Build Systems

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CONTENTS

RPI Open Source Software - Spring 2021

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CHAPTER

ONE

INTRODUCTION

1.1 Reading and Reference Material

- Overview of build systems
  - https://medium.com/@julienjorge/an-overview-of-build-systems-mostly-for-c-projects-ac9931494444
- Makefiles
  - https://www.tutorialspoint.com/makefile/
- CMake
  - https://cmake.org/cmake/help/latest/index.html – read cmake-buildsystem

1.2 What is a Build System?

- Specifies how to turn source files into useful programs.

- Organizes code to share among programs.
- Requirements vary by language, tools, and platform; here we focus on `C` and `C++` languages.

CHAPTER

TWO

MOTIVATION

2.1 One Source File

Consider a source file `hi.c`:

```
#include <stdio.h>
int main() {
  printf("hello\n");
  return 0;
}
```

Compile and run the program:

```
$ cc hi.c -o hi
$ ./hi
hello
```

2.2 Build System: Compiler Driver

The compiler driver is a simple build system.

It runs the compiler and linker internally:

```
$ gcc hi.c -o hi -###
cc1 hi.c -o /tmp/tmp1.s
as -o /tmp/tmp2.o /tmp/tmp1.s
collect2 -o hi /tmp/tmp2.o -lgcc ...
```

2.3 Reusable Source File

Declare a `hello()` function in a `hello.h` header:

```
void hello(void);
```

Implement the function in a `hello.c` source:

```
#include "hello.h"
#include <stdio.h>
void hello(void) {
```

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```
  printf("hello\n");
}
```

Copy `hi.c` to `hi1.c` and update the main program in the `hi1.c` source:

```
#include "hello.h"
int main(void) {
  hello();
  return 0;
}
```

Give both source files to the compiler driver:

```
$ cc hi1.c hello.c -o hi1
$ ./hi1
hello
```

The compiler driver runs the compiler and linker internally:

```
$ gcc hi1.c hello.c -o hi1 -###
cc1 hi1.c -o /tmp/tmp1.s
as -o /tmp/tmp2.o /tmp/tmp1.s
cc1 hello.c -o /tmp/tmp3.s
as -o /tmp/tmp4.o /tmp/tmp3.s
collect2 -o hi1 /tmp/tmp2.o /tmp/tmp4.o -lgcc ...
```

2.4 Sharing Source Files

Now add a `hi2.c` executable sharing the `hello()` function:

```
#include "hello.h"
int main(void) {
  hello();
  hello();
  return 0;
}
```

Use `hello.c` source file for both programs:

```
$ cc hi1.c hello.c -o hi1
$ cc hi2.c hello.c -o hi2
$ ./hi1
hello
$ ./hi2
hello
hello
```

2.5 Build System: Shell Script

List commands in a shell script, e.g. `build.sh`:

```
cc hi1.c hello.c -o hi1
cc hi2.c hello.c -o hi2
```

Run the script to drive the build:

```
$ sh -x build.sh
+ cc hi1.c hello.c -o hi1
+ cc hi2.c hello.c -o hi2
```

2.6 Sharing Source Files

The compiler driver runs the compiler and linker internally:

```
$ gcc hi1.c hello.c -o hi1 -###
cc1 hi1.c -o /tmp/tmp1.s
as -o /tmp/tmp2.o /tmp/tmp1.s
cc1 hello.c -o /tmp/tmp3.s
as -o /tmp/tmp4.o /tmp/tmp3.s
collect2 -o hi1 /tmp/tmp2.o /tmp/tmp4.o -lgcc ...
$ gcc hi2.c hello.c -o hi2 -###
cc1 hi2.c -o /tmp/tmp1.s
as -o /tmp/tmp2.o /tmp/tmp1.s
cc1 hello.c -o /tmp/tmp3.s
as -o /tmp/tmp4.o /tmp/tmp3.s
collect2 -o hi2 /tmp/tmp2.o /tmp/tmp4.o -lgcc ...
```

- Compiles `hello.c` twice.
- Re-uses source file but not compiler output.

2.7 Sharing Object Files

- Compile `hello.c` to an *object file*.
- Use the object file to link each executable.
- Called "separate compilation".

```
$ sh -x build.sh
+ cc -c hello.c -o hello.o
+ cc hi1.c hello.o -o hi1
+ cc hi2.c hello.o -o hi2
$ ./hi1
hello
$ ./hi2
hello
hello
```

The compiler driver runs the compiler and linker internally:

```
$ gcc hello.c -o hello.o -###
cc1 hello.c -o /tmp/ccjdUPnL.s
as --64 -o hello.o /tmp/ccjdUPnL.s
$ gcc hi1.c hello.o -o hi1 -###
cc1 hi1.c -o /tmp/ccYmx5bQ.s
as --64 -o /tmp/ccZsgmJR.o /tmp/ccYmx5bQ.s
collect2 -o hi1 /tmp/ccZsgmJR.o hello.o
$ gcc hi2.c hello.o -o hi2 -###
cc1 hi2.c -o /tmp/cc8bugZV.s
as --64 -o /tmp/cccpkgnU.o /tmp/cc8bugZV.s
collect2 -o hi2 /tmp/cccpkgnU.o hello.o
```

- Compiles `hello.c` only once.

2.8 Sharing Multiple Sources

Split `hello.c` into `hello1.c`:

```
#include "hello.h"
extern void print_hello(const char *s);
void hello(void) {
  print_hello("world");
}
```

and `hello2.c`:

```
#include <stdio.h>
void print_hello(const char *s) {
  printf("hello: %s\n", s);
}
```

