` command line too and will override the preset, where relevant. For instance, the above example defines the `CMAKE_BUILD_TYPE` cache variable. Other cache variables can be added with `-D` options on the command line, or even override the `CMAKE_BUILD_TYPE`.

Cache variables can be defined in the simple *key:value* form as shown in the above example, or they can be defined as a JSON object. The non-object form will define the variable as type `BOOL` if the value is an unquoted `true` or `false`, or type `STRING` otherwise. The object form allows the variable type to be specified, which can improve the way the variable is presented in GUI applications.

```
{
  "version": 1,
  "configurePresets": [
    {
      "name": "ninja",
      "generator": "Ninja",
      "binaryDir": "build",
      "cacheVariables": {
        "CMAKE_TOOLCHAIN_FILE": {
          "type": "FILEPATH",
          "value": "/path/to/toolchain.cmake"
        }
      }
    }
  ]
}
```

42.2.2. Inheritance

Presets can inherit from one or more other presets of the same type (configure, build, test or package) to add or override fields. This can be used to compose presets from common building blocks, thereby avoiding duplication and reducing errors. A preset can also be hidden, indicating it only exists so that other presets can inherit from it.

The `include` field adds constraints to what may be inherited. Each preset file must include other files that define any preset it inherits. This is analogous to the C/C++ `#include` behavior, where each source file is required to include headers to define anything that source file references. For the purposes of this constraint, `CMakeUserPresets.json` implicitly includes `CMakePresets.json`, so user presets can inherit project presets, but not vice versa.

CMakePresets.json

```
{
  "version": 1,
  "configurePresets": [
    {
      "name": "ci-enable-all",
      "hidden": true,
      "binaryDir": "build",
      "cacheVariables": {
        "MYPROJ_FEATURE_X": true,
        "MYPROJ_FEATURE_Y": true
      }
    },
    {
      "name": "ci-linux",
      "hidden": true
    }
  ]
}
```

```

    "inherits": "ci-enable-all",
    "displayName": "Linux continuous integration setup",
    "generator": "Ninja",
    "cacheVariables": { "CMAKE_BUILD_TYPE": "Release" }
},
{
  "name": "ci-macos",
  "inherits": "ci-enable-all",
  "displayName": "macOS continuous integration setup",
  "generator": "Xcode"
}
]
}

```

CMakeUserPresets.json

```

{
  "version": 1,
  "configurePresets": [
    {
      "name": "sibling-build-dir",
      "hidden": true,
      "binaryDir": "${sourceParentDir}/build/${sourceDirName}"
    },
    {
      "name": "ninja",
      "inherits": ["sibling-build-dir", "ci-enable-all"],
      "displayName": "Ninja Debug",
      "generator": "Ninja",
      "cacheVariables": { "CMAKE_BUILD_TYPE": "Debug" }
    }
  ]
}

```

The `CMakePresets.json` file defines a base configure preset called `ci-enable-all` which the other two configure presets in that file both inherit from. This allows the common set of cache options and the `binaryDir` to be shared without having to repeat them.

everywhere. The `ci-linux` and `ci-macos` configure presets only need to define the information specific to their own generator and platform.

The `CMakeUserPresets.json` file shows how to inherit from multiple presets, including one defined in `CMakePresets.json`. Both `ci-enable-all` and `sibling-build-dir` define a `binaryDir`. In such cases where multiple base presets define the same field and the derived preset doesn't override it, the one that appears earlier in the `inherits` list takes precedence. In this case, for the `ninja` preset, the `binaryDir` from `sibling-build-dir` is used because it appears before `ci-enable-all`. If the `ninja` preset itself defined a `binaryDir`, that would override the others.

Note how the names given to the presets in `CMakePresets.json` all have a `ci-` prefix. Good practice is to choose preset names in `CMakePresets.json` that would be unlikely to clash with names a developer might define in their own `CMakeUserPresets.json` file. Since continuous integration setup is something that the project should define, a `ci-` prefix is typically a good choice. This also clearly communicates the intended use case for the presets.

42.2.3. Macros

Another feature demonstrated by the `CMakeUserPresets.json` example above is the use of macros of the form `${macroName}`. These evaluate to a computed value much like how CMake variables work. The CMake documentation provides the full list

of available macro names and the fields that support them. Some of the more useful macro names include:

presetName

The name of the preset selected by the developer. When used in a base preset, it provides the name of the final preset that was selected, not the name of the base preset.

generator

The generator as seen by the final selected preset (i.e. taking inheritance into account).

sourceDir

The full absolute path to the project source directory.

sourceParentDir

The full absolute path to the parent of the project source directory.

sourceDirName

The name of the project source directory without any path. This is the same as the last part of sourceDir, i.e. the part after the last path separator.

fileDir

The full absolute path to the directory containing the preset file being processed. For CMakePresets.json and CMakeUserPresets.json, this will be the same as sourceDir, but

for included files, it may be different. This macro requires schema version 4 or higher.

hostSystemName

Provides the same value as the `CMAKE_HOST_SYSTEM_NAME` variable. Requires schema version 3 or higher.

The `CMakeUserPresets.json` in the earlier example shows how `${sourceParentDir}` and `${sourceDirName}` can be used to make a preset file more generic. This could be important if re-using it across multiple projects (e.g. by copying or symlinking it into each project's source directory). `${sourceParentDir}` allows the build directories to be placed outside the project source directory, as recommended in [Section 2.2, “Out-of-source Builds”](#). When all project sources are siblings of each other, this conveniently collects all build directories under a single location. `${sourceDirName}` provides the project-specific part that ensures each project's build directory is unique.

42.2.4. Environment Variables

Configure presets can modify the configure step's environment with an environment map. This does not carry forward to the build step unless a build preset is used (discussed further in [Section 42.3, “Build Presets”](#)). Environment variables can also be evaluated with either `$env{varName}` or `$penv{varName}` in fields where macros are supported. The only difference between the two is that `$penv{varName}` always provides the

value from the parent environment, whereas `$env{varName}` will take into account changes made to the environment by the preset. `$penv{varName}` is necessary when the current value of an environment variable needs to be included in the new value, as is common for variables like PATH. An environment variable can also be given the value `null` to cause it to be unset.

```
{
  "version": 1,
  "configurePresets": [
    {
      "name": "ninja",
      "generator": "Ninja",
      "binaryDir": "build",
      "environment": {
        "PATH": "${sourceDir}/scripts:$penv{PATH}",
        "PATH_COPY": "$env{PATH}",
        "CLEAR_ME_PLEASE": null
      }
    }
  ]
}
```

When a preset inherits from another and they both define an environment, the result is a merged union of all presets in the inheritance hierarchy. If multiple presets define the same environment variable, the value taken follows the same inheritance rules as described earlier (base values are overridden by derived presets, earlier inherited presets take precedence over later ones in the `inherits` list). Similar merging behavior is used for `cacheVariables` as well.

42.2.5. Toolchains

Details about the toolchain are typically provided by a toolchain file. All schema versions allow a toolchain file to be specified by setting the `CMAKE_TOOLCHAIN_FILE` cache variable in a configure preset. Schema version 3 and later support a dedicated `toolchainFile` field which achieves the same thing. The following example shows both ways of setting the toolchain file:

```
{
  "version": 3,
  "configurePresets": [
    {
      "name": "gcc",
      "displayName": "GNU toolchain",
      "generator": "Ninja",
      "binaryDir": "build-gcc",
      "cacheVariables": {
        "CMAKE_TOOLCHAIN_FILE": "toolchain-gcc.cmake"
      }
    },
    {
      "name": "clang",
      "displayName": "Clang toolchain",
      "generator": "Ninja",
      "binaryDir": "build-clang",
      "toolchainFile": "toolchain-clang.cmake"
    }
  ]
}
```

When a configure preset uses a Visual Studio generator, it may also want to specify an architecture or host toolset. Dedicated fields are provided for this and can be specified as either simple

strings or as objects. The following example shows the simple string case:

```
{  
  "version": 1,  
  "configurePresets": [  
    {  
      "name": "vs2019-arm64",  
      "displayName": "Visual Studio 2019 - ARM64",  
      "generator": "Visual Studio 16 2019",  
      "architecture": "ARM64",  
      "toolset": "host=x86",  
      "binaryDir": "build-arm64"  
    }  
  ]  
}
```

A common problem when using the Visual Studio toolchain with other generators is the need to set up the environment in which CMake runs and in which the build is performed. Traditionally, CMake requires the user to manage the toolchain environment on their own. However, when presets are used, some IDEs attempt to infer the toolchain environment from the information provided by the preset. Such IDEs typically analyze the `architecture` and `toolset` fields, along with the `CMAKE_C_COMPILER` and `CMAKE_CXX_COMPILER` cache variables. The `architecture` and `toolset` fields generally need to be defined as objects, and they must set the strategy to `external`. The `external` strategy means CMake won't enforce the setting. Instead, CMake will expect the environment to already be set up (by the IDE, or by the developer when running `cmake` directly).

The following example shows how one might define a preset that uses the 64-bit host toolchain with the standard `cl` compilers, and a second preset that uses the `clang-cl` toolchain.

```
{
  "version": 2,
  "configurePresets": [
    {
      "name": "msvc",
      "displayName": "Visual Studio cl toolchain",
      "generator": "Ninja",
      "binaryDir": "build-msvc",
      "architecture": {
        "value": "x64",
        "strategy": "external"
      },
      "toolset": {
        "value": "host=x64",
        "strategy": "external"
      },
      "cacheVariables": {
        "CMAKE_C_COMPILER": "cl.exe",
        "CMAKE_CXX_COMPILER": "cl.exe"
      }
    },
    {
      "name": "msvc-clang",
      "displayName": "Visual Studio clang-cl toolchain",
      "generator": "Ninja",
      "binaryDir": "build-msvc-clang",
      "architecture": {
        "value": "x64",
        "strategy": "external"
      },
      "toolset": {
        "value": "ClangCL,host=x64",
        "strategy": "external"
      },
      "cacheVariables": {
```

```
        "CMAKE_C_COMPILER": "clang-cl.exe",
        "CMAKE_CXX_COMPILER": "clang-cl.exe"
    }
}
]
}
```

Note that a user building directly from the command line would still need to set up the toolchain environment themselves. The above only shows how to provide enough information to VS Code so that it can do that on the user's behalf when configuring and building directly from the IDE.

42.2.6. Conditions

The version 3 schema supports a condition object, which can be used to enable a preset based on certain rules. For example, a preset with a Xcode generator would only be useful on a macOS machine. The condition can be a constant, string equality, inequality, regular expression match or a check for whether a list contains a particular value. Boolean logic can also be expressed using allOf, anyOf and not relationships. The official CMake documentation defines the supported conditions fairly comprehensively, but the following examples give an idea of some typical uses:

```
{
  "version": 3,
  "configurePresets": [
    {
      "name": "default-generator",
      "binaryDir": "build"
```

```
},
{
  "name": "xcode",
  "generator": "Xcode",
  "binaryDir": "build-xcode",
  "condition": {
    "type": "equals",
    "lhs": "${hostSystemName}",
    "rhs": "Darwin"
  }
}
]
```

```
{
  "version": 3,
  "configurePresets": [
    {
      "name": "package-release",
      "generator": "Ninja",
      "binaryDir": "build",
      "condition": {
        "type": "allOf",
        "conditions": [
          {
            "type": "equals",
            "lhs": "$ENV{CI_COMMIT_REF_PROTECTED}",
            "rhs": "true"
          },
          {
            "type": "matches",
            "string": "$ENV{CI_COMMIT_TAG}",
            "regex": "release/.*"
          }
        ]
      }
    }
  ]
}
```

42.2.7. Comments

With presets schema version 9 and earlier, there is no direct support for putting comments in a presets file. The official JSON specification does not allow comments, and CMake follows that specification. Some IDEs support the non-standard extension of specifying comments in JSON files, but CMake itself will reject such files.

Starting with presets schema version 10, a presets file can use a `$comment` field essentially anywhere in the presets file. This field will be ignored by CMake and should also be ignored by anything else that reads that file. Do not use this field as a way to record information that a custom tool might read. Use a `vendor` field for such cases.

The following example shows two uses of `$comment` to help developers understand aspects of the configure preset. The first `$comment` provides guidance on what the preset is intended to be used for. It uses an array to allow the comment to span multiple lines for easier reading. The second `$comment` shows a way to attach additional context to a CMake variable as a single string. In both cases, such information isn't intended for displaying in any IDE, it is meant for preset authors.

```
{  
  "version": 10,  
  "configurePresets": [  
    {  
      "$comment": [
```

```

    "All cert presets must inherit from this one.",
    "It conforms to requirement XYZ-123."
],
{
  "name": "cert",
  "displayName": "Certification",
  "generator": "Ninja",
  "binaryDir": "build-cert",
  "cacheVariables": {
    "$comment": "Cert requires specific settings",
    "CMAKE_TOOLCHAIN_FILE": {
      "type": "FILEPATH",
      "value": "/path/to/cert_toolchain.cmake"
    }
  }
}
]
}

```

Keep in mind that once a presets file contains a `$comment` field, that raises the minimum CMake, IDE, and tool versions it can be used with. `$comment` cannot be used if the presets file needs to be used with CMake 3.30 or earlier. In such situations, a workaround is to use a `vendor` field. These can be specified at the preset level only, so they are not as flexible as `$comment` fields, but they may be enough for simple cases.

A `vendor` field is essentially a free-form JSON object. The recommended convention is that it should have a single field whose name follows the form `domainName/appName/version`. The value can be anything, but is usually a JSON object when not being used as a comment workaround. The following shows one way to approximate the comments of the previous example:

```
{  
  "version": 6,  
  "configurePresets": [  
    {  
      "vendor": {  
        "mycompany.com/comment/1.0": [  
          "All cert presets must inherit from this one.",  
          "It conforms to requirement XYZ-123.",  
          "Cert requires specific settings,",  
          "defined by the toolchain file specified below."  
        ]  
      },  
      "name": "cert",  
      "displayName": "Certification",  
      "generator": "Ninja",  
      "binaryDir": "build-cert",  
      "cacheVariables": {  
        "CMAKE_TOOLCHAIN_FILE": {  
          "type": "FILEPATH",  
          "value": "/path/to/cert_toolchain.cmake"  
        }  
      }  
    }  
  ]  
}
```

42.3. Build Presets

The preceding discussions focused on `configurePresets`, which apply to the `configure` phase. The `buildPresets` provide a similar capability for when running the build tool. The developer can select a build preset to use at build time like so:

```
cmake --build --preset name
```

Build presets support many of the same fields as configure presets, such as name, displayName, inherits, hidden, environment, vendor, and \$comment. Each of these work the same way as for configure presets. In addition, a build preset must specify (or inherit) the name of a configure preset in a field called configurePreset, which is used to determine the location of the build directory. A build preset also inherits any environment from the configure preset by default, although this can be disabled. The following example demonstrates these capabilities:

```
{
  "version": 2,
  "configurePresets": [
    {
      "name": "ninja",
      "generator": "Ninja Multi-Config",
      "binaryDir": "build",
      "environment": { "PATH": "/tools/dir:$env{PATH}" }
    }
  ],
  "buildPresets": [
    {
      "name": "base",
      "hidden": true,
      "configurePreset": "ninja",
      "configuration": "Release"
    },
    {
      "name": "devtools",
      "inherits": "base",
      "inheritConfigureEnvironment": false,
      "targets": ["hexdump", "logger"]
    }
  ]
}
```

```
        "name": "alldocs",
        "inherits": "base",
        "targets": ["manual", "api", "quickstart"]
    }
]
}
```

Listing the available build presets for the above example, it can be confirmed that two build presets are available. Either of the following commands can be used to list the non-hidden build presets:

```
cmake --list-presets build

cmake --build --list-presets
```

```
Available build presets:
```

```
"devtools"
"alldocs"
```

Both of these build presets inherit the hidden base build preset, which in turn is associated with the `ninja` configure preset. The result is that both `devtools` and `alldocs` will be associated with the build directory defined by the `ninja` configure preset. The `devtools` build preset also explicitly discards the environment changes defined by the configure preset.

Many other command line options can also be expressed as part of a build preset. For instance, the above example specifies the Release configuration as part of the base build preset, which is

then inherited by devtools and alldocs too. The CMake documentation specifies the full list of available fields and the command line option each one corresponds to.

It should be noted that build presets can be problematic in practice. They are useful in `CMakeUserPresets.json` for defining a few custom build scenarios of interest to the developer. They are much less convenient if trying to cover all combinations of configure presets and different build configurations. This largely stems from the constraint that each build preset must be associated with exactly one configure preset. The result is a combinatorial explosion of build presets, which becomes difficult to maintain and typically isn't well presented in IDE environments. The early design of presets expected that IDEs would base their UI around build presets. As experience with presets has grown, and problems like the above have emerged, IDEs are tending toward making configure presets more of a primary part of their UI instead.

42.4. Test Presets

Test presets follow a very similar pattern to build presets, except they are applied to invocations of `ctest`:

```
ctest --list-presets  
ctest --preset name
```

Test presets support the same common fields, such as name, displayName, inherits, hidden, environment, vendor, and \$comment, plus others that map to various ctest command line options. They can specify commonly used combinations of test fixture settings, regular expressions for selecting or excluding tests, test output options, and so on. They are also an excellent way of setting run-time sanitizer or coverage options (see [Section 33.1, “Sanitizers”](#) and [Section 33.2, “Code Coverage”](#)). The following illustrates how some of these features can be used:

```
{
  "version": 2,
  "configurePresets": [
    {
      "name": "ninja", ...
    }
  ],
  "testPresets" : [
    {
      "name": "mytests",
      "configurePreset": "ninja",
      "environment": {
        "LLVM_PROFILE_FILE": "profiling/test.%p.profraw",
        "ASAN_OPTIONS":
"check_initialization_order=true:detect_stack_use_after_return=true"
        "UBSAN_OPTIONS": "print_stacktrace=1"
      }
      "filter": {
        "include": {
          "name": "SomeFeature"
        },
        "exclude": {
          "label": "Slow"
        }
      }
    }
  ]
}
```

```
]  
}
```

Test presets suffer from the same combinatorial explosion as build presets. For the same reasons, they are potentially useful for a few developer-specific test presets in `CMakeUserPresets.json`, but they are not well-suited to covering a wide range of scenarios.

42.5. Package Presets

The primary use of package presets is as part of a workflow (see [Section 42.6, “Workflow Presets”](#)). They follow the same pattern as build and test presets, but they apply to invocations of `cpack`:

```
cpack --list-presets  
cpack --preset name
```

Again, the usual common fields like `name`, `displayName`, `inherits`, `hidden`, `environment`, `vendor`, and `$comment` are supported. Other options specific to the `cpack` command can also be given. Most details related to packaging would typically be set within the project, but a preset may want to override some settings for specific scenarios.

The `generators` field can be used to specify the types of packages to be produced. This is an array of CPack generator names. Normally, this would be specified by the project using the `CPACK_GENERATOR` variable, as discussed in [Section 36.1](#),

[“Packaging Basics”](#). However, a preset may want to narrow the focus to produce only a particular type of package for a particular workflow.

The configurations field is important if the package needs to include things from both Debug and Release builds (see [Section 36.3, “Multi Configuration Packages”](#)). An array of configurations can be specified with this field. These configurations will be passed to the cpack command using the -C command line option, and they will be added to the package in the order specified. The order may be important if the same file is installed by different configurations with different contents. See [Section 42.6, “Workflow Presets”](#) for further discussion of this scenario.

```
{
  "version": 6,
  "configurePresets": [
    { "name": "ci-multi-config", ... }
  ],
  "packagePresets": [
    {
      "name": "ci-sdk",
      "configurePreset": "ci-multi-config",
      "generators": [ "7Z", "ZIP" ],
      "configurations": [ "Debug", "Release" ]
    }
  ]
}
```

42.6. Workflow Presets

Workflows specify a sequence of steps, where each step is defined by other non-workflow presets. They are especially useful for defining the steps of a continuous integration job. Executing a workflow preset is done like so:

```
cmake --workflow --preset name
```

With CMake 3.31 or later, the `--preset` option can be omitted:

```
cmake --workflow name
```

The set of defined workflow presets can be queried with either of the following commands:

```
cmake --list-presets workflow  
cmake --workflow --list-presets
```

Workflows are specified by a `workflowPresets` array. Each item of that array must have a unique `name`, which is used to identify the workflow preset to run. A `displayName` may also be provided. As usual, it is the `name` and `displayName` that are shown by `--list-presets`.

A workflow preset must have a `steps` array, which defines the sequence of steps for that workflow. The first item in that `steps` array must be a `configure` preset. After that, any number of `build`, `test` or `package` presets can be given, all of which are required to specify the `configure` preset from the first step as their own `configurePreset`.

Each step must contain a type and a name. The type corresponds to the preset type of that step (configure, build, test or package). The name must match one of the defined presets of the nominated type. The workflow can have multiple items of the same preset type, except for configure presets.

```
{
  "version": 6,
  "configurePresets": [
    { "name": "ci-multi-config", ... }
  ],
  "buildPresets": [
    { "name": "ci-sdk-debug", "configurePreset": "ci-multi-config", ... },
    { "name": "ci-sdk-release", "configurePreset": "ci-multi-config", ... }
  ],
  "test": [
    { "name": "ci-release", "configurePreset": "ci-multi-config", ... }
  ],
  "packagePresets": [
    { "name": "ci-sdk", "configurePreset": "ci-multi-config", ... }
  ],
  "workflowPresets": [
    {
      "name": "ci-sdk",
      "steps": [
        { "type": "configure", "name": "ci-multi-config" },
        { "type": "build", "name": "ci-debug" },
        { "type": "build", "name": "ci-release" },
        { "type": "test", "name": "ci-release" },
        { "type": "package", "name": "ci-sdk" }
      ]
    }
  ]
}
```

The above example demonstrates typical steps for producing a package that contains contents from both Debug and Release builds. Note how it contains two build steps, building the `ci-debug` and then the `ci-release` build presets. This allows package presets to list Debug and Release in their configurations array to install both configurations (see the example in [Section 42.5, “Package Presets”](#) which does this).

Note also how the second build preset and the test preset both have the same name, `ci-release`. This is fine, since the type field specifies what type of preset each step corresponds to, and all presets of a particular type must be unique within that preset type. Names are not required to be unique across different preset types.

In schema version 6, workflows do not support custom or script-based steps. However, it is common for continuous integration jobs to need to carry out tasks that do not fit strictly into one of the defined preset types. For example, code coverage results may need to be collected and processed to produce a summary or report. One way to achieve this is to define a custom build target which is not part of the default ALL build target, but which can be explicitly requested by a build preset.

In the following example, the `coverage_report.cmake` script is assumed to implement the logic needed to generate the code coverage report when run from the top of the build directory.

```

add_custom_target(coverage_report
  WORKING_DIRECTORY ${CMAKE_BINARY_DIR}
  COMMAND ${CMAKE_COMMAND} -P
    ${CMAKE_CURRENT_LIST_DIR}/coverage_report.cmake
)

```

```

{
  "version": 6,
  "configurePresets": [ "name": "ci-coverage", ... ],
  "buildPresets": [
    { "name": "ci-coverage", ... },
    {
      "name": "ci-coverage-report",
      "configurePreset": "ci-coverage",
      "targets": [ "coverage_report" ]
    }
  ],
  "test": [ "name": "ci-coverage", ... ],
  "workflowPresets": [
    {
      "name": "ci-coverage",
      "steps": [
        { "type": "configure", "name": "ci-coverage" },
        { "type": "build", "name": "ci-coverage" },
        { "type": "test", "name": "ci-coverage" },
        { "type": "build", "name": "ci-coverage-report" }
      ]
    }
  ]
}

```

42.7. Recommended Practices

Projects should only provide a `CMakePresets.json` file and let developers create their own `CMakeUserPresets.json` file if they want to. Add `CMakeUserPresets.json` to the user-wide source

control ignore list to minimize the chances of that file ever being committed to a repository.

Avoid using preset names in `CMakePresets.json` that would be likely to clash with names developers would use in their own user presets file. A good strategy is to start each preset name in `CMakePresets.json` with a prefix like `ci-`.

Use `inherits` to compose presets in a "mix-in" fashion to avoid repeating the same details across related presets. If the number of presets is large, consider using the `include` functionality to break up the presets into more manageable chunks and inherit as needed to build up the final set of desired presets.

For developers, consider creating a `CMakeUserPresets.json` file that captures common configurations which can be used across different projects, or at least that require minimal tailoring per project. The `include` functionality may also help with being able to reuse preset logic between projects.

Prefer not to define many build or test presets that cover all conceivable scenarios. Instead, let the developer define those build and test presets that matter to them. Defining too many build and test presets makes them harder to use in IDE tools and lowers the maintainability of the project.

Consider using workflow presets to define the steps of continuous integration jobs. This makes local testing of CI

workflows very straightforward. It also avoids having to rely on a potentially platform-specific scripting language to define the steps involved. When testing locally, use the `--fresh` command line option to discard any configuration details from an earlier run:

```
cmake --workflow --preset ci-coverage --fresh
```

43. PROJECT STRUCTURE

The factors that contribute to an effective project structure are many and varied. What works for one project may not work for another, but there are typically some things that do tend to be common. Choosing a flexible but predictable directory structure early in the life of a project allows it to evolve with minimal friction and reorganization.

One of the most important decisions is whether a project should be structured as a superbuild or as a regular project. The two are fundamentally different and have their own strengths and weaknesses. The decision largely comes down to how the project wants to treat its dependencies and whether there is a desire and opportunity to absorb them directly or keep them isolated in their own sub-builds. For those projects without any dependencies (and importantly without any future prospect of ever having any dependencies), a regular project is the obvious choice. But when there are dependencies, the right project structure can be the difference between fighting against the build and having it work smoothly.

One of the most common topics that arise on mailing lists, issue trackers and Q&A sites relates to problems stemming from trying to use one project structure, but expecting it to have the capabilities of another. In many cases, this occurs because a project is started with a particular structure, but as dependencies are added, that structure no longer supports what the developer wants the project to be able to do. Those involved have become accustomed to working with the existing structure, so changing it will likely be very disruptive and will often meet with considerable resistance. The older a project is, the harder such a change is likely to be. Therefore, decide how dependencies should be handled early in the life of the project, with due consideration for future expectations.

43.1. Superbuild Structure

Where dependencies do not use CMake as their build system, a superbuild tends to be the preferred structure. This treats each dependency as its own separate build, with the main project directing the overall sequence and the way details are passed from one dependency's build to another. Each separate build is added to the main build using `ExternalProject`. Such an arrangement allows CMake to look at what each build produces and automatically detect information that can then be passed on to other dependencies. This avoids having to manually hard-code such information in the main build. Even if all the dependencies use CMake, a superbuild may still be preferred

for other reasons, such as to avoid target name clashes or problems with projects that assume they are always the top level project.

A superbuild allows precise control over the sequencing of the separate dependency builds. One or more dependencies can be required to fully complete their own build, including their install step, before other dependencies run their own configuration phase. For such situations, the later configuration steps can see the installed artifacts and work out the appropriate file names, locations, etc. automatically. This is not possible in a regular build.

Superbuilds can be implemented with a top level `CMakeLists.txt` file that follows a fairly predictable pattern. One variation uses a common install area for all dependencies. Another alternative is to install each dependency to its own separate location. While both are similar, using a common install area is slightly simpler to define:

```
cmake_minimum_required(VERSION 3.0)
project(SuperbuildExample)
include(ExternalProject)

set(installDir ${CMAKE_CURRENT_BINARY_DIR}/install)

ExternalProject_Add(someDep1 ①
...
INSTALL_DIR ${installDir}
CMAKE_ARGS -DCMAKE_INSTALL_PREFIX:PATH=<INSTALL_DIR>
)
ExternalProject_Add(someDep2
```

```

...
INSTALL_DIR ${installDir}
CMAKE_ARGS -DCMAKE_INSTALL_PREFIX:PATH=<INSTALL_DIR>
            -DCMAKE_PREFIX_PATH:PATH=<INSTALL_DIR> ②
)
ExternalProject_Add_StepDependencies( ③
    someDep2 configure someDep1
)

```

- ① At least one dependency must require no others.
- ② For other dependencies that use `find_package()` to locate their dependencies, setting `CMAKE_PREFIX_PATH` to the common install directory is typically enough.
- ③ A step dependency is added to ensure the `configure` step only runs after other required dependencies have been installed.

A cleaner separation can be obtained by installing each dependency to its own subdirectory below a common location. By carefully selecting the name of each subdirectory, it may still be possible to set `CMAKE_PREFIX_PATH` to just the common base location. If each dependency provides a CMake config package file and the name of the subdirectory matches the dependency's package name in each case, then `find_package()` will still find it with just the common base in `CMAKE_PREFIX_PATH`.

```

set(installBaseDir ${CMAKE_CURRENT_BINARY_DIR}/install)

ExternalProject_Add(someDep1
    ...
    INSTALL_DIR ${installBaseDir}/someDep1
    CMAKE_ARGS -DCMAKE_INSTALL_PREFIX:PATH=<INSTALL_DIR>
)
ExternalProject_Add(someDep2
    ...
    INSTALL_DIR ${installBaseDir}/someDep2
    CMAKE_ARGS -DCMAKE_INSTALL_PREFIX:PATH=<INSTALL_DIR>
)

```

```
-DCMAKE_PREFIX_PATH:PATH=${installBaseDir}  
)
```

If a dependency doesn't use CMake as its build system, sharing a single install location may be the easier of the two structural variations presented above. Such dependencies might not provide a CMake config package file, so the main project will likely be relying on finding individual libraries and headers rather than whole packages. If each dependency is in its own subdirectory, that would require adding each subdirectory to CMAKE_PREFIX_PATH instead of just the common base location.

For non-CMake dependencies, the general structure doesn't need to change, only the way the dependency's build details are defined. For instance, a dependency that uses a build system like autotools might be specified like so:

```
ExternalProject_Add(someDep3  
    INSTALL_DIR  
    ${installDir}  
    CONFIGURE_COMMAND  
    <SOURCE_DIR>/configure --prefix <INSTALL_DIR>  
    ...  
)
```

Other options might also need to be passed to such a configure script to tell it where to find its dependencies. This will obviously vary based on the dependency's configuration capabilities.

Packaging is less straightforward in superbuilds. In some respects, each dependency is really in control of its own packaging, so the top level project is ultimately unlikely to be packaging anything. Instead, one or more `ExternalProject_Add()` calls are likely to be given a custom packaging step, if indeed packaging needs to be supported at all. [Section 38.4, “Step Management”](#) demonstrated how to implement this with the `ExternalProject_Add_Step()` function like so (a similar approach can be used for non-CMake subprojects):

```
ExternalProject_Add_Step(MyProj package
    COMMAND      ${CMAKE_COMMAND}
                --build <BINARY_DIR>
                --target package
    DEPENDES     build
    ALWAYS       YES
    EXCLUDE_FROM_MAIN YES
)
ExternalProject_Add_StepTargets(MyProj package)
```

In general, the key thing to keep in mind is that superbuilds work well when all they do is bring together other external projects. They usually rely on all the external projects having well-defined install rules. Each project should also be able to find its own dependencies if made aware of the location of the other external projects. If any of these things are not true, then the top level project will inevitably end up having to hard code platform specific details about one or more projects, at which point the benefits of a superbuild start decreasing.

43.2. Non-superbuild Structure

If a project has no dependencies, or if dependencies are being brought into the main build using `FetchContent` or a mechanism like `git submodules`, then some forward planning will help avoid difficulties later. A practice which really helps a project to remain easy to understand and work with is to think of its top level `CMakeLists.txt` as more like a table of contents. The structure can be divided up into the following sections:

Preamble

This includes the most basic setup, such as the calls to `cmake_minimum_required()` and `project()`. It may also include some use of the `FetchContent` module to bring in things like toolchain files and CMake helper repositories. This section should typically be quite short.

Project wide setup

This high level section would do things like set some global properties and default variables, perhaps define some build options in the CMake cache and may include a small amount of logic to work out some things needed by the whole build. Setting default language standards, build types and various search paths is common in this section.

Dependencies

Bring in external dependencies so that they are available to the rest of the project. If there are more than a few simple

`find_package()` calls, defining these in a separate `dependencies.cmake` file and using `include()` to bring that into the top level `CMakeLists.txt` file can be cleaner and easier to work with.

Main build targets

This section should ideally just be one or more `add_subdirectory()` calls.

Tests

While unit tests may be embedded within the same directory structure as the main sources, integration tests may sit outside this in their own separate area. These would be added after the main build targets.

Packaging

This should generally be the last thing the project defines, again ideally in its own subdirectory or file to help keep the top level uncluttered.

The recurring pattern in the above is that apart from the preamble and project wide setup, most things are best defined in subdirectories added via `add_subdirectory()`, or a separate file brought in using `include()`. Not only does this make the top level `CMakeLists.txt` file easy to read and understand, it allows each subdirectory or included file to focus on a particular area. This helps make things easier to find. In the case of subdirectories, it also means directory scopes can be used to

minimize exposing variables from unrelated areas to things that don't need to know about them. An example of a simple top level CMakeLists.txt that follows the above guidelines might look like this:

```
# Preamble
cmake_minimum_required(VERSION 3.21)
project(MyProj)

enable_testing()

# Project wide setup
set(CMAKE_CXX_STANDARD 11)
set(CMAKE_CXX_STANDARD_REQUIRED YES)
set(CMAKE_CXX_EXTENSIONS NO)

# Externally provided content
include(dependencies.cmake)

# Main targets built by this project
add_subdirectory(src)

# Not typically needed if there is a parent project
if(PROJECT_IS_TOP_LEVEL)
    add_subdirectory(tests)
    add_subdirectory(packaging)
endif()
```

In practice, the project-wide setup will likely contain more than shown above, and there may be other directories for things built by the project (e.g. for documentation, adding other installable content such as scripts, images and so on). There may also be project-specific cache variables which enable or

disable some subdirectories to give the developer more granular control.

If following the above advice, the top directory of the project's source tree will typically contain mostly just administrative files. These might include a readme file of some kind, license details, contribution instructions and so on. Continuous integration systems also frequently look for a particular file name or subdirectory in the top level directory. Keeping source files out of this top level directory ensures that it remains focused on the high level description of the project.

Past advice used to recommend delegating the dependency handling to its own subdirectory rather than a `dependencies.cmake` file brought in using `include()`. Due to improvements in `FetchContent` and its integration with `find_package()` in CMake 3.24, it is now more advantageous to bring dependencies into the top level scope rather than a separate subdirectory scope. Defining the dependencies in a separate file that the top level brings in via `include()` is now the recommended structure. Such a file might mix `FetchContent` and `find_package()` to bring in the project's dependencies, each in the most appropriate way for that dependency.

dependencies.cmake

```
# Things that we expect will have to be built from source
include(FetchContent)
FetchContent_Declare(privateThing ...)
FetchContent_Declare(patchedDep ...)
```

```
FetchContent_MakeAvailable(privateThing patchedDep)

# Other things the developer is responsible for making
# available to us by whatever method they prefer
find_package(fmt REQUIRED)
find_package(zlib REQUIRED)
```

Of the other main project's top level subdirectories, adding tests and packaging doesn't require anything special. They should just follow the recommended practices already covered in the preceding chapters. The contents and structure of the tests subdirectory will be specific to the project. The packaging subdirectory typically only needs a `CMakeLists.txt` file and maybe a few other files to be configured into the build directory for use by `cpack`. It may also contain resources used by some package generators. The structure of the `src` directory is a larger topic covered in its own section in [Section 43.5, “Defining Targets”](#) further below.

43.3. Common Top Level Subdirectories

The previous section already mentioned some directory names often found as subdirectories immediately below the top of the source tree. Commonly used top level subdirectories include `cmake`, `doc`, `src`, `tests` and `packaging`. In the absence of any other conventions, projects are encouraged to use these same directory names.

Collecting CMake helper scripts in a `cmake` subdirectory makes them easy to find, allowing developers to browse through the contents of that directory and discover useful utilities they may otherwise not have known about. With just a single `list()` call in the project-wide setup section of the top level `CMakeLists.txt` file, they can be made available to the entire project.

```
list(APPEND CMAKE_MODULE_PATH ${CMAKE_CURRENT_SOURCE_DIR}/cmake)
```

The `doc` subdirectory can be a convenient place to collect documentation. This can be useful if using formats like Markdown or Asciidoc and files contain relative links to each other.

There are a few subdirectory names that projects should avoid. By default, calling `add_subdirectory()` with just a single argument will result in a corresponding directory of the same name in the build directory. The project should avoid using a source directory name that may result in a clash with one of the pre-defined directories created in the build area. Names to avoid include the following:

- Testing
- CMakeFiles
- CMakeScripts
- Any of the default build types (i.e. any of the values of `CMAKE_CONFIGURATION_TYPES`).

- Any directory name starting with an underscore.