```
$ sh -x build.sh
+ cc -c hello1.c -o hello1.o
+ cc -c hello2.c -o hello2.o
+ cc -c hi1.c -o hi1.o
+ cc -c hi2.c -o hi2.o
+ cc hi1.o hello1.o hello2.o -o hi1
+ cc hi2.o hello1.o hello2.o -o hi2
$ ./hi1
hello: world
$ ./hi2
hello: world
hello: world
```

Callers of `hello()` function must use both `hello1.o` and `hello2.o` together, but should not have to know that.

2.9 Static Libraries

Create an archive of object files; use to link executables:

```
$ sh -x build.sh
+ cc -c hello1.c -o hello1.o
+ cc -c hello2.c -o hello2.o
+ ar qc libhello.a hello1.o hello2.o
+ cc -c hi1.c -o hi1.o
+ cc -c hi2.c -o hi2.o
+ cc hi1.o libhello.a -o hi1
+ cc hi2.o libhello.a -o hi2
$ ./hi1
hello: world
$ ./hi2
hello: world
hello: world
```

List the object files in the archive:

```
$ ar t libhello.a
hello1.o
hello2.o
```

2.10 Shared Libraries

Link object files into a shared library; link executables to it:

```
$ sh -x build.sh
+ cc -fPIC -c hello1.c -o hello1.o
+ cc -fPIC -c hello2.c -o hello2.o
+ cc -shared -o libhello.so hello1.o hello2.o
+ cc -c hi1.c -o hi1.o
+ cc -c hi2.c -o hi2.o
+ cc hi1.o libhello.so -o hi1 -Wl,-rpath='$ORIGIN'
+ cc hi2.o libhello.so -o hi2 -Wl,-rpath='$ORIGIN'
$ ./hi1
hello: world
$ ./hi2
hello: world
hello: world
```

For OSX, we need to use:

```
+ cc hi1.o libhello.so -o hi1 -Wl,-rpath .
+ cc hi2.o libhello.so -o hi2 -Wl,-rpath .
```

View dependency of executable on shared library:

```
$ readelf -d hi1 | grep NEEDED
 0x0000000000000001 (NEEDED) Shared library: [libhello.so]
 0x0000000000000001 (NEEDED) Shared library: [libc.so.6]
$ readelf -d hi1 | grep RUNPATH
 0x000000000000000f (RPATH) Library rpath: [$ORIGIN]
```

For OSX, we need to use:

```
$ otool -l hi1
```

2.11 Review of File Types

Source files (`*.c`, `*.cpp`) Define "symbols" implementing functions and storage of global data.

Header files (`*.h`, `*.hpp`) Define interfaces shared among source files (e.g. function prototypes).

Object files (`*.o`, `*.obj` on Windows) Compiler output from source files.

Executables (no extension, `*.exe` on Windows) Object files linked together into programs with `main`.

Static libraries (`*.a`, `*.lib` with MS tools)

- Archives of object files.
- Searched by linker for objects implementing needed symbols.
- All symbols with "extern linkage" exposed publicly.

Shared libraries (`*.so`, `.dylib` on OSX, `*.dll` on Windows)

- Objects linked together into libraries loaded by programs at runtime.
- A subset of symbols with "extern linkage" exposed publicly via explicit markup.
- On Windows, associated "import library" (`.lib`).

2.12 Build System: Shell Script

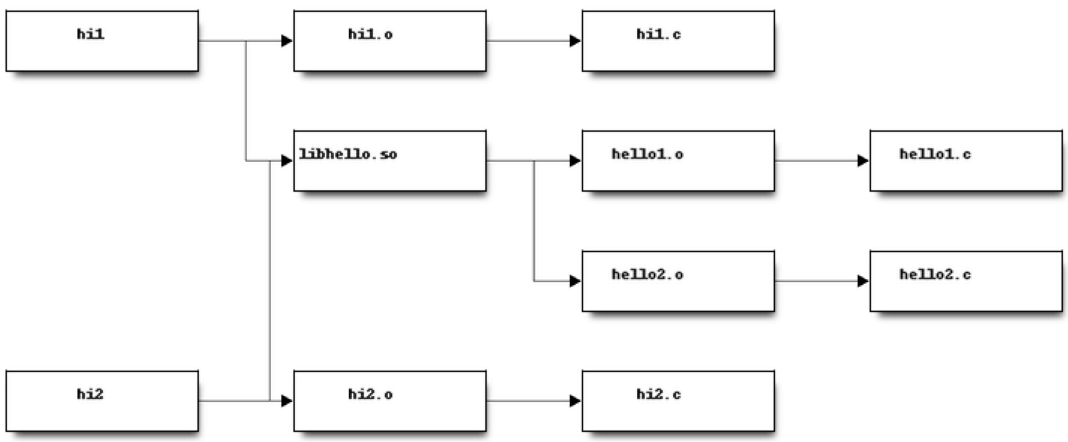
- `build.sh` always runs all commands.
- No concurrency.
- No partial builds.
- No incremental rebuilds.
- Does not scale.
- Rarely used in practice.

CHAPTER

THREE

BUILD SYSTEM: MAKE

3.1 Build Dependencies



3.2 Makefile

A `Makefile` expresses build dependencies:

```
all: hi1 hi2
hi1: hi1.o libhello.so
hi2: hi2.o libhello.so
hi1.o: hi1.c
hi2.o: hi2.c
libhello.so: hello1.o hello2.o
hello1.o: hello1.c
hello2.o: hello2.c
```

A `Makefile` also specifies build commands:

```
all: hi1 hi2
clean:
        rm hi1 hi2 hi1.o hi2.o libhello.so hello1.o hello2.o
hi1: hi1.o libhello.so
```

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```
	cc hi1.o libhello.so -o hi1 -Wl,-rpath='$$ORIGIN'
hi2: hi2.o libhello.so
	cc hi2.o libhello.so -o hi2 -Wl,-rpath='$$ORIGIN'
hi