Since some file systems may be case-insensitive, all the above names should not be used in any upper/lowercase combination. Other common directory names used as install destinations may also appear in the build directory, depending on the strategy used for built binary locations (discussed further below in [Section 43.5.2, “Target Output Locations”](#)). Therefore, it would also be wise to avoid source directory names like `bin`, `lib`, `share`, `man` and so on.

A few projects choose to define a top level `include` directory and collect public headers there rather than keeping them next to their associated implementation files. Be aware that some IDE tools may be unable to find headers automatically if they are split out like this, so such an arrangement may be less convenient for some developers. It also tends to make changes for a particular feature or bug fix less localized. On the other hand, a dedicated `include` directory clearly communicates which headers are intended to be public, and they can have the same directory structure as they would when installed. Both approaches have their merits.

43.4. IDE Projects

When using project generators such as Xcode or Visual Studio, a project or solution file is created at the top of the build directory. This can be opened in the IDE just like any other

project file for that application, but it is still under the control of CMake. Importantly, these project files are generated as part of the build, so they should not be checked into a version control system. Also note that changes made to the project from within the IDE will be lost the next time CMake runs.

Because CMake generates the Xcode or Visual Studio project files, the way the project's targets and files are presented in the project hierarchy or file tree are also under the project's control. CMake provides a number of properties that can influence how targets and files are grouped and labeled in some IDE environments. The first level of grouping is for targets, which can be enabled by setting the `USE_FOLDERS` global property to true (CMake 3.26 made this the default, subject to policy `CMP0143`). The location of each target can then be specified using the `FOLDER` target property, which holds a case sensitive name under which to place that target. To create a tree-like hierarchy, forward slashes can be used to separate the nesting levels. If the `FOLDER` property is empty or not set, the target is left ungrouped at the top level of the project. Both the Xcode and the Visual Studio generators honor the `FOLDER` target property.

```
set_property(GLOBAL PROPERTY USE_FOLDERS YES)

add_executable(Foo ...)
add_executable(Bar ...)
add_executable(test_Foo ...)
add_executable(test_Bar ...)

set_target_properties(Foo Bar PROPERTIES
```

```
FOLDER "Main apps"
)
set_target_properties(test_Foo test_Bar PROPERTIES
    FOLDER "Main apps/Tests"
)
```

Up to CMake 3.11, the FOLDER target property is empty by default, whereas from CMake 3.12, it is initialized from the value of the CMAKE_FOLDER variable.

The name displayed for the target itself within the IDE defaults to the same target name that CMake uses. Visual Studio generators allow this display name to be overridden by setting the PROJECT_LABEL target property, but the Xcode generator does not honor this setting.

```
set_target_properties(Foo PROPERTIES
    PROJECT_LABEL "Foo Tastic"
)
```

Some targets are created by CMake itself, such as for installing, packaging, running tests and so on. For Xcode, most of these are not shown in the file/target tree, but for Visual Studio they are grouped under a folder called CMakePredefinedTargets by default. This can be overridden with the PREDEFINED_TARGETS_FOLDER global property, but there is usually little reason to do so.

The grouping of individual files under each target can also be controlled by the CMake project. This is done using the

`source_group()` command and is independent of the target folder grouping (i.e. it is always supported, even if the `USE_FOLDERS` global property is false or unset). The command has two forms, the first of which is used to define a single group:

```
source_group(group
    [FILES src...]
    [REGULAR_EXPRESSION regex]
)
```

The group can be a simple name under which to group the relevant files, or it can specify a hierarchy similar to that for targets. With CMake 3.18 or later, either forward slashes or back slashes can be used as the separator between nesting levels. For CMake 3.17 or earlier, only back slashes are supported. Be aware that to get through CMake's parsing correctly, back slashes must be escaped, so a group `Foo` with a nested `Bar` underneath it would be specified like so:

```
# Backslashes require escaping
source_group(Foo\\Bar ...)

# Forward slashes don't need escaping, but their
# support requires CMake 3.18 or later
source_group(Foo/Bar ...)
```

Individual files can be specified with the `FILES` argument, with relative paths assumed to be relative to `CMAKE_CURRENT_SOURCE_DIR`. Because the command is not specific to a target, this option is the way to ensure the grouping only

affects specific files. If the project wants to define a grouping structure that should be applied more generally, the REGULAR_EXPRESSION option is more appropriate. It can be used to effectively set up grouping rules that will be applied to all targets in the project. Where a particular file could match more than one grouping, a FILES entry takes precedence over a REGULAR_EXPRESSION. Where a file matches multiple regular expressions, REGULAR_EXPRESSION groups defined later take precedence over those defined earlier.

The following example sets up general rules for all targets such that files with commonly used source and header file extensions will be grouped under Sources. Test sources and headers will override that grouping and be placed under a Tests group instead, while the special case special.cxx will be put in its own dedicated subgroup below Sources.

```
source_group(Sources
    REGULAR_EXPRESSION "\\.(c(xx|pp)?|hh?)$"
)

# Overrides the above
source_group(Tests
    REGULAR_EXPRESSION "test.*"
)

# Overrides both of the above
source_group(Sources\\Special
    FILES special.cxx
)
```

CMake provides default groups `Source Files` for sources and `Header Files` for headers, but these are easily overridden, as the above example demonstrates. Other default groups such as `Resources` and `Object Files` are also defined.

The second form of the `source_group()` command allows the group hierarchy to follow the directory structure for specific files. It is available with CMake 3.8 or later.

```
source_group(TREE    root
             [PREFIX prefix]
             [FILES  src...]
)
```

The `TREE` option directs the command to group the specified files according to their own directory structure below `root`. The `PREFIX` option can be used to place that grouping structure under the `prefix` parent group or group hierarchy. This can be used very effectively in conjunction with the `SOURCES` target property to reproduce the directory structure of all sources that make up a target, but only if all of those sources are below a common point (e.g. no generated sources from the build directory). Many targets satisfy these conditions, so the following example pattern can often be used to quickly and easily give some structure to the way a target is presented in an IDE.

```
# Only suitable if SOURCES does not contain generated
# files in this example
get_target_property(sources someTarget SOURCES)
```

```
source_group(TREE ${CMAKE_CURRENT_SOURCE_DIR}
             PREFIX "Magic\\Sources"
             FILES ${sources})
)
```

IDEs generally only show files that are explicitly added as sources of a target. If a target is defined with only its implementation files added as sources, its headers won't usually appear in the IDE file lists. Therefore, it is common practice to explicitly list headers as well, even though they won't be compiled directly. CMake will effectively ignore them except to add them to IDE source lists. This extends to more than just header files, it can also be used to add other non-compiled files as well, such as images, scripts, and other resources. Some features such as those associated with the `MACOSX_PACKAGE_LOCATION` source property require a file to be listed as a source file to have any effect.

In certain situations, it may be desirable for a source file to appear in IDE file lists, but not be compiled. Platform-specific files that should only be compiled and linked on other target platforms are an example of this. To prevent CMake from trying to compile a particular file, that source file's `HEADER_FILE_ONLY` source property can be set to true. Do not be confused by the property name, it can be used for more than just headers.

```
add_executable(MyApp main.cpp net.cpp net_win.cpp)

if(NOT WIN32)
    # Don't compile this file for non-Windows platforms
```

```
set_source_files_properties(net_win.cpp PROPERTIES
    HEADER_FILE_ONLY YES
)
endif()
```

43.5. Defining Targets

The preceding chapters have presented a range of CMake features that allow a target to be defined in detail. This includes the sources and other files that a target is built up from, how a target should be built and how a target interacts with other targets. The focus of this section is to demonstrate how to use these techniques in a way that makes the project easy to understand, produces a robust build, provides flexibility, and promotes maintainability.

For simple projects, the number of source files and targets is likely to be small, in which case it is relatively manageable for all the relevant details to be given in a single `CMakeLists.txt` file. If following the project directory structure recommended earlier in this chapter, this would mean the `src` subdirectory would have no further subdirectories and its `CMakeLists.txt` file would define all that was needed. Initially, it may look as simple as something like this:

`src/CMakeLists.txt`

```
add_executable(Planter main.cpp soy.cpp coffee.cpp)
target_compile_definitions(Planter
    PUBLIC COFFEE_FAMILY=Robusta
)
```

```
add_test(NAME NoArgs COMMAND Planter)
add_test(NAME WithArgs COMMAND Planter beanType=soy)
```

This makes a number of assumptions about how the project will be used, but perhaps the biggest ones are that the project won't be installed or packaged and that it won't be absorbed into a larger project hierarchy by some other project. These limitations should be avoided (see [Chapter 40, *Making Projects Consumable*](#)). The specific weaknesses of the simple case above include:

- The target name is not specific to the project. If this project was later incorporated into a larger parent project, the target name may clash with targets defined elsewhere. Using a project-specific prefix on the target name is an easy way to address this weakness.
- There are no install rules, so the target cannot easily be installed or be included in a package.
- No namespaced alias target is defined. Even if an `install()` command was later added and packaging was implemented, other projects would have to use different target names for pre-built binary versus source inclusion.
- The test names are not very specific and there's no mechanism for a parent project to prevent the tests from being added.
- Headers are not listed as sources, so they won't show up in some IDEs.

Addressing the above points and following the recommended practices of the previous chapters, the example expands out to more like the following (assuming a project name of BagOfBeans):

```
#=====
# Define targets
#=====

add_executable(BagOfBeans_Planter
    main.cpp soy.cpp soy.h coffee.cpp coffee.h
)
add_executable(BagOfBeans::Planter
    ALIAS BagOfBeans_Planter
)
set_target_properties(BagOfBeans_Planter PROPERTIES
    OUTPUT_NAME Planter
    EXPORT_NAME Planter
)
target_compile_definitions(BagOfBeans_Planter
    PUBLIC COFFEE_FAMILY=Robusta
)

#=====
# Testing
#=====

if(BAGOFBEANS_ENABLE_TESTING OR PROJECT_IS_TOP_LEVEL)
    add_test(NAME Planter.NoArgs
        COMMAND BagOfBeans_Planter
    )
    add_test(NAME Planter.WithArgs
        COMMAND BagOfBeans_Planter beanType=soy
    )
endif()

#=====
# Packaging
#=====

include(GNUInstallDirs)
```

```
install(TARGETS BagOfBeans_Planter
        EXPORT BagOfBeans_Apps
        DESTINATION ${CMAKE_INSTALL_BINDIR}
        COMPONENT BagOfBeans_Apps
)
```

That may be a surprising amount of detail for a fairly simple executable, but it highlights that for real-world projects, there's more to consider than just building a binary in isolation. The added complexity is mostly for unique names to reduce the likelihood of clashes. The addition of packaging logic also tends to add a fair amount of detail that an inexperienced developer probably hasn't had much exposure to. Adding clear sections to the file as shown above can help make it easier to understand for newer developers and also keep it organized as the project evolves.

43.5.1. Building Up A Target Across Directories

When the number of source files increases, having them all in the one directory can make them more difficult to work with. This is generally addressed by placing them under subdirectories grouped by functionality, which brings a few other benefits too. Not only does it help keep things from becoming too cluttered, it also makes it easy to turn certain features on and off based on CMake cache options or other configure time logic. For example:

```

add_executable(BagOfBeans_Planter main.cpp)

option(BAGOFBEANS_SOY      "Enable planting soy beans"      ON)
option(BAGOFBEANS_COFFEE  "Enable planting coffee beans"  ON)

if(BAGOFBEANS_SOY)
    add_subdirectory(soy)
endif()

if(BAGOFBEANS_COFFEE)
    add_subdirectory(coffee)
endif()

```

In the preceding chapters, executables and libraries were usually defined in the one directory. That meant the full list of files could be supplied directly to the `add_executable()` or `add_library()` call. In the above arrangement, the subdirectories add sources to the target after it has been defined using the `target_sources()` command (see [Section 16.2.6, “Source Files”](#) for a detailed discussion of important considerations when using this command in subdirectories).

src/coffee/CMakeLists.txt

```

# Assumes CMake 3.13 or later and policy CMP0076 set to NEW
target_sources(BagOfBeans_Planter
PRIVATE
    coffee.cpp
    coffee.h
)

target_compile_definitions(BagOfBeans_Planter
PUBLIC COFFEE_FAMILY=Robusta
)

target_include_directories(BagOfBeans_Planter

```

```
PUBLIC ${BUILD_INTERFACE:${CMAKE_CURRENT_LIST_DIR}}
)
```

The above also demonstrates how other `target_...()` commands can be moved into the subdirectories too, not just `target_sources()`. This helps keep things local to the code they relate to. For example, compile definitions, compiler flags, and header search paths that are specific to a particular feature can be added only if that feature is enabled. If the directory structure needed to be reorganized and this directory moved elsewhere, nothing in this file would need to change. Other sources in the target that had `#include "coffee.h"` would continue to work unmodified.

One exception to this localization of details is `target_link_libraries()`. As mentioned in [Section 16.2.1, “Linking Libraries”](#), CMake 3.12 and earlier prohibited `target_link_libraries()` from operating on a target defined in a different directory. If a subdirectory needed to make the target link to something, it couldn’t do so from within that subdirectory. The call to `target_link_libraries()` would have to be made in the same directory as where `add_executable()` or `add_library()` was called. If, for example, the `BagOfBeans_Planter` target needed to link against a library called `Weather`, it would have to add the call in `src/CMakeLists.txt` rather than `src/coffee/CMakeLists.txt`. This would result in something like the following:

```
option(BAGOFBEANS_COFFEE "Enable planting coffee beans" ON)
if(BAGOFBEANS_COFFEE)
    add_subdirectory(coffee)
    target_link_libraries(BagOfBeans_Planter
        PRIVATE Weather
    )
endif()
```

CMake 3.13 lifted this restriction, allowing subdirectories to be truly self-contained. For CMake versions from 3.1 to 3.12, subdirectories can be fully self-contained apart from adding libraries that a target should link to. Before CMake 3.1, a completely different approach was needed which relied on building up lists of sources in a variable and only creating the target once all subdirectories had been added. Such an arrangement might look like this:

```
# Pre-CMake 3.1 method, avoid using this approach
unset(planterSources)
unset(planterDefines)
unset(planterOptions)
unset(planterLinkLibs)

# Subdirs add to the above variables using PARENT_SCOPE
option(BAGOFBEANS_SOY      "Enable planting soy beans"      ON)
option(BAGOFBEANS_COFFEE "Enable planting coffee beans" ON)
if(BAGOFBEANS_SOY)
    add_subdirectory(soy)
endif()
if(BAGOFBEANS_COFFEE)
    add_subdirectory(coffee)
endif()

# Lastly define the target and its other details.
# All variables are assumed to name PRIVATE items.
add_executable(BagOfBeans_Planter ${planterSources})
```

```
target_compile_definitions(BagOfBeans_Planter
    PRIVATE ${planterDefines})
)
target_compile_options(BagOfBeans_Planter
    PRIVATE ${planterOptions})
)
target_link_libraries(BagOfBeans_Planter
    PRIVATE ${planterLinkLibs})
)
```

The above would get even more complicated if some items needed to be anything other than PRIVATE. The use of variables like this is fragile, as it relies on nothing in subdirectories using the same variables for a different target. Typos in variable names would not be caught as an error by CMake with this approach. Furthermore, it also enforces a stronger coupling between parent and child directories, since each child subdirectory would have to pass all relevant variables back up to its parent using `set(... PARENT_SCOPE)`. For deeply nested directories, this quickly gets tedious and is error-prone.

43.5.2. Target Output Locations

When a library or executable is built, its default location will be either `CMAKE_CURRENT_BINARY_DIR` or a configuration-specific subdirectory below it, depending on the generator used. For projects with many subdirectories or deeply nested hierarchies, this can be inconvenient for developers. This default can be overridden using the following set of target properties:

`RUNTIME_OUTPUT_DIRECTORY`

Used for executables on all platforms and DLLs on Windows.

LIBRARY_OUTPUT_DIRECTORY

Used for shared libraries on non-Windows platforms.

ARCHIVE_OUTPUT_DIRECTORY

Used for static libraries on all platforms and import libraries associated with DLLs on Windows.

For all three of the above, multi-configuration generators like Visual Studio, Xcode, and Ninja Multi-Config will automatically append a configuration-specific subdirectory to each value unless it contains a generator expression. Associated per-configuration properties with _<CONFIG> appended are also supported for historical reasons, but those should be avoided in favor of using generator expressions where configuration-specific behavior is needed.

A common use of these target properties is to collect libraries and executables together in a similar directory structure as they would have when installed. This is helpful if applications expect various resources to be located at a particular location relative to the executable's binary. On Windows, it can also simplify debugging, since executables and DLLs can be collected into the same directory, allowing the executables to find their DLL dependencies automatically (this isn't needed on other platforms, since RPATH support embeds the necessary locations in the binaries themselves).

Following the usual pattern, these target properties are each initialized by a CMake variable of the same name with `CMAKE_` prepended. When all targets should use the same consistent output locations, these variables can be set at the top of the project so that the properties don't have to be set for every target individually. To allow the project to be incorporated into a larger project hierarchy, these variables should only be set if they are not already set so that parent projects can override the output locations. They should also use a location relative to `PROJECT_BINARY_DIR` or `CMAKE_CURRENT_BINARY_DIR` rather than `CMAKE_BINARY_DIR`. The following example shows how to safely collect binaries under a `stage` subdirectory of the current binary directory unless a parent project overrides this.

```
set(stageDir ${CMAKE_CURRENT_BINARY_DIR}/stage)

include(GNUInstallDirs)
if(NOT CMAKE_RUNTIME_OUTPUT_DIRECTORY)
    set(CMAKE_RUNTIME_OUTPUT_DIRECTORY
        ${stageDir}/${CMAKE_INSTALL_BINDIR}
    )
endif()
if(NOT CMAKE_LIBRARY_OUTPUT_DIRECTORY)
    set(CMAKE_LIBRARY_OUTPUT_DIRECTORY
        ${stageDir}/${CMAKE_INSTALL_LIBDIR}
    )
endif()
if(NOT CMAKE_ARCHIVE_OUTPUT_DIRECTORY)
    set(CMAKE_ARCHIVE_OUTPUT_DIRECTORY
        ${stageDir}/${CMAKE_INSTALL_LIBDIR}
    )
endif()
```

Avoid creating `CMAKE_..._OUTPUT_DIRECTORY` as cache variables, they should not be under the control of the developer. They should be controlled by the project because parts of the project may make assumptions about the relative layout of the binaries. More importantly, leaving them as ordinary variables also means they can be unset within subdirectories where test executables are defined, allowing them to avoid being collected with the other main binaries and cluttering up that area.

Older projects sometimes read the `LOCATION` target property to try to obtain the output location of a binary and use it in places like custom target commands. As already highlighted in [Section 15.4, “Recommended Practices”](#), this is problematic for multi-configuration generators, since the location depends on the configuration and the `LOCATION` target property doesn’t account for that. Projects should use generator expressions like `$<TARGET_FILE:...>` instead. CMake 3.0 and later will warn if a project tries to set this target property.

43.6. Cleaning Files

Project generators usually provide some kind of clean target that can be used to remove all the generated files, build outputs, etc. This is sometimes used by IDE tools to provide a basic rebuild feature as a clean followed by a build, or by developers to simply remove build outputs to force rebuilding everything on the next build attempt. Sometimes a project defines a custom

rule in such a way that it creates files that CMake doesn't know about, so they are not included in the `clean` step and have the potential to still affect the next build.

There are a variety of mechanisms by which files can become part of the set to be removed by a `clean` operation. The Ninja generators will automatically add any generated files to the `clean` set. Any files listed as `BYPRODUCTS` of a custom command or custom target are also recognized as generated and are added to the `clean` set as well. With CMake 3.13 and later, Makefile generators also add generated and byproduct files to the `clean` set.

For other files, the preferred approach depends on the minimum CMake version. For CMake 3.15 or later, the `ADDITIONAL_CLEAN_FILES` directory and target properties can be used to specify a list of files to be cleaned. Miscellaneous files created as part of building a particular target should be added to the target property. If files are not associated with a single target, add them to the directory property instead. Only Ninja and Makefile generators support the `ADDITIONAL_CLEAN_FILES` properties. For CMake 3.14 or earlier, the `ADDITIONAL_MAKE_CLEAN_FILES` directory property can be used instead, but it is officially deprecated as of CMake 3.15. It works the same way as the `ADDITIONAL_CLEAN_FILES` directory property, but it is only supported by Makefile generators.

43.7. Re-running CMake On File Changes

Certain more advanced techniques may require CMake to be re-run if a particular file changes. Normally, CMake does a good job of automatically tracking dependencies for things it controls, such as copying files with the `configure_file()` command, but custom commands and other tasks may rely on files for which CMake isn't aware of the dependency. Such files can be added to the `CMAKE_CONFIGURE_DEPENDS` directory property, and if any of the listed files change, CMake will be re-run before the next build. If a file is specified with a relative path, it will be taken to be relative to the source directory associated with the directory property.

Most projects won't typically need to make use of `CMAKE_CONFIGURE_DEPENDS`, but it can and should be used where CMake doesn't have the opportunity to know about files which act as input to the configure or generation steps. Most file dependencies are build time dependencies, not configure or generation time. Therefore, before using this property, check whether the project really does need to re-run CMake rather than simply recompiling a source file or target as part of the regular build.

43.8. Injecting Files Into Projects

There will inevitably come a time when a project from some external source needs to be added to a build, but it has some

sort of problem that prevents it from working correctly. Common examples include not setting variables or properties that should have been set, or old policy settings that block otherwise desirable behavior. These things are especially common when working with projects that support very old CMake versions and have not been updated to handle newer CMake features and techniques. For some of these issues, it is possible to inject CMake code without having to actually modify the external project and work around the problem.

[Section 41.1, “Top Level Setup Injection Point”](#) already introduced the `CMAKE_PROJECT_TOP_LEVEL_INCLUDES` variable. It can be used to inject code at the first `project()` command in the top level `CMakeLists.txt` file. This is ideal for inserting logic that should be applied at the whole-of-build level, but it won’t typically help with targeting problems deeper in the project hierarchy. For such cases, the `project()` command also supports additional variables which can be used to inject code at other places in the build.

Each `project()` call will look for a variable with a name of the form `CMAKE_PROJECT_<PROJNAME>_INCLUDE`, where `<PROJNAME>` is the project name as given to the `project()` command. If that variable is defined, it is assumed to hold the name of a file that CMake should include as the last thing the `project()` command does before returning. CMake 3.17 also added support for `CMAKE_PROJECT_<PROJNAME>_INCLUDE_BEFORE`, which can name a file

to include before a `project()` command. For these variables, because the named file only gets read for that specific project, this can be a great way to target a specific problem local to one project.

When using CMake 3.15 or later, two other variables are available to inject files as part of *every* `project()` command, regardless of the project name given. These variables, `CMAKE_PROJECT_INCLUDE_BEFORE` and `CMAKE_PROJECT_INCLUDE`, allow code to be inserted before or after the normal processing of *every* `project()` command. They are mostly useful for situations where the project name may not be readily known, such as when a build is driven by generic scripts that are re-used across multiple project builds. The effective behavior of these variables is loosely equivalent to the following:

```
# CMake 3.15 or later only
if(DEFINED CMAKE_PROJECT_INCLUDE_BEFORE)
    include(${CMAKE_PROJECT_INCLUDE_BEFORE})
endif()

# CMake 3.17 or later only
if(DEFINED CMAKE_PROJECT_SomeProj_INCLUDE_BEFORE)
    include(${CMAKE_PROJECT_SomeProj_INCLUDE_BEFORE})
endif()

project(SomeProj)

# CMake 3.15 or later only
if(DEFINED CMAKE_PROJECT_INCLUDE)
    include(${CMAKE_PROJECT_INCLUDE})
endif()
```

```
# All CMake versions
if(DEFINED CMAKE_PROJECT_SomeProj_INCLUDE)
    include(${CMAKE_PROJECT_SomeProj_INCLUDE})
endif()
```

With CMake 3.29 and later, each of the four above-mentioned `CMAKE_PROJECT_...INCLUDE...` variables can contain a list, not just a single file name. Furthermore, CMake module names can be given too, although it would be more typical to include modules directly within the files listed in these variables.

Injecting files into `project()` commands using these variables should not be part of the normal development of a project. They have specific uses for overcoming deficiencies in older projects and for very controlled situations, such as in continuous integration builds. Outside those cases, developers should generally prefer to modify the project's `CMakeLists.txt` files to address the underlying problems directly.

43.9. Recommended Practices

The way projects are structured and used can vary considerably. Some things that used to be commonplace are now considered poor practice. New features and lessons learned allow older methods to be replaced by newer ones that are more robust, more flexible, and allow things that were not possible previously. Tools are upgraded, languages evolve, dependencies change. All of these things mean that projects will also need to adapt over time. For CMake projects in particular,

those that continue to target older CMake versions before 3.0 will increasingly face a bumpy path. There is a strong move toward a target-centric model, and much of CMake's development is geared in that direction. Therefore, prefer to set a minimum CMake version that allows the project to make use of those features. Anything less than CMake 3.5 is likely to be too restrictive and will generate deprecation warnings when a recent version of CMake processes them. CMake 3.14 provides a reasonable base of features, but if presets are important, then 3.19 or later is essential. If working with newer tools like CUDA or a very recent language standard, the latest CMake release is strongly advised. New releases of Visual Studio or Xcode also tend to require recent CMake versions to pick up fixes and additions for changes in those toolchains.

A fundamental choice that every project needs to make is whether to structure itself as a superbuild or as a regular build. If the project can set a minimum CMake version of 3.11, the non-superbuild arrangement has more powerful features available to it for dependency management which may make the need for a superbuild unnecessary. Consider whether the `FetchContent` module and the promotion of local imported targets to global scope offer more flexibility and a better experience for developers. Where all dependencies of a project are relatively mature and have well-defined install rules, a superbuild may still be a suitable alternative and comes with the advantage that it can be used with much older CMake

versions. Both methods have their place, but the earlier in a project's life that the decision can be made on whether to use a superbuild, the more likely the project can avoid large-scale disruptive restructuring later on.

Irrespective of whether a project is a superbuild or not, aim to keep the top level of the project focused on the higher level details. Think of the top level `CMakeLists.txt` file as being more like a table of contents for the project. The top level directory should mostly just contain administrative files and a set of subdirectories each focused on a particular area. Avoid subdirectory names that may cause clashes with those created in the build directory automatically. Prefer instead to use fairly standard names unless there is an existing convention that must be followed. For regular projects, aim to make the top level `CMakeLists.txt` file follow the common section pattern of:

- Preamble
- Project wide setup
- Dependencies
- Main build targets
- Tests
- Packaging

Ideally, clearly delineate each section with comment blocks, which will help encourage developers working on the project to

maintain that structure. Establishing this pattern across projects will help reinforce the focus on keeping the top level `CMakeLists.txt` file streamlined and acting as a high-level overview.

When defining build targets that have sources spread across directories, prefer to create the target first, then have each subdirectory add sources to it using `target_sources()`. Where appropriate, group the subdirectories by functionality or feature so that they can be easily moved around or enabled/disabled as a unit. In many cases, the other target-focused commands (i.e. `target_compile_definitions()`, `target_compile_options()`, and `target_include_directories()`) can then also be used locally within the subdirectory that they relate to. This helps keep information close to the location where it is relevant rather than spreading it across directories. Avoid using variables to build up lists of sources to be passed back up through directory hierarchies and eventually used to create a target, define compiler flags, etc. The use of variables instead of operating on targets directly is much more fragile, more verbose, and less likely to result in CMake catching typos or other errors.

Following on from the above and reiterating one of the recommendations from [Chapter 4, *Building Simple Targets*](#), avoid the all too common practice of unnecessarily using a

variable to hold the name of a target or project. The following pattern in particular should be avoided:

```
set(projectName ...)  
project(${ projectName })  
add_executable(${ projectName } ...)
```

The above example ties together things that should not be so strongly related. The project name should rarely change. Specify the name of the project directly in the `project()` command and use the standard variables CMake provides if it needs to be referred to elsewhere in the project. For targets, the target name is used so widely that trying to carry it around in a variable is both cumbersome and error-prone. Give the target a name and use that name consistently throughout the project. Even if there is only one target in the whole project, it doesn't necessarily have to be the same as the project name, and the two should be considered distinct.

When adding tests, consider keeping the test code close to the code being tested. This helps keep logically related code together and encourages developers to keep tests up to date. Tests that are distributed to other parts of the source directory hierarchy can easily be forgotten. For tests that draw on multiple areas such as integration tests, the locality principle is not as strong, so collecting these higher level tests in a common place may be appropriate. The top level `tests` subdirectory is intended for situations such as this.

For larger projects, consider whether it is worth organizing the way the project is presented in IDE tools. If there are many targets, it can be challenging to work with the project unless some structure is added using the FOLDER target property. For those targets with many sources, they too can be organized using the source_group() command, which can be used to define group hierarchies around whatever concepts or features make sense.

VII: SPECIAL TOPICS

These final chapters draw on many of the techniques and features introduced throughout the book. Various CMake capabilities work together to enable customizing the debugging experience. CMake's long history in supporting Qt has also resulted in a rich set of functionality for projects using that powerful toolkit.

44. DEBUGGING EXECUTABLES

While running tests is usually part of a project's continuous integration setup, developers also need to be able to run and debug applications locally. Depending on the platform and IDE tool used, developers may need to set up additional things to be able to run the built executables. CMake provides a number of ways to help automate much of that process.

44.1. Working Directory

For some executables, the current working directory is important. The executable might look for files relative to the working directory. On Windows, the working directory is one of the DLL search locations, so it can affect whether the executable can even start.

When running an executable outside any IDE, developers will manage their own working directory as part of their shell or terminal. But when using an IDE, the working directory is much less visible, often being hidden away in some project setting. In large projects, it can be impractical to manually set the working directory for each executable.

CMake provides support for specifying the working directory when a target is executed in some IDEs. CMake 4.0 added a DEBUGGER_WORKING_DIRECTORY target property, which follows the usual pattern of taking its initial value from the CMAKE_DEBUGGER_WORKING_DIRECTORY variable, if defined. This is then included in CMake's file API replies, so any IDE that uses CMake's file API for understanding the structure of the project can make use of this setting when debugging project executables.

```
add_executable(MyApp ...)

# Tell debuggers to start the executable in the source
# directory. This requires CMake 4.0 or later to be useful.
set_property(TARGET MyApp
    PROPERTY DEBUGGER_WORKING_DIRECTORY
    ${CMAKE_CURRENT_SOURCE_DIR}
)
```

44.1.1. Visual Studio Generators

When using one of the Visual Studio CMake generators with CMake 4.0 or later, if the DEBUGGER_WORKING_DIRECTORY property is set, it will be written to the Visual Studio project file. The VS_DEBUGGER_WORKING_DIRECTORY target property achieves the same thing with CMake 3.8 or later (support for generator expressions requires at least CMake 3.13). If both DEBUGGER_WORKING_DIRECTORY and VS_DEBUGGER_WORKING_DIRECTORY are set, the latter always takes precedence.

```
# Visual Studio-specific, only requires CMake 3.8.  
# This overrides DEBUGGER_WORKING_DIRECTORY.  
set_property(TARGET MyApp  
    PROPERTY VS_DEBUGGER_WORKING_DIRECTORY  
    ${CMAKE_CURRENT_SOURCE_DIR})
```

44.1.2. Xcode Generator

A similar situation exists for the Xcode generator. With CMake 3.17 or later, the XCODE_SCHEME_WORKING_DIRECTORY target property sets the scheme's working directory for running or profiling that executable target. With CMake 4.0.2 or later, if XCODE_SCHEME_WORKING_DIRECTORY isn't set, the DEBUGGER_WORKING_DIRECTORY property acts as a fallback value. Scheme generation must be enabled for either case (see [Section 25.7, “Creating And Exporting Archives”](#) and [Section 33.1.3, “Xcode Generator”](#)).

```
# Usually want to create a scheme for each target, which is  
# normally achieved by setting this project-wide variable  
set(CMAKE_XCODE_GENERATE_SCHEME YES)  
  
add_executable(MyApp ...)  
  
# Xcode-specific, only requires CMake 3.17.  
# This overrides DEBUGGER_WORKING_DIRECTORY.  
set_property(TARGET MyApp  
    PROPERTY XCODE_SCHEME_WORKING_DIRECTORY  
    ${CMAKE_CURRENT_SOURCE_DIR})
```

44.2. Environment Variables

In some situations, it may be necessary to modify the environment within which an executable is run. Some applications use environment variables to customize their behavior. On Windows, the PATH environment variable may need to be modified so that the system can find any DLLs required by the executable.

When running executables under `ctest`, the `ENVIRONMENT_MODIFICATION` or `ENVIRONMENT` test properties discussed in [Section 27.2, “Test Environment”](#) can be used to customize the environment:

```
add_executable(test_Algo ...)  
target_link_libraries(test_Algo PRIVATE Algo)  
  
add_test(NAME CheckAlgo COMMAND test_Algo)  
  
if(WIN32)  
    set(algoDir "<SHELL_PATH:<TARGET_FILE_DIR:Algo>>")  
    set(otherDllDir "C:\\path\\to\\another\\dll")  
    set_property(TEST CheckAlgo  
        APPEND PROPERTY ENVIRONMENT_MODIFICATION  
        PATH=path_list_prepend:${algoDir}  
        PATH=path_list_prepend:${otherDllDir})  
endif()
```

This is a good solution for testing, but it doesn't help developers debugging the application in their IDE outside of `ctest`.

CMake doesn't provide a generic property for augmenting an executable target's debugging environment, but generator-

specific properties are supported.

44.2.1. Visual Studio Generators

CMake 3.13 and later supports a `VS_DEBUGGER_ENVIRONMENT` target property, which only the Visual Studio generators use. This has similarities to the `ENVIRONMENT` test property, but there are some important differences. `VS_DEBUGGER_ENVIRONMENT` specifies environment variables to set when running the executable in the Visual Studio IDE debugger. The value can refer to existing environment variable values using the standard Windows `%varName%` notation. Unlike the `ENVIRONMENT` test property, which can only record environment variable values at configure time, the `%varName%` notation defers evaluation to run time. The value can also use Visual Studio macros like `$(Path)`.

If setting multiple environment variables, they must be separated with a newline character. Values can contain semicolons, which require no special handling other than ensuring CMake's command parsing and quoting rules don't break up properties in unexpected ways. Using the `set_property()` command instead of `set_target_properties()` will help avoid most such problems.

```
set(pathEnv "PATH=${otherDllDir};${algoDir};$(Path)")
set(appOptsEnv "MyAppOpts=Algo:2,Verbosity:1")

set_property(TARGET MyApp
    PROPERTY VS_DEBUGGER_ENVIRONMENT
```

```
    "${pathEnv}\n${appOptsEnv}"  
)
```

44.2.2. Xcode Generator

Xcode schemes provide a setting for modifying the environment of an executable target. The `XCODE_SCHEME_ENVIRONMENT` target property can be used to populate that setting with a CMake list of `name=value` items. Because CMake treats semicolons as a list separator between items, if a value needs to contain a semicolon, the `$<SEMICOLON>` generator expression must be used. The following example assumes scheme generation has been enabled, which is usually done project-wide by setting the `CMAKE_XCODE_GENERATE_SCHEME` variable to true before defining any targets.

```
set_property(TARGET MyApp  
    PROPERTY XCODE_SCHEME_ENVIRONMENT  
        TrickyOne=blah$<SEMICOLON>something=5  
        MyAppOpts=Algo:2,Verbosity:1  
)
```

The above example results in defining a `TrickyOne` environment variable with the value `blah;something=5`. If a ; was used instead of `$<SEMICOLON>`, then `TrickyOne` would have ended up with the value `blah` and a separate `something` environment variable would have been defined with the value 5.

44.3. Finding Windows DLLs At Runtime

Windows' lack of support for RPATH causes a number of problems for developers. When running an executable during development, any DLLs the executable requires must be either in the same directory or be located in one of the directories listed in the PATH environment variable.

The techniques presented earlier in [Section 44.1, “Working Directory”](#) and [Section 6.2, “Environment Variables”](#) are often used to ensure an executable's DLLs can be found at run time. However, they don't cover all scenarios in which an executable may be run. They may also require more recent CMake versions, which can be an obstacle for projects that need to maintain compatibility with older CMake versions.

For the project's main binaries, properties like `RUNTIME_OUTPUT_DIRECTORY` or its configuration-specific variants (see [Section 43.5.2, “Target Output Locations”](#)) can be used to place executables and shared libraries in the same location. This has the advantage that no matter how an executable is launched, its DLLs can be found at run time. Older CMake projects often use this approach.

```
add_executable(MyApp ...)
add_library(Algo SHARED ...)
target_link_libraries(MyApp PRIVATE Algo)

set_target_properties(MyApp Algo
  PROPERTIES
    RUNTIME_OUTPUT_DIRECTORY ${PROJECT_BINARY_DIR}/bin
)
```

Choosing an appropriate output directory needs some care. A common problem is where the output directory is specified with a path that starts with `${CMAKE_BINARY_DIR}`. If the project is absorbed into the build of a larger parent project, such as by `FetchContent`, the relative location in the parent build will be different to if the project was being built standalone. Depending on what assumptions the project makes, this could break the build or runtime behavior in obvious or subtle ways. This is why the above example uses `${PROJECT_BINARY_DIR}` instead.

It may be tempting to use the `CMAKE_RUNTIME_OUTPUT_DIRECTORY` variable to default all executables and DLLs to the same output location throughout the project. In simple terms, that might look something like this:

```
cmake_minimum_required(VERSION 3.30)
project(example)

# Overly greedy specification, often not ideal
set(CMAKE_RUNTIME_OUTPUT_DIRECTORY
    ${CMAKE_CURRENT_BINARY_DIR}/bin
)

# Add project targets here and in subdirectories...
```

This can be problematic when the project has many test executables. It may be undesirable to have so many test-related files in the same directory as the main applications. If setting `CMAKE_RUNTIME_OUTPUT_DIRECTORY` like in the above example, the project may then have to clear that variable before the

`add_executable()` call for every test target it creates to avoid this problem. It may be less work to instead set the `RUNTIME_OUTPUT_DIRECTORY` property on each shared library target and executable target that isn't a test.

44.4. Command Line Arguments

Some applications expect one or more command-line arguments to be given. When debugging in an IDE, it can be tedious to have to manually set up an appropriate set of initial command lines for each application in the project. CMake offers some IDE-specific mechanisms for controlling the command line used by the debugger when launching the process.

44.4.1. Visual Studio Generators

CMake 3.13 and later supports a `VS_DEBUGGER_COMMAND_ARGUMENTS` target property. It sets the `LocalDebuggerCommandArguments` property in the target's Visual Studio project file. Users can still make their own local overrides, which will be saved in a separate `.vcxproj.user` file that CMake doesn't modify. Regenerating the CMake project will preserve the developer's settings. Thus, `VS_DEBUGGER_COMMAND_ARGUMENTS` acts more like a default set of arguments.

Unlike most CMake properties, this is not a semicolon-separated list of values. Visual Studio expects it to be a space-separated set of command-line arguments, exactly as it would be written if

given at a terminal or in a script. Values can use Visual Studio macros, which can be useful for things like `$(Configuration)` or `$(NUMBER_OF_PROCESSORS)`.

```
add_executable(MyApp ...)

set_target_properties(MyApp PROPERTIES
    VS_DEBUGGER_COMMAND_ARGUMENTS "1 2 $(Configuration)"
)
```

CMake 3.12 and later also supports a `VS_DEBUGGER_COMMAND` target property, which can be used to change the executable launched by the debugger. This may initially seem not all that useful, but one of the more interesting things it enables is setting debugger details for a shared library target. A project might have a generic executable that links to a set of libraries. When a developer is working on a particular library, they may want to run that executable with a specific set of arguments so that the library's code paths are used. For example:

```
add_executable(MyApp ...)
add_library(Algo SHARED ...)
target_link_libraries(MyApp PRIVATE Algo)

set_target_properties(Algo PROPERTIES
    VS_DEBUGGER_COMMAND $<TARGET_FILE:MyApp>
    VS_DEBUGGER_COMMAND_ARGUMENTS "algoCheck --verbose"
)
```

With the above example, the developer could set the `Algo` target as their Startup Project in the Visual Studio IDE. The `MyApp` executable would then be run with the specified command line

arguments whenever the developer runs the debugger, or even if they run without debugging.

44.4.2. Xcode Generator

CMake supports similar features for the Xcode generator via scheme properties, although there are some differences and limitations. `XCODE_SCHEME_ARGUMENTS` serves the same purpose as `VS_DEBUGGER_COMMAND_ARGUMENTS`. It uses CMake's usual semicolon-separate list to specify values, not space-separated like Visual Studio. Generator expressions are not supported, and there is no Xcode equivalent of Visual Studio's macros.

```
set(CMAKE_XCODE_GENERATE_SCHEME YES)
add_executable(MyApp ...)

set_target_properties(MyApp PROPERTIES
    XCODE_SCHEME_ARGUMENTS "1;2;3"
)
```

CMake also supports a `XCODE_SCHEME_EXECUTABLE` target property, but it does not support generator expressions either. This makes it difficult to robustly specify the location of an executable target, or any other file built by the project for that matter. An absolute path can be provided, and while it will allow the specified executable to be used, it lacks the same cohesive connection to targets in the Xcode IDE compared to selecting it through the Xcode Edit Scheme dialog.

```
add_executable(MyApp ...)
add_library(Algo SHARED ...)
```

```
target_link_libraries(MyApp PRIVATE Algo)

set_target_properties(Algo PROPERTIES
    XCODE_SCHEME_EXECUTABLE ${CMAKE_CURRENT_BINARY_DIR}/Debug/MyApp
    XCODE_SCHEME_ARGUMENTS "algoCheck;--verbose"
)
```

Note how both the location and configuration of the executable has to be hard-coded due to the lack of generator expression support.

44.5. PDB Generation

Another aspect unique to the Visual Studio toolchain is that for executables and DLLs, it is typical for a PDB (program database) file to be generated so that debugging information is available during development. There are two kinds of PDB files, and CMake provides features for both.

For shared libraries and executables, the PDB_NAME and configuration-specific PDB_NAME_<CONFIG> target properties can be used to override the base name of the PDB file. The default name is normally the most appropriate though, since it matches the DLL or executable name except it has a .pdb suffix instead of .dll or .exe. The PDB file is placed in the same directory as the DLL or executable by default, but this can be overridden with the PDB_OUTPUT_DIRECTORY and configuration-specific PDB_OUTPUT_DIRECTORY_<CONFIG> target properties. Note that

`PDB_OUTPUT_DIRECTORY` only supports generator expressions with CMake 3.12 or later.

A second kind of PDB file may also be created which holds information for the individual object files built for a target. This PDB file is less useful during development, except perhaps for static libraries. For C++, this latter PDB file has a default name `VCxx.pdb` where `xx` represents the version of Visual C++ being used (e.g. `VC14.pdb`). Because the default name is not target-specific, it is easy to make mistakes and mix up the PDBs for different targets in some situations. CMake allows the name of each target's object PDB file to be controlled with the `COMPILE_PDB_NAME` target property or the associated configuration-specific `COMPILE_PDB_NAME_<CONFIG>` target properties. The location of these object PDB files can also be overridden with the `COMPILE_PDB_OUTPUT_DIRECTORY` and `COMPILE_PDB_OUTPUT_DIRECTORY_<CONFIG>` target properties. Note that these object PDB files are of little use for DLL and executable targets, since the main PDB already contains all the debugging information required.

Generating compilation PDBs typically defeats compiler caching, as highlighted in [Section 26.5.1, “Ccache Configuration”](#). Given the huge benefit compiler caching usually provides, the generation of compilation PDBs is therefore typically something to avoid.

44.6. Recommended Practices

If the working directory changes the behavior of an executable, consider setting its `DEBUGGER_WORKING_DIRECTORY` target property to a location that makes the out-of-the-box IDE debugging experience easier. Only if support for CMake versions before 4.0 is important, consider also setting the `VS_DEBUGGER_WORKING_DIRECTORY` property for Visual Studio, and the `XCODE_SCHEME_WORKING_DIRECTORY` property for Xcode. With CMake 4.0 and later, setting `DEBUGGER_WORKING_DIRECTORY` alone is enough.

Give special consideration to projects that are expected to be built on Windows, especially where developers may use the Visual Studio IDE. The lack of RPATH support means executables rely on finding their DLL dependencies in either the same directory or via the PATH environment variable. This impacts test programs run through `ctest` and the developer's ability to run or debug executables from within the Visual Studio IDE. Forcing all executables and DLLs into the same output directory is one solution to this problem, made possible by the various ... `OUTPUT_DIRECTORY` target properties and their associated `CMAKE_...OUTPUT_DIRECTORY` variables. These are sometimes used to create a directory layout that mirrors the layout when the project is installed.

Avoid copying DLLs in post-build rules or custom tasks to put them in multiple locations so that other executables can find them. This is fragile and can easily result in stale DLLs mistakenly being used.

Ideally, test programs would not be collected in the same place as the main programs and DLLs. Some test code may need to find other files relative to their own location, so keeping them separate may even be a requirement. Use the ENVIRONMENT_MODIFICATION test property to specify an appropriate PATH to ensure tests can find their DLLs when run through `ctest`. Also consider populating the VS_DEBUGGER_ENVIRONMENT property on all executable targets too so that they can be run directly from within the Visual Studio IDE.

When using the Visual Studio generator, prefer to leave the PDB settings at their defaults. This typically results in the PDB file appearing in the location developers expect and with a name that matches the executable or library they correspond to. Trying to change the output directory of PDB files has implementation complexities when generator expressions are used, and it can be challenging to get the PDB files into the desired directory in some cases. Avoid generating compilation PDBs, as they usually defeat compile caching (see [Section 26.5.1, “Ccache Configuration”](#) and [Section 16.8.5, “Debug Information Format Selection”](#)).

45. WORKING WITH QT

Qt has enjoyed direct support in CMake for some time. This support has evolved over many releases of both projects and can loosely be grouped under the following three broad areas:

- Running Qt tools like `moc`, `uic` and `rcc` as needed during the build.
- Defining variables and imported targets to simplify building Qt applications and libraries.
- Deploying Qt applications to various platforms.

For Qt 4 and earlier, support for these features was provided exclusively by CMake. With Qt 5, most of the features are provided by Qt itself, with CMake only handling some of the more automated aspects of the Qt tool support. Qt 6 switched to CMake as its primary build system, and this brought significant improvements with more complete functionality. Qt 6 has now matured to the point that projects should prefer to target that as their minimum version rather than Qt 5. The last Qt 5 LTS release series (5.15) reaches official extended end-of-life in May 2025 (license conditions apply).

The CMake Manual provided as part of the official Qt 6 documentation should be consulted for the most up to date and complete reference for what functionality is provided. This chapter here focuses more on functionality provided by CMake, and on some important differences in CMake support between Qt 6 and Qt 5.

Qt 6 requires at least CMake 3.16, but later versions provide increasing levels of automation for certain situations. In practice, anything older than CMake 3.19 should be avoided. Some platforms may need at least CMake 3.21, and the best experience will be provided with CMake 3.24 or later.

45.1. Making Qt Available To The Project

Any project that uses Qt needs to find a suitable Qt installation. Given Qt's size, it is not generally practical to build Qt from source as part of the project. Instead, packages are usually obtained from the official Qt website, a package manager, or built separately from sources beforehand.

The most common way to bring Qt into the project's build is to use `find_package()` to search for the Qt6 package and specify which Qt components the project needs. The following example shows how to require the `Gui` and `Widgets` components, but leave `DBus` as an optional component. It also specifies that Qt 6.7 or later is needed.

```
find_package(Qt6 6.7 REQUIRED
    COMPONENTS Gui Widgets
    OPTIONAL_COMPONENTSDBus
)
```

In many cases, Qt won't be installed in one of CMake's default search locations. Developers will typically need to provide that information to CMake using the `CMAKE_PREFIX_PATH` cache variable. When running CMake from an IDE, this typically has to be set in the project or IDE settings. When running CMake from the command line, it can be done in the usual way, like so:

```
cmake -D CMAKE_PREFIX_PATH=/Users/mylogin/Qt/6.7.2/macos ...
```

Qt also provides a command-line wrapper around `cmake` which can be used for configuring instead (it cannot be used to wrap calls like `cmake --build` or `cmake --install`):

```
/Users/mylogin/Qt/6.7.2/macos/bin/qt-cmake ...
```

If successful, the `find_package()` call will define an imported target for each component found. These imported targets will be named `Qt6::<ModuleName>`, such as `Qt6::Gui`, `Qt6::Widgets`, and so on. When project targets link against these imported targets, they will automatically have the relevant compiler defines, header search paths, and library dependencies added to them. As a result, defining targets that use Qt should generally be quite straightforward:

```
find_package(Qt6 6.3 REQUIRED COMPONENTS Widgets)

# This is equivalent to add_executable(), but with added
# Qt-specific automation (discussed later in this chapter)
qt_add_executable(SimpleGUI MACOSX_BUNDLE WIN32 main.cpp)

target_link_libraries(SimpleGUI PRIVATE Qt6::Widgets)
```

Historically, each Qt component could alternatively be found independently with separate calls to `find_package()`. For example, the following arrangement used to be recommended in earlier versions of the Qt documentation:

```
# WARNING: Do not use this approach
find_package(Qt5Widgets 5.9 REQUIRED)
find_package(Qt5Gui      5.9 REQUIRED)
find_package(Qt5DBus     5.9)
```

The danger with this approach is that it potentially allows mixing libraries from different Qt installations. This would generally be discouraged, since it opens up the possibility of using an inconsistent set of libraries, and potentially hard-to-trace bugs. Using one `find_package()` call to find the umbrella Qt5 or Qt6 package is safer and more clearly communicates the project's intent for component handling.

Regardless of whether finding the Qt5 or Qt6 umbrella package or the individual components separately, the same set of imported targets and variables will be defined. In general, projects should prefer to work with the imported targets rather

than the variables, but there are a couple of per-component variables that may be useful:

Qt6<component>_FOUND

This set of variables is most useful for checking whether an optional component was found. Another choice would be to test whether the relevant imported target is defined, but checking the variable may be more readable.

Qt6<component>_VERSION

This records the version of a found component. It can be useful for things like working around known issues or recording build details.

Some of the Qt components also define associated CMake commands. A number of these are discussed in this chapter.

45.2. Standard Project Setup

An important improvement of Qt 6 over Qt 5 is the added support for more automated project setup. Qt 6 projects are expected to call `qt_standard_project_setup()` in their top level `CMakeLists.txt` file before creating any targets. The general pattern looks like this:

```
cmake_minimum_required(VERSION 3.24)
project(MyProj)

set(CMAKE_CXX_STANDARD 17)
set(CMAKE_CXX_STANDARD_REQUIRED ON)
```

```
find_package(Qt6 REQUIRED COMPONENTS Core)
qt_standard_project_setup()
```

The `qt_standard_project_setup()` command adjusts various defaults to give behavior more in line with what typical Qt projects would want to use. In some ways, it has similarities to the `cmake_minimum_required()` command in that it defines the behavior expected by the project. Starting with Qt 6.5, `qt_standard_project_setup()` supports keywords for a Qt-specific policy mechanism which work very similarly to CMake's policies. See the Qt documentation for `qt_standard_project_setup()` for how the policies operate and what Qt policies are defined.

If a project provides language translations, additional options will typically be passed to `qt_standard_project_setup()`. See [Section 45.6, “Translations”](#) for discussion of this aspect.

45.3. Command And Target Names

As part of supporting projects as they transition from Qt 5 to Qt 6, Qt provides mechanisms for using versionless names for commands and CMake targets. There are opposing views on what should be the recommended practice for whether to use versioned or versionless names, but a clear recommendation can be made based on API evolution and robustness concerns.

Most CMake commands provided by Qt can be called using either a versioned name starting with `qt6_...`, or a versionless name starting with `qt_....` While versioned names may seem to make clear the command that was intended when the project's code was written, it doesn't account for potential future improvements and API evolution, which can happen even within a particular Qt major version. It is not unusual for CMake commands to gain new features or change certain behaviors, and policies provide backward compatibility for such changes. Therefore, a better strategy is for projects to use versionless command names, and use policy settings in the call to `qt_standard_project_setup()` to control the behavior they expect.

For CMake targets provided by Qt, versioned target names are always defined. These take the form `Qt6::Core`, `Qt6::Widgets`, and so on. Versionless targets of the form `Qt::Core`, etc. may also be defined, but their use is discouraged. Target properties cannot be read from the versionless targets like they can from the versioned targets. Target names also affect transitive usage requirements which propagate to consumers, and using the versioned target names is the only way to make those robust. Therefore, never use the versionless target names, use only the versioned ones.

45.4. Defining Targets

Qt 6 provides more automated handling for Qt-specific aspects of target creation. Certain additional processing needs to occur after targets have been defined, but that processing is usually deferred to the end of the scope in which the target is created. This is called *target finalization*. It is usually deferred so that the project has an opportunity to modify target properties which affect finalization.

Qt sets up finalization of targets through wrappers around the standard `add_executable()` and `add_library()` commands. These wrappers are `qt_add_executable()` and `qt_add_library()`, which can be used as drop-in replacements for their corresponding built-in CMake counterparts. There is also a `qt_add_plugin()` command which offers a more specialized replacement for `add_library()` when defining a Qt plugin target. Projects should use these `qt_...()` commands to define Qt-specific targets instead of calling `add_executable()` or `add_library()` directly.

When using these `qt_add_...()` wrapper commands, target finalization is automatically deferred when using CMake 3.19 or later. With earlier CMake versions, finalization can still be deferred, but the project must invoke it manually. The `MANUAL_FINALIZATION` keyword for the `qt_add_...()` commands must be used to achieve this. Manual finalization is covered in the Qt documentation for these commands, but projects should strongly prefer to use CMake 3.19 or later to avoid the need for it.

45.5. Autogen

Qt provides a number of command-line tools which process sources and generate other source files to be consumed by the build. The three most important and heavily used of these tools are `moc`, `uic`, and `rcc`. CMake provides dedicated features that automate the way these tools are used within a project. CMake commands provided by Qt also allow projects to use these tools in a more manual, granular way for greater control, if required.

Unless already set by the project, the `qt_standard_project_setup()` command enables automatic handling for `moc` and `uic` by setting `CMAKE_AUTOMOC` and `CMAKE_AUOUIC` to true. With Qt 6, resources are best handled by dedicated commands, so automatic handling for `rcc` is done differently and `CMAKE_AUTORCC` is not modified. These variables and their effects are discussed in detail in the next three subsections.

45.5.1. Moc

Qt uses its own meta-object system to implement signals and slots, run-time type information, and its own property system. It provides the `moc` tool which scans source code looking for particular macros (e.g. `Q_OBJECT` and `Q_GADGET`) and generates C++ code implementing the underlying functions the macros declare. The following is a typical example of a class that requires processing by `moc`:

```
class SomeClass : public QObject
{
    Q_OBJECT
public:
    SomeClass(QObject* parent);
    ~SomeClass();
    // ... various signals, slots,
    // properties, member functions, etc....
};
```

CMake provides a fully automated way of managing how and when `moc` should be run on source files of a given target. This functionality is enabled by setting the `AUTOMOC` target property to true. The property is initialized from the value of the `CMAKE_AUTOMOC` variable when the target is created. When `AUTOMOC` is enabled, files are scanned at build time and `moc` is run on the relevant files. The generated code will be incorporated into the target in the appropriate way, depending on the structure of the project and its source files. If extra command line options need to be passed to the `moc` tool, they can be specified in the `AUTOMOC_MOC_OPTIONS` target property.

In the simplest scenario, a class like the one above is defined in a header and uses the `Q_OBJECT` macro. No other project source files make any assumptions about the file name(s) that `moc` will generate. The project lets `AUTOMOC` take care of compiling the generated files and linking them into the target. This is very simple to set up and gives `AUTOMOC` the most control over the way the generated code is added to the build.

```
find_package(Qt6 REQUIRED COMPONENTS Core)

# This also handles setting CMAKE_AUTOMOC to true
qt_standard_project_setup()

qt_add_executable(MyQtApp
    main.cpp
    myclass.cpp
    myclass.h
)
target_link_libraries(MyQtApp PRIVATE Qt6::Core)
```

One weakness of the above approach is that, with more recent CMake versions, all generated sources may be combined into a single implementation file. If the number of classes processed by AUTOMOC in this way is very large, it can put pressure on compiler resources, potentially even causing build failure in extreme cases. At the very least, it can make larger builds less efficient. Therefore, it may be desirable for the generated files to be compiled individually to take advantage of build parallelism and reduce resource requirements. One way to achieve that is for project sources to explicitly include the generated sources themselves rather than leaving AUTOMOC to add them to the build. A target can have a C++ source file which contains a line like the following (basename is just a placeholder in this example):

```
basename.cpp
#include "moc_basename.cpp"
```

If a file called `basename.h` is found (or with any other recognized header file extension), then AUTOMOC will run `moc` on that header such that it generates a file called `moc_basename.cpp`. Since the implementation file already pulls in that generated file via an `#include` statement, AUTOMOC doesn't have to do anything more to add it to the build. It will already be compiled as part of `basename.cpp`. In other words, adding an include for `moc_basename.cpp` makes that source file take over adding the generated file to the build instead of letting AUTOMOC combine it with other generated files. An added advantage is that it integrates quite naturally with CMake's unity build support (see [Section 26.1, “Unity Builds”](#)). The generated `moc_basename.cpp` effectively becomes part of the `basename.cpp` file it belongs to. Unity builds have a configurable limit to how many target sources will be merged into one batch, so this will conveniently also limit how many generated `moc_*.cpp` files get combined into one compilation unit.

In some cases, a private class may be declared in a C++ implementation file rather than in a header. If such a class uses `Q_OBJECT`, `moc` must be run on that C++ file. To account for this, if a source file contains a line that includes a `.moc` file like shown just below, AUTOMOC will run `moc` on that source file even if it isn't a header. In such cases, it will use the specified file name for the generated code:

```
#include "basename.moc"
```

Again, the source file pulls in the generated code on its own, so AUTOMOC doesn't have to do anything more to add it to the build. That has the same benefit for unity builds as mentioned previously.

By default, AUTOMOC scans for the macros Q_OBJECT, Q_GADGET, and Q_NAMESPACE. CMake 3.17 added Q_NAMESPACE_EXPORT to this list as well. From CMake 3.10, this list of macro names is taken from the AUTOMOC_MACRO_NAMES target property, which is initialized from the CMAKE_AUTOMOC_MACRO_NAMES variable when the target is created. CMake 3.27 added the INTERFACE_AUTOMOC_MACRO_NAMES target property, which allows targets to propagate a set of macro names to its consumers.

For most projects, the default macro names are fine. If the conventional macro names are embedded within wrapper macros, the names of those wrapper macros need to be added to AUTOMOC_MACRO_NAMES or INTERFACE_AUTOMOC_MACRO_NAMES. The following contrived example demonstrates such a scenario:

mywrapper.h

```
#define MY_WRAPPER Q_OBJECT
```

someclass.cpp

```
#include mywrapper.h

class SomeClass : public QObject
{
    MY_WRAPPER
public:
```

```
// ...  
};
```

For such a case, the project might handle this by adding the wrapper macro to the global defaults:

```
# Works for CMake 3.10 or later  
list(APPEND CMAKE_AUTOMOC_MACRO_NAMES MY_WRAPPER)
```

All targets in the build would then recognize `MY_WRAPPER` as a macro name. If CMake 3.27 or later can be assumed, a better approach may be to set the `INTERFACE_AUTOMOC_MACRO_NAMES` property on the target to which `SomeClass` belongs. Consumers of that target would then automatically have the `MY_WRAPPER` custom name added as a usage requirement.

```
add_library(SomeClassWithWrapper ...)  
  
# Recognize MY_WRAPPER when building the target  
set_property(TARGET SomeClassWithWrapper APPEND PROPERTY  
    AUTOMOC_MACRO_NAMES MY_WRAPPER  
)  
  
# Recognize MY_WRAPPER when building consumers.  
# This requires CMake 3.27 or later.  
set_property(TARGET SomeClassWithWrapper APPEND PROPERTY  
    INTERFACE_AUTOMOC_MACRO_NAMES MY_WRAPPER  
)
```

If the wrapper macro refers to a file name that should be considered a dependency for the `moc` generation, the `AUTOMOC_DEPEND_FILTERS` target property should be used to express that dependency. This property is seldom needed, so the

interested reader is referred to the official CMake documentation for that property for further details.

When using AUTOMOC, CMake 3.8 and later will generate the `moc_*.cpp` or `*.moc` files in a separate directory set aside for such auto-generated files. That directory will be automatically added to the target's header search path, so the project doesn't need to do anything else. Earlier CMake versions generated files in the current build directory, and that directory is *not* automatically added to the header search path. It is therefore common to see projects written for older CMake and Qt versions set the `CMAKE_INCLUDE_CURRENT_DIR` variable to true so that the current source and build directories are added to the header search path. This is no longer necessary for CMake versions needed by Qt 6, or even recent Qt 5 versions.

In some situations, it may be necessary to prevent `moc` from processing a particular file. This is most easily achieved by setting that file's `SKIP_AUTOMOC` source property to true. If other autogen tools like `uic` and `rcc` should also skip the file, the `SKIP_AUTOGEN` source property can be set to true instead.

```
qt_add_executable(MyApp noMocPlease.cpp noAutoGen.cpp ...)

set_source_files_properties(noMocPlease.cpp PROPERTIES
    SKIP_AUTOMOC TRUE
)
set_source_files_properties(noAutoGen.cpp PROPERTIES
    SKIP_AUTOGEN TRUE
)
```

While setting AUTOMOC to true is the generally recommended way of enabling `moc` to be run on the relevant sources, in very large projects the performance cost of scanning many sources may be non-trivial. If only some sources need `moc` processing and others don't, projects can manually specify which ones to process with the following command provided by the `Core` component instead of using AUTOMOC:

```
qt_wrap_cpp(outVar sources...
    [TARGET target]
    [OPTIONS ...]
    [DEPENDS ...]
)
```

The files to be processed with `moc` should be listed as the `sources`. The resultant set of generated `moc_*.cpp` files will be provided back to the caller in the `outVar` variable. The project is responsible for ensuring that the generated sources listed in that `outVar` variable are added to the build, and at least one target must depend on them. There are a couple of ways this can be done, which are discussed just after the example below.

The `TARGET` keyword is used to specify the target the project will later add the sources to. The paths from that target's `INCLUDE_DIRECTORIES` property will be added to the `moc` header search path. The target's `COMPILE_DEFINITIONS` will also be added to the defines given to `moc`. It is strongly advised to always provide `TARGET` so that `moc` can find all the required headers and make correct decisions based on defined symbols when it

processes sources and headers. Note that providing the TARGET keyword does *not* add the generated sources to that target. This ensures that the project can choose the most appropriate way to bring the generated sources into the build, as discussed further below. The TARGET keyword also does *not* add to the target those sources listed as inputs to the command. The project is still responsible for doing that separately.

Any extra command-line options to be passed to the `moc` tool can be specified after the OPTIONS keyword. The DEPENDS keyword should only be needed if the input files have dependencies on things not otherwise discoverable by CMake or the build tool (see the `qt_wrap_cpp()` documentation for further details).

```
find_package(Qt6 REQUIRED COMPONENTS Core)

qt_add_executable(MyQtApp
    main.cpp
    myclass.cpp
    myclass.h
)

# Process moc manually rather than using AUTOMOC
set_target_properties(MyQtApp PROPERTIES AUTOMOC FALSE)
qt_wrap_cpp(genMocs myclass.h TARGET MyQtApp)
target_sources(MyQtApp PRIVATE ${genMocs})
```

The above example shows one way to add the generated sources to the target. Another way to add them to the build is to `#include` the generated `moc_*.cpp` file within one of the existing source files and create a custom target that depends on the files

listed in `outVar`. The custom target is needed to ensure that build rules are created for the custom `moc` execution steps. Note that the `qt_wrap_cpp()` command will generate its output files in the current build directory similar to the `AUTOMOC` behavior of CMake 3.7 and earlier, so `CMAKE_INCLUDE_CURRENT_DIR` may be needed if using this method. Such an arrangement may look something like this:

```
find_package(Qt6 REQUIRED COMPONENTS Core)

set(CMAKE_INCLUDE_CURRENT_DIR YES)
qt_add_executable(MyQtApp
    main.cpp
    myclass.cpp
    myclass.h
)

set_target_properties(MyQtApp PROPERTIES AUTOMOC FALSE)
qt_wrap_cpp(genMocs myclass.h TARGET MyQtApp)
add_custom_target(MyMocs DEPENDS ${genMocs})
```

myclass.cpp

```
#include "moc_myclass.cpp"
// Rest of the file as normal...
```

The first method is simpler, whereas the second method may be useful if `AUTOMOC` had been used previously and the source files were already modified to `#include` the generated `moc_*.cpp` files directly. Either method should integrate with unity builds in a natural way.

45.5.2. Widgets

Qt GUI applications can be based on different UI technologies. They can use the QML declarative language, widgets based on the C++ QWidget hierarchy, or sometimes a combination of both. CMake provides no QML support directly, that all comes from Qt and is not discussed further in this book. See the Qt documentation for full details on CMake support for QML.

Widgets can be implemented purely in C++ code, but they can also be defined using an XML-based UI description file. These UI files typically have a `.ui` file extension and are processed by the `uic` tool to produce C++ code. That generated C++ code is then compiled into the project just like any other source file.

The `uic` tool has many similarities to `moc`, both in the way the tools work and the CMake support available. CMake provides the `AUTOUIC` target property which fulfills a very similar role to `AUTOMOC`. The `AUTOUIC` property is initialized from the value of the `CMAKE_AUTOUIC` variable when the target is created. When `AUTOUIC` is set to true, CMake will scan that target's source files at build time looking for `#include` statements that pull in header files of the form `ui_basename.h`. When it finds such statements, it searches for a matching `basename.ui` file in the same directory, or any directories listed in that target's `AUTOUIC_SEARCH_PATHS` target property. If the `#include` statement has a path component before the `ui_basename.h`, the search will be performed with and without that path. If a `basename.ui` file is found, it will be processed with the `uic` tool to generate the header.

```
find_package(Qt6 REQUIRED COMPONENTS Widgets Core)

# This also handles setting CMAKE_AUTOUIC to true
qt_standard_project_setup()

qt_add_executable(MyQtApp
    main.cpp
    mainwindow.cpp
    mainwindow.h
)
target_link_libraries(MyQtApp PRIVATE
    Qt6::Widgets
    Qt6::Core
)
```

When using AUTOUIC, CMake 3.8 and later will generate the `ui_*.h` files in a separate directory set aside for such auto-generated files. The behavior is exactly the same as for AUTOMOC, with that directory being automatically added to the target's header search path. Again, projects written for older CMake versions may set the `CMAKE_INCLUDE_CURRENT_DIR` variable to true, but this should no longer be necessary with CMake versions required for Qt 6.

In another similarity to AUTOMOC, if a source file should not be scanned by AUTOUIC for some reason, its `SKIP_AUTOUIC` source property can be set to true. If that source file should also be skipped by other Qt tools like `moc` and `rcc`, the `SKIP_AUTOGEN` source property should be set to true instead.

In some projects, it may be necessary to customize the command-line options given to `uic`. For example, the `--tr`

option can be used to specify a different translation function. Such command-line options can be specified in the AUTOUIC_OPTIONS target property, which takes its initial value from the CMAKE_AUTOUIC_OPTIONS variable when the target is created. In addition, a target can enforce uic options transitively on anything that links to it by setting the INTERFACE_AUTOUIC_OPTIONS target property. This is useful, for example, when the target itself provides the translation function, and it wants to ensure that libraries that link to it will use that translation function instead of the default one. The CMake documentation contains examples of this scenario in its Qt manual.

The use of AUTOUIC on large projects can have similar performance implications as AUTOMOC. If a project wants to avoid the automatic source scanning and specify the .ui files to be processed directly, it can do so with the command provided by the Widgets component:

```
qt_wrap_ui(outVar uiFiles... [OPTIONS ...])
```

Unlike `qt_wrap_cpp()` which produces .cpp files, the `qt_wrap_ui()` command produces headers. The list of headers provided back to the caller in the output variable should be added directly to a target to ensure that the custom build rules created by `qt_wrap_ui()` are applied.

```
qt_wrap_ui(genUiHeaders mainwindow.ui)
qt_add_executable(MyQtApp
    main.cpp
    mainwindow.cpp
    mainwindow.h
    ${genUiHeaders}
)
```

Regardless of whether AUTOUIC is used or not, projects may choose to list .ui files as sources directly for a target. This will not affect how those files are processed, but it does make those files show up in the list of sources in some IDE tools. Projects may even want to define a source group to improve the organization within some IDEs. For example:

```
source_group("UI Files" REGULAR_EXPRESSION [.*\.ui])
```

45.5.3. Resources

With Qt 5 and earlier, Qt resources were typically defined in *.qrc files. These are XML descriptions of other files (images, .qml files, etc.) which the application will access using the Qt resource system. These .qrc files need to be processed by the rcc tool, which generates either a source file embedding the resources as C++ code, or a binary file that can be dynamically loaded at run time.

With Qt 6, manually written .qrc files are usually not necessary. Resources can instead be added directly with the `qt_add_resources()` command, which is provided by the Core Qt

module. There are two forms of the command, but only the following form should be used by Qt 6 projects (the other form was provided by Qt 5 and requires .qrc files):

```
qt_add_resources(target resourceName
    FILES files...
    PREFIX prefix      # Optional with Qt 6.5 or later
    [BIG_RESOURCES]
    [otherOptions...]
)
```

Internally, this command will generate a .qrc file listing all the files and pass that off to rcc for processing. The generated .qrc file will use resourceName as its resource name, and the sources generated by rcc will be automatically added to the specified target. If BIG_RESOURCES is specified, rcc will generate object files directly instead of generating C++ sources to be compiled (see the Qt documentation for limitations of this keyword). BIG_RESOURCES may be necessary when embedding large assets, such as image files or textures. Generating object files directly can avoid time-consuming compilation of large generated C++ sources and potentially avoid out-of-memory issues.

The prefix is also included in the generated .qrc file, but it can be omitted with Qt 6.5 or later. When no PREFIX ... is given, the default is taken from the QT_RESOURCE_PREFIX target property, or / will be used if the target property is not defined. The command supports a few other options, which are detailed in the Qt documentation.

```
qt_add_executable(MyQtApp ...)

qt_add_resources(MyQtApp images
PREFIX /images
FILES
    sample.png
    screenshot.png
)
```

With Qt 5 and earlier, an older form of the `qt_add_resources()` command (not discussed here) or the AUTORCC functionality had to be used. AUTORCC operates in a similar way to AUTOMOC and AUTOUIC:

```
# Qt 5 example
set(CMAKE_AUTORCC YES)
add_executable(MyQtApp
    main.cpp
    myclass.cpp
    myclass.h
    myApp.qrc
)
```

AUTORCC processes .qrc files listed as target sources. For each .qrc file, a C++ source file is generated and automatically added to the target. The AUTORCC property takes its initial value from the `CMAKE_AUTORCC` variable when the target is created. Command line options for `rcc` can be provided in the `AUTORCC_OPTIONS` target property, but this should not typically be required. Similar to the other autogen capabilities, AUTORCC can be skipped for a particular .qrc file by setting its `SKIP_AUTORCC` source file property, or by setting `SKIP_AUTOGEN` if it should be

skipped by `moc` and `uic` as well. Projects migrated from Qt 5 to Qt 6 may still use `AUTORCC`, but they should ideally be updated to use `qt_add_resources()` instead.

Qt also supports the creation of a binary version of resources to be loaded dynamically at run time:

```
qt_add_binary_resources(target qrcFiles...
    [OPTIONS ...]
    [DESTINATION rccFile]
)
```

The `qt_add_binary_resources()` command, available since Qt 5.12, requires the project to once again go back to the old method of explicitly providing a `.qrc` file listing the set of resources. Instead of generating C++ sources to link into a target, it produces a single `.rcc` file which can be loaded by the application at run time. The command creates the named target as part of the call. The project must then ensure that either some other target depends on the created target, or another target must depend on the generated `.rcc` file. This ensures the `.rcc` file is generated by the build.

```
qt_add_binary_resources(resLoadable runtimeLoadable.qrc
    DESTINATION runtimeLoadable.rcc
)

qt_add_executable(MyQtApp MACOSX_BUNDLE
    ${CMAKE_CURRENT_BINARY_DIR}/runtimeLoadable.rcc
    ...
)
```

```
# Include generated .rcc file in the app bundle on Apple
set_target_properties(MyQtApp PROPERTIES
    RESOURCE
        ${CMAKE_CURRENT_BINARY_DIR}/runtimeLoadable.rcc
)
```

Note in the above how the generated `runtimeLoadable.rcc` file is added to the `MyQtApp` target. This satisfies the requirement that a target must depend on the generated `.rcc` file. Another reason for using that approach is so that the `.rcc` file can be listed in the target's `RESOURCE` property, which is a requirement for ensuring the file is installed as part of the target on Apple platforms. See [Section 25.2.2, “Sources, Resources And Other Files”](#) for a related discussion of other ways that resources can be handled on Apple platforms.

45.6. Translations

A core part of Qt is its ability to provide localized text. Strings are wrapped with a call to a special translation function in the C++ code, then a separate tool named `lupdate` is run on the code to produce one or more separate `.ts` files which can be given to a translator. The tool can also process other file types, such as QML, UI, and resource files. Each `.ts` file is updated by the translator with translations for a given language. At some point, a tool named `lrelease` is run on the `.ts` files to produce a set of `.qm` translation files, which are distributed with the application. The `.qm` file format is a more efficient format intended only for run time, whereas `.ts` files are intended for translators to load

into the Qt Linguist application. The `lupdate` tool can be re-run at any time to rescan the sources and update the `.ts` files with any changes without losing previously translated text.

CMake does not provide any direct assistance with coordinating the above process, but the `LinguistTools` component does provide a number of CMake commands which make the steps fairly straightforward. Qt 6.2 added the `qt_add_translations()` command as a technology preview, and it became formally supported in Qt 6.7. However, the API introduced in Qt 6.2 was deprecated at the same time, although it still remains supported for the time being. Qt 6.7 added a new signature for `qt_add_translations()`, which should be preferred. The following demonstrates the simplest way to use `qt_add_translations()` with Qt 6.7 or later:

```
# In the top level CMakeLists.txt, soon after project()
find_package(Qt6 REQUIRED COMPONENTS LinguistTools Core)
qt_standard_project_setup(
    I18N_TRANSLATED_LANGUAGES de fr ja
)

# Define all project targets, possibly in subdirectories...

# Now process translations for the whole project
qt_add_translations(TARGETS targets...)
```

When called as shown above, the `qt_add_translations()` command will extract all translatable strings from all source files in the project. It will generate `.ts` files for each of the

languages given with the I18N_TRANSLATED_LANGUAGES option in the call to qt_standard_project_setup(). These .ts files will be converted to .qm files, which are then embedded as resources into each of the listed targets. These embedded resources are made available under the /i18n resource prefix.

An application may want to avoid embedding their translations directly in the application's resources in some cases. For example, larger applications that support many languages may not want to pay the extra memory cost of holding all translations in memory at run time. They may instead choose to keep translation files separate and install them to the file system, then only load the ones needed at run time. The qt_add_translations() command provides the QM_FILES_OUTPUT_VARIABLE keyword for this scenario. When that keyword is given, the generated .qm files are not embedded in any targets. Instead, the list of generated .qm files is passed back to the caller in the nominated variable. It is then up to the project to ensure those files are installed to an appropriate location where the applications can find them at run time.

```
qt_add_translations(  
    TARGETS targets...  
    QM_FILES_OUTPUT_VARIABLE qmFiles  
)  
  
# Over-simplified way of installing the .qm files. It isn't  
# appropriate for Apple app bundles, but is ok elsewhere.  
install(FILES ${qmFiles} DESTINATION translations)
```

When `QM_FILES_OUTPUT_VARIABLE` is specified, all targets that will eventually use the generated `.qm` files must still be listed with the `TARGETS` keyword. Without this, CMake will not be able to set up correct dependencies in all situations. The `qt_add_translations()` command also issues a fatal error if at least one target is not given.

As a special case, if only one target needs to be specified, the `TARGETS` keyword can be omitted and the target can be given as the first argument. Furthermore, instead of letting `qt_add_translations()` work out the set of `.ts` files to generate from the `I18N_TRANSLATED_LANGUAGES` values given to `qt_standard_project_setup()`, the project can specify them with `TS_FILES`. When these behaviors are combined, a `qt_add_translations()` call can be constructed which will work as far back as Qt 6.2, but projects should use the `TARGETS` form shown above if possible.

```
# Only use this form if compatibility with Qt 6.6 or
# earlier is required
qt_add_translations(MyApp
    TS_FILES
        MyApp_de.ts
        MyApp_fr.ts
        MyApp_ja.ts
)
```

`qt_add_translations()` supports many other options, providing a lot of flexibility for translation processing and handling. These options include control over the source files to be scanned, the

location and naming of .ts and .qm files, and much more. These are all discussed in the Qt documentation of the `qt_add_translations()` command.

Internally, `qt_add_translations()` calls a couple of other commands, `qt_add_lupdate()` and `qt_add_lrelease()`, along with the `qt_add_resources()` command discussed earlier in [Section 45.5.3, “Resources”](#). Projects can call these same commands directly instead if they need to handle scenarios not covered by `qt_add_translations()`. The new `qt_add_translations()` API added in Qt 6.7 should be flexible enough for most needs, but projects restricted to the older, less flexible API from Qt 6.2 may need to resort to driving the underlying commands directly. Whether calling the lower level commands directly or not, it may be helpful to read their Qt documentation to gain a better understanding of the options available. The `qt_add_translations()` command provides many of the same options, and will pass them through to the underlying commands.

Historically, handling translations with Qt 5 was much less convenient. Do not be confused by the now deprecated `qt_add_translation()` and `qt_create_translation()` commands. Together, they were intended to provide a similar outcome as `qt_add_translations()`, but they had a number of usability and implementation drawbacks. In particular, it was challenging to handle the creation and updating of .ts files conveniently and

robustly. Avoid those deprecated commands, prefer instead to update existing projects to call `qt_add_translations()` with the Qt 6.7 API.

45.7. Deployment

Installing and packaging Qt applications is a non-trivial exercise due to the various different files that must be included with the main application executable. An incomplete list of things that may need to be installed or packaged includes:

- Qt libraries (unless Qt is linked statically).
- Qt plugins and platform files.
- A `qt.conf` file.
- Translation files from both Qt itself and the application, if not embedded directly as resources.
- Images, icons, or other resources that are not compiled into the application.

The application must also be installed with the right RPATH settings to allow libraries and frameworks to be found when the application is run (see the discussions in [Section 35.2.1, “RPATH”](#) and [Section 35.2.2, “Apple-specific Targets”](#)). On Apple platforms, the unique directory layout of app bundles further complicates deployment (see [Chapter 25, Apple Features](#)).

45.7.1. High Level Deployment Commands

Qt 6 provides considerably more assistance with deployment than earlier Qt versions. In particular, the `qt_generate_deploy_app_script()` handles most of the additional Qt-specific aspects. The command accepts a range of options, but typically only a couple are needed. Its usage is best shown by example:

```
cmake_minimum_required(VERSION 3.24)
project(MyProj)

set(CMAKE_CXX_STANDARD 17)
set(CMAKE_CXX_STANDARD_REQUIRED ON)

find_package(Qt6 REQUIRED COMPONENTS Widgets)
qt_standard_project_setup()

qt_add_executable(MyQtApp MACOSX_BUNDLE WIN32 main.cpp)
target_link_libraries(MyQtApp PRIVATE Qt6::Widgets)
if(APPLE)
    # Assume targeting macOS to keep this example simple
    set_target_properties(MyQtApp PROPERTIES
        INSTALL_RPATH @executable_path/../Frameworks
    )
endif()

install(TARGETS MyQtApp
    BUNDLE DESTINATION .
    RUNTIME DESTINATION ${CMAKE_INSTALL_BINDIR}
)

# Additional Qt-specific logic to be executed after the
# above target install is carried out
qt_generate_deploy_app_script(
    TARGET MyQtApp
    OUTPUT_SCRIPT deployApp
)
install(SCRIPT "${deployApp}")
```

The `qt_generate_deploy_app_script()` command doesn't install things directly. Rather, it writes out a script which must be executed at install time. The name of that script is provided to the caller through the variable given after the `OUTPUT_SCRIPT` keyword. As shown above, the project then uses `install(SCRIPT)` to add that script to the install-time logic.

The generated deployment script does a number of things, all of which are covered in the Qt documentation. Important highlights of those steps include:

- Run-time dependencies of the target are installed. This includes Qt libraries and Qt plugins associated with those libraries.
- Qt translations are installed, except on macOS.
- An appropriate `qt.conf` file may be generated and installed, depending on the target platform.

The logic provided by `qt_generate_deploy_app_script()` works in partnership with `qt_standard_project_setup()`. The latter command sets up defaults for the relative install locations. For Linux applications, it also sets `RPATH` defaults consistent with that installed directory layout. The deployment script generated by `qt_generate_deploy_app_script()` also expects the same installed directory layout, which is relevant for its handling of run-time dependencies and `qt.conf` file generation. And of course, since the deploy script is part of the regular CMake

install process, it also works when producing packages with `cpack` (see [Chapter 36, Packaging](#)).

45.7.2. Qt Deployment Tools

The `qt_generate_deploy_app_script()` command doesn't cover every scenario. It only supports Windows, macOS, and Linux, and only if not cross compiling. Prior to Qt 6.7, it also lacks flexibility for controlling the underlying deployment tools, where such tools are used (Qt 6.7 added support for a `DEPLOY_TOOL_OPTIONS` keyword). For some scenarios, the project may need to call Qt's command line deployment tools directly, which was also the only choice with Qt 5 and earlier. These tools include `macdeployqt`, `windeployqt`, and `androiddeployqt`.

```
macdeployqt [options...] app-bundle  
windeployqt [options] files...  
androiddeployqt options...
```

Each tool has its own set of options, but the general idea is the same. They copy the necessary Qt libraries, frameworks, plugins, and platform files to the relevant location within the application bundle or directory structure. They may also create a simple `qt.conf` file in the appropriate location. Command line options can be used to tailor the tool's behavior, all of which are described in the Qt documentation and the tool's own `--help` output. Access to these options with Qt 6.6 and earlier may be a reason projects invoke the tools directly instead of using

`qt_generate_deploy_app_script()`. The reader should consult the Qt documentation for the specific tool being used to familiarize themselves with its requirements and available options.

Discussion here in this section focuses on the CMake-specific aspects of integrating these tools into a CMake project. It is assumed that the project already defines the relevant `install()` commands and any associated properties are set appropriately. [Chapter 35, *Installing*](#), [Chapter 25, *Apple Features*](#), and [Chapter 21, *Working With Files*](#) are especially relevant.

When running the Qt deployment tool directly, it needs to be invoked at install time after targets and files have been installed. The `install(SCRIPT)` command adds the install-time logic, typically at the end of the directory scope where the application and its files are installed. An example of a fairly generic custom install script invoking the deployment tool for macOS might look like this (code for other platforms has been omitted for brevity):

```
qt_add_executable(MyQtApp MACOSX_BUNDLE WIN32 ...)
set_target_properties(MyQtApp PROPERTIES
    INSTALL_RPATH @executable_path/../Frameworks
)
install(TARGETS MyQtApp BUNDLE DESTINATION . . .)

set(deployApp
    ${CMAKE_CURRENT_BINARY_DIR}/deployapp-<CONFIG>.cmake
)
file(GENERATE OUTPUT "${deployApp}" CONTENT [[
execute_process(
```

```

WORKING_DIRECTORY ${CMAKE_INSTALL_PREFIX}
COMMAND "<TARGET_FILE:Qt6::macdeployqt>" 
    MyQtApp.app
    -verbose=2
    "-codesign=Apple Development"
COMMAND_ERROR_IS_FATAL LAST
)
])
install(SCRIPT "${deployApp}")

```

It is worth noting that the command-line options passed to `macdeployqt` can be used to do things like handle code signing (shown in the above example) and to skip plugins that do not meet app store requirements due to their use of private APIs. See the `macdeployqt` help for details.

The above pattern would be very similar for `windployqt` as well. The main differences would be:

- The `INSTALL_RPATH` target property would be ignored.
- The `COMMAND` would use `Qt6::windployqt` instead of `Qt6::macdeployqt`.
- The command-line options would be specific to the `windployqt` tool.

The `windployqt` tool uses a different default directory layout to `qt_standard_project_setup()` and CMake's `GNUInstallDirs` module. The tool assumes the application binary is at the base install location instead of in a `bin` subdirectory below that point. Command-line options can be used to coerce the tool to produce

a layout more closely aligned with CMake's defaults if required. For example, if the `MyQtApp` target in the earlier example is using the standard `GNUInstallDirs` layout described in [Section 35.1, “Directory Layout”](#) (which `qt_standard_project_setup()` establishes by default), the following set of `windeployqt` command line options could be used:

```
set(deployApp
    ${CMAKE_CURRENT_BINARY_DIR}/deployapp-$<CONFIG>.cmake
)

file(GENERATE OUTPUT "${deployApp}" CONTENT [[
execute_process(
    WORKING_DIRECTORY ${CMAKE_INSTALL_PREFIX}
    COMMAND "<TARGET_FILE:Qt6::windeployqt>"
        bin/MyQtApp.exe
        --dir .
        --libdir bin
        --plugindir plugins
    COMMAND_ERROR_IS_FATAL LAST
)
]]
)
install(SCRIPT "${deployApp}")
```

The other step required is to install a `qt.conf` file that accounts for the installed layout changes discussed above. It should be installed to the same directory as the application binary, which would be in the `bin` directory for the standard directory layout.

The `windeployqt` tool doesn't write a `qt.conf` file, so the project has to create one itself. Only a very minimal file is needed

though, typically containing just a [Paths] section with nothing more than the Prefix:

qt.conf

```
[Paths]
Prefix = ..
```

The androiddeployqt tool is a little different. With Qt 6, it is typically executed at build time rather than as part of an install step. Build targets like aab or apk take care of invoking the deployment tool with appropriate arguments. Much of the extra setup is provided by `qt_add_executable()` and various target properties (see the Qt documentation for details).

Qt does not provide an official deployment tool for Linux. There is a community-supported linuxdeployqt tool, but it is not officially endorsed and has some philosophical and design differences compared to the official Qt tools. Projects will likely need to handle all aspects of Linux deployment themselves. That said, the `qt_generate_deploy_app_script()` command does support Linux, and it may be enough for simple cases.

45.7.3. Deploying Translation Files

Embedding translation files directly in an application's executable is by far the simplest way to deploy them. They require no special handling, since they are part of the application itself. When an application does not embed its

translation files directly in the application's executable, its translation files must be deployed along with the application.

Deploying translation files is similar to installing any other arbitrary file or resource, but the translation files that come with Qt itself may require special handling. Qt splits its translation files based on components, but there can be advantages to merging the files the application needs into one file per translated language for deployment. This makes development and deployment easier because only one file of the form `qt_xx.qm` needs to be loaded at runtime to handle Qt's translations. The `windeployqt` tool handles this automatically and will create these translation files by default, but it can be disabled if desired. The `macdeployqt` tool does not offer this functionality, so projects would need to implement it themselves.

The `lconvert` tool provided by Qt can be used to merge the appropriate `.qm` files. This can be done at install time, but it must be executed after the target is installed and before the deployment tool or generated deployment script. When using Qt 6.7 or later, the `QT_I18N_TRANSLATED_LANGUAGES` and `QT_I18N_SOURCE_LANGUAGE` variables will be defined by the `qt_standard_project_setup()` command based on the arguments given to it. All languages listed in these variables must be deployed. It may be tempting to omit the `QT_I18N_SOURCE_LANGUAGE`, but doing so can lead to a surprising

language selection for UI elements at run time on Apple platforms.

The following example combines the Qt base language file with the translations for the Qt Multimedia module. It uses generator expressions that require CMake 3.24 or later to keep the example concise. Earlier CMake versions can be supported with slightly more verbose logic.

merge_qm.cmake.in

```
# Assuming Qt6::Core is a macOS framework
set(inDir
"${PATH:NORMAL_PATH,${TARGET_FILE_DIR:Qt6::Core}/../../../../translations}")
set(outDir "${CMAKE_INSTALL_PREFIX}/MyQtApp.app/Contents/translations")

file(MAKE_DIRECTORY "${outDir}")

# These variables require Qt 6.7 or later
set(deployLanguages
@QT_I18N_SOURCE_LANGUAGE@
@QT_I18N_TRANSLATED_LANGUAGES@
)

foreach(lang IN LISTS deployLanguages)
execute_process(
    COMMAND "${TARGET_FILE:Qt6::lconvert}"
        -o ${outDir}/qt_${lang}.qm
        ${inDir}/qtbase_${lang}.qm
        ${inDir}/qtmultimedia_${lang}.qm
    RESULT_VARIABLE result
    COMMAND_ERROR_IS_FATAL LAST
)
endforeach()
```

CMakeLists.txt

```

# See earlier sections for code leading up to this point

qt_standard_project_setup(
    I18N_TRANSLATED_LANGUAGES de fr ja
)

# Defining MyQtApp omitted, see earlier sections...
install(TARGETS MyQtApp BUNDLE DESTINATION . . .)

configure_file(merge_qm.cmake.in merge_qm.cmake.in @ONLY)
file(GENERATE
    OUTPUT ${CMAKE_CURRENT_BINARY_DIR}/merge_qm.cmake
    INPUT ${CMAKE_CURRENT_BINARY_DIR}/merge_qm.cmake.in
)
install(SCRIPT "${CMAKE_CURRENT_BINARY_DIR}/merge_qm.cmake")

# Now perform the rest of the deployment, either using the
# helper command as shown here, or a custom deploy script.
qt_generate_deploy_app_script(
    TARGET MyQtApp
    OUTPUT_SCRIPT deployApp
)
install(SCRIPT "${deployApp}")

```

The above example shows how to install the translation files to the translations directory. Assuming the project is following the standard layout as recommended in [Section 35.1, “Directory Layout”](#), this matches the default location used by `QLibraryInfo` and `qt.conf` files. As a result, the project does not need to provide its own custom `qt.conf` file, the one provided by `macdeployqt` is sufficient. Note that the deploy tool doesn’t typically provide a way to change the `qt.conf` file it produces. It may issue warnings if the project tries to install its own, so following the defaults is desirable. On the other hand, the

default translations directory doesn't follow Apple guidelines for how to structure a proper app bundle. If this is a concern, the application may choose to put the translations under the Resources directory and add that to the relevant translations search path using `QDir::addSearchPath()`.

For more advanced use cases, Qt 6.5 provides a `qt_deploy_translations()` command as a technology preview. It is used internally by commands like `qt_generate_deploy_app_script()`, and it supports deploying translations on Windows, macOS and Linux.

45.8. Recommended Practices

Projects should be moving to Qt 6, if not already there. Qt 6 has had multiple LTS releases, so it should be mature enough for typical production use. The considerably improved CMake support available with Qt 6 is further incentive to move on from Qt 5. To be able to take the most advantage of these features, CMake 3.24 or later is strongly recommended.

Do not mix Qt 5 and Qt 6 in the one project. Also prefer to move on from Qt 5 completely rather than trying to allow the project to be built with either Qt 5 or Qt 6. Switching exclusively to Qt 6 will allow the project to take full advantage of the improved CMake API provided.

When bringing Qt into a project with `find_package()`, prefer to find the `Qt6` umbrella package and specify `COMPONENTS` in that one call rather than finding each component as its own separate `find_package()` call. This communicates the intent more clearly and is more robust, since it ensures all Qt components come from the same Qt installation.

Avoid referring to things Qt provides through variables. Instead, prefer to use the imported targets like `Qt6::Core`, `Qt6::Gui`, and so on. The imported targets are much more robust and more convenient to use, as they come with transitive properties that greatly simplify the task of defining targets which link against Qt libraries.

Prefer to use the CMake API provided by Qt for defining targets. Use `qt_add_executable()` instead of `add_executable()`, and `qt_add_library()` or `qt_add_plugin()` instead of `add_library()`. These more specific commands handle a number of Qt-specific tasks for the target, such as finalization. They may also select a more appropriate type of target in some cases (e.g. `qt_add_executable()` actually creates a library when targeting Android).

Always call `qt_standard_project_setup()` as early as possible in the project's top level `CMakeLists.txt` file. This would normally be done immediately after the `find_package(Qt6)` call. This establishes defaults that are more suitable for Qt projects, as

well as setting up some overall project finalization tasks for some target platforms. It must be called before any targets are defined with commands like `qt_add_executable()` or `qt_add_library()`.

If the project supports translations, always specify the set of supported languages with the `I18N_TRANSLATED_LANGUAGES` option in the call to `qt_standard_project_setup()`. This prepares the project's targets for the supported languages. For example, on Apple platforms, the language information will be included in a target's `Info.plist` file.

Projects should prefer to use `AUTOMOC` and `AUTOUIIC` over the manual commands provided by Qt. The `qt_standard_project_setup()` command enables them by default. These features are considerably simpler and more concise than calling the manual wrapper commands `qt_wrap_cpp()` and `qt_wrap_ui()`. Only where it is clear that the impact on build performance warrants the extra effort, or where the desired processing isn't supported (e.g. dynamically loadable resources) should either of the two wrapper commands be used.

Prefer to use `qt_add_resources()` to add resources to a target. With Qt 5 and earlier, `AUTORCC` was the preferred method, but that required writing a `.qrc` file and did not handle generated resources very well. The `qt_add_resources()` command is more

flexible, more direct, and more consistent with how CMake projects add files to targets more generally.

Consider using `qt_add_translations()` to robustly add translations to targets. It greatly simplifies the handling of `.ts` and `.qm` files, including embedding them into the application's resources. Avoid the `qt_add_translation()` and `qt_create_translation()` commands, which were available with Qt 5, but have robustness and usability problems. Also avoid the deprecated, more target-centric form of `qt_add_translations()`, which was added in Qt 6.2 as a technology preview. Prefer the new project-wide form added in Qt 6.7, which is better aligned with the needs of most production-grade projects.

If a project is constrained to using Qt versions older than 6.7, the older `qt_add_translations()` API requires specifying `.ts` files directly. For such files, prefer to follow the same default naming convention that Qt Linguist uses. Translation files should ideally be named according to the pattern `something_xx_YY.ts`, where `xx` is a lowercase ISO639 language code, and `YY` is an uppercase ISO3166 country code. The `_YY` part can be omitted if country-based localization isn't needed. Avoid using more than one period character in the name. In particular, do not use names of the form `something.xx_YY.ts`, even though some examples in the Qt documentation do this. Historically, those names triggered a bug in some Qt-provided CMake commands when using Qt 5.12.4 or earlier, which could break the build.

Prefer to use the deployment tools provided by Qt where they are available. Tools like `macdeployqt`, `windeployqt`, and `androiddeployqt` handle much of the Qt-specific aspects of deploying an application, freeing the project from having to maintain logic for the different platforms and Qt versions. Consider using the `qt_generate_deploy_app_script()` convenience command instead of running the deployment tools directly. When it meets the project's needs, that command greatly simplifies the deployment task. If specific options need to be passed to the underlying `macdeployqt` or `windeployqt` tools, use Qt 6.7 or later and pass the options to `qt_generate_deploy_app_script()` with `DEPLOY_TOOL_OPTIONS`.

If memory and executable size constraints allow it, prefer to embed localizations directly in the application. This leads to much simpler deployment and application logic. Where localizations are not embedded directly in an application's executable, ensure that Qt's own `.qm` files are included in the deployment, and that the application knows where to find them. Handling of these Qt-provided `.qm` files is not covered by all deployment tools, so projects may need to implement that for themselves.

If creating packages for a Qt GUI application, consider using the [IFW package generator](#), which uses the Qt Installer Framework. The same end user experience can be provided across all desktop platforms, the look and feel can be customized to

match the application, and localization of the installer is supported.

APPENDIX A: FULL COMPILER CACHE EXAMPLE

This example combines the individual generator-specific parts described in [Section 26.5, “Compiler Caches”](#) into a single function. It provides a common default set of Ccache environment variables, but allows the developer to override them. This would be suitable for production use in most projects.

The function also forces the use of the Multi-ToolTask scheduler for the Visual Studio generator, which is essential for Ccache to make efficient use of CPU resources. See [Section 26.3.3, “Visual Studio Generators”](#) for more details about that scheduler.

In keeping with the principles discussed in [Chapter 40, Making Projects Consumable](#), especially those in [Section 40.2, “Don’t Assume A Top Level Build”](#), it would only be appropriate to set up compiler launchers if the caller is the top level project. The function includes a check and does nothing if called from anywhere other than the top level.

cmake/UseCompilerCache.cmake

```

cmake_minimum_required(VERSION 3.20...3.26)

function(useCompilerCache)
  if(NOT CMAKE_CURRENT_SOURCE_DIR STREQUAL CMAKE_SOURCE_DIR)
    return()
  endif()

  find_program(CCACHE_EXECUTABLE ccache)
  if(NOT CCACHE_EXECUTABLE)
    return()
  endif()

# Ccache 4.7.4 manual says -fno-pch-timestamp is required
# for Clang
foreach(lang IN ITEMS C CXX OBJC OBJCXX)
  if(CMAKE_${lang}_COMPILER_ID MATCHES "Clang")
    add_compile_options(
      "$<${COMPILE_LANGUAGE};${lang}>:SHELL:-Xclang -fno-pch-timestamp"
    )
  endif()
endforeach()

if(MSVC)
  # Disable use of separate PDB, Ccache won't cache
  # things otherwise
  foreach(lang IN ITEMS C CXX)
    foreach(config IN LISTS
      CMAKE_BUILD_TYPE CMAKE_CONFIGURATION_TYPES)
      set(var CMAKE_${lang}_FLAGS)
      if(NOT config STREQUAL "")
        string(TOUPPER "${config}" config)
        string(APPEND var "_${config}")
      endif()
      string(REGEX REPLACE "[/-]Z[ti]" "-Z7"
        ${var} "${${var}}"
      )
      set(${var} "${${var}}" PARENT_SCOPE)
    endforeach()
  endforeach()
endif()

```

```

if(DEFINED CMAKE_MSVC_DEBUG_INFORMATION_FORMAT)
    string(REGEX REPLACE
        "ProgramDatabase|EditAndContinue" "Embedded"
        replaced "${CMAKE_MSVC_DEBUG_INFORMATION_FORMAT}"
    )
    set(CMAKE_MSVC_DEBUG_INFORMATION_FORMAT "${replaced}"
        PARENT_SCOPE
    )
else()
    set(CMAKE_MSVC_DEBUG_INFORMATION_FORMAT
        "$<${CONFIG}:Debug,RelWithDebInfo>:Embedded"
        PARENT_SCOPE
    )
endif()
endif()

# Use a cache variable so the user can override this
set(CCACHE_ENV
    CCACHE_SLOPPINESS=pchDefines,time_macros
    CACHE STRING
    "List of environment variables for ccache, each in key=value form"
)

if(CMAKE_GENERATOR MATCHES "Ninja|Makefiles")

    foreach(lang IN ITEMS C CXX OBJC OBJCXX CUDA)
        set(CMAKE_${lang}_COMPILER_LAUNCHER
            ${CMAKE_COMMAND} -E env
            ${CCACHE_ENV} ${CCACHE_EXECUTABLE}
        PARENT_SCOPE
    )
    endforeach()
elseif(CMAKE_GENERATOR STREQUAL Xcode)

    foreach(lang IN ITEMS C CXX)
        list(JOIN CCACHE_ENV "\nexport " setEnv)
        if(NOT setEnv STREQUAL "")
            string(PREPEND setEnv "export ")
        endif()
        set(launch${lang} ${CMAKE_BINARY_DIR}/launch-${lang})
        file(WRITE ${launch${lang}})

```

```

#!/bin/bash\n"
"${setEnv}\n"
exec "${CCACHE_EXECUTABLE}" "
\"${CMAKE_${lang}_COMPILER}\" \"$@\n"
)
execute_process(COMMAND chmod a+r ${launch${lang}})
endforeach()

set(CMAKE_XCODE_ATTRIBUTE_CC ${launchC}
PARENT_SCOPE)
set(CMAKE_XCODE_ATTRIBUTE_CXX ${launchCXX}
PARENT_SCOPE)
set(CMAKE_XCODE_ATTRIBUTE_LD ${launchC}
PARENT_SCOPE)
set(CMAKE_XCODE_ATTRIBUTE_LDPLUSPLUS ${launchCXX}
PARENT_SCOPE)

elseif(CMAKE_GENERATOR MATCHES "Visual Studio")

cmake_path(NATIVE_PATH CCACHE_EXECUTABLE ccacheExe)
list(JOIN CCACHE_ENV "\nset " setEnv)
if(NOT setEnv STREQUAL "")
  string(PREPEND setEnv "set ")
endif()

# At least one of C or CXX must be enabled
get_property(langs GLOBAL PROPERTY ENABLED_LANGUAGES)
if(CXX IN_LIST langs)
  set(compiler "${CMAKE_CXX_COMPILER}")
else()
  set(compiler "${CMAKE_C_COMPILER}")
endif()
file(WRITE ${CMAKE_BINARY_DIR}/launch-cl.cmd
"@echo off\n"
"${setEnv}\n"
"\${ccacheExe} \"\${compiler}\" %*\n"
)

list(FILTER CMAKE_VS_GLOBALS EXCLUDE
REGEX "^(CLTool(Path|Exe)|Track FileAccess)=.*$"
)

```

```

list(APPEND CMAKE_VS_GLOBALS
    CLToolPath=${CMAKE_BINARY_DIR}
    CLToolExe=launch-cl.cmd
    TrackFileAccess=false
)
if(NOT CMAKE_VS_GLOBALS MATCHES
    "(^|;)UseMultiToolTask=")
    list(APPEND CMAKE_VS_GLOBALS UseMultiToolTask=true)
endif()
if(NOT CMAKE_VS_GLOBALS MATCHES
    "(^|;)EnforceProcessCountAcrossBuilds=")
    list(APPEND CMAKE_VS_GLOBALS
        EnforceProcessCountAcrossBuilds=true
    )
endif()
set(CMAKE_VS_GLOBALS "${CMAKE_VS_GLOBALS}"
    PARENT_SCOPE)

endif()
endfunction()

```

The above function should be called after the first `project()` command, since it needs details of the C and C++ compilers to already be available. The following minimal example demonstrates the usage.

CMakeLists.txt

```

cmake_minimum_required(VERSION 3.20)
project(CompilerCacheExample)

include(cmake/UseCompilerCache.cmake)
useCompilerCache()

# Define targets as usual...
add_executable(AppC main.c ...)
add_executable(AppCXX main.cpp ...)

```

APPENDIX B: SANITIZERS EXAMPLE

This is a more complete example of the one in [Section 33.1.4, “Sanitizer Implementation Strategies”](#). It shows how to set up sanitizers with in-project logic, giving the developer cache options for selecting which sanitizer(s) to enable. Some basic checking of the enabled sanitizers is performed.

When running `ctest` with the tests as defined here, expect to see some test failures with Debug builds. Depending on the configuration being built and the toolchain used, some tests may unexpectedly pass, especially for higher levels of optimization. Sanitizers won’t detect a problem if the test code is optimized in a way that removes the issue expected to be detected. Also, the behavior of the same sanitizer on different platforms or toolchain versions may be different. Consider the code here to be a starting point for experimentation, it is not intended to be a rigorous or exhaustive example.

To use a toolchain file to specify the sanitizer flags instead of using in-project logic, comment out the call to `include(Sanitizers.cmake)` in the `CMakeLists.txt` file.

CMakeLists.txt

```
cmake_minimum_required(VERSION 3.23)
project(MyProj)
enable_testing()

if(PROJECT_IS_TOP_LEVEL)
    include(Sanitizers.cmake)
endif()

# Add dependencies here after flags are already set up...
include(FetchContent)
FetchContent_Declare(
    gtest
    GIT_REPOSITORY https://github.com/google/googletest.git
    GIT_TAG        v1.12.0
)
FetchContent_MakeAvailable(gtest)
include(GoogleTest)

# Add targets and tests...
add_executable(tests tests.cpp)
target_link_libraries(tests PRIVATE GTest::gtest_main)
gtest_discover_tests(tests DISCOVERY_MODE PRE_TEST)
```

Sanitizers.cmake

```
option(ENABLE_ASAN "Enable AddressSanitizer" YES)

if(MSVC)
    if(ENABLE_ASAN)
        string(REPLACE "/RTC1" ""
            CMAKE_C_FLAGS_DEBUG "${CMAKE_C_FLAGS_DEBUG}"
        )
        string(REPLACE "/RTC1" ""
            CMAKE_CXX_FLAGS_DEBUG "${CMAKE_CXX_FLAGS_DEBUG}"
        )
        add_compile_options(
            /fsanitize=address
            /fsanitize-address-use-after-return
        )
    
```

```

endif()

elseif(CMAKE_C_COMPILER_ID MATCHES "GNU|Clang")
    option(ENABLE_LSAN "Enable LeakSanitizer" NO)
    option(ENABLE_TSAN "Enable ThreadSanitizer" NO)
    option(ENABLE_UBSAN "Enable UndefinedBehaviorSanitizer" YES)
    if(NOT APPLE)
        option(ENABLE_MSAN "Enable MemorySanitizer" NO)
    endif()

if((ENABLE_ASAN AND (ENABLE_TSAN OR ENABLE_MSAN)) OR
    (ENABLE_LSAN AND (ENABLE_TSAN OR ENABLE_MSAN)) OR
    (ENABLE_TSAN AND ENABLE_MSAN))
    message(FATAL_ERROR
        "Invalid sanitizer combination:\n"
        "  ENABLE_ASAN: ${ENABLE_ASAN}\n"
        "  ENABLE_LSAN: ${ENABLE_LSAN}\n"
        "  ENABLE_TSAN: ${ENABLE_TSAN}\n"
        "  ENABLE_MSAN: ${ENABLE_MSAN}"
    )
endif()

add_compile_options(
    -fno-omit-frame-pointer
    $<$<BOOL:${ENABLE_ASAN}>:-fsanitize=address>
    $<$<BOOL:${ENABLE_LSAN}>:-fsanitize=leak>
    $<$<BOOL:${ENABLE_MSAN}>:-fsanitize=memory>
    $<$<BOOL:${ENABLE_TSAN}>:-fsanitize=thread>
    $<$<BOOL:${ENABLE_UBSAN}>:-fsanitize=undefined>
)
add_link_options(
    $<$<BOOL:${ENABLE_ASAN}>:-fsanitize=address>
    $<$<BOOL:${ENABLE_LSAN}>:-fsanitize=leak>
    $<$<BOOL:${ENABLE_MSAN}>:-fsanitize=memory>
    $<$<BOOL:${ENABLE_TSAN}>:-fsanitize=thread>
    $<$<BOOL:${ENABLE_UBSAN}>:-fsanitize=undefined>
)
endif()

```

The source code in the following test examples is especially trivial. Almost any level of optimization will likely make some or all of the issues they are intended to trigger disappear. The behavior of some compilers may also mask issues, such as debug builds auto-initializing variables or arrays to zero.

tests.cpp

```
#include <gtest/gtest.h>
#include <iostream>

// Detected by AddressSanitizer, if enabled.
// May also be detected by UndefinedBehaviorSanitizer.
TEST(Sanitizers, AccessOutsideBounds)
{
    int things[10];
    things[10] = 27;
    std::cout << "Unsafe value: " << things[10] << std::endl;
}

// Detected by AddressSanitizer, if enabled
TEST(Sanitizers, UseAfterFree)
{
    int* things = new int;
    *things = 23;
    std::cout << "Before: " << *things << std::endl;
    delete things;
    std::cout << "Boom!" << *things << std::endl;
}

// Detected by MemorySanitizer, if enabled.
// May not be detected in debug builds if compiler zero-initializes "a".
TEST(Sanitizers, UseUninitialized)
{
    int* a = new int[10];
    a[5] = 0;
    int index = 1;
    std::cout << "Uninitialized item " << index << ": " << a[index] <<
    std::endl;
```

```
    delete[] a;  
}
```

APPENDIX C: TIMER DEPENDENCY PROVIDER

This is the full implementation of the example in [Section 41.2.5, “Preserving Variable Values”](#).

```
cmake_minimum_required(VERSION 3.24)

macro(startTimer var)
    string(TIMESTAMP ${var} "%ssec %fusec")
endmacro()

function(reportTimeSince label t0)
    set(regex "([0-9]+)sec ([0-9]+)usec")

    string(REGEX MATCH "${regex}" discard "${t0}")
    set(t0_sec ${CMAKE_MATCH_1})
    set(t0_usec ${CMAKE_MATCH_2})

    string(TIMESTAMP t1 "%ssec %fusec")
    string(REGEX MATCH "${regex}" discard "${t1}")
    set(t1_sec ${CMAKE_MATCH_1})
    set(t1_usec ${CMAKE_MATCH_2})

    math(EXPR dt_sec "${t1_sec} - ${t0_sec}")
    math(EXPR dt_msec "(${t1_usec} - ${t0_usec}) / 1000")
    if(t1_usec LESS t0_usec)
        math(EXPR dt_sec "${dt_sec} - 1")
        math(EXPR dt_msec "${dt_msec} + 1000")
    endif()

```

```

message(STATUS "${label}: ${dt_sec}s ${dt_msec}ms")
endfunction()

macro(timer_provide_dependency method depName)
    startTimer(t0)
    list(APPEND providerVarStack "${t0}")

    if("${method}" STREQUAL "FIND_PACKAGE")
        find_package(${depName} ${ARGN} Bypass_Provider)
    else()
        # FETCHCONTENT_MAKEAVAILABLE_SERIAL
        FetchContent_MakeAvailable(${depName})
    endif()

    list(POP_BACK providerVarStack t0)
    reportTimeSince("Time for ${depName}" "${t0}")
endmacro()

cmake_language(
    SET_DEPENDENCY_PROVIDER timer_provide_dependency
    SUPPORTED_METHODS
        FIND_PACKAGE
        FETCHCONTENT_MAKEAVAILABLE_SERIAL
)

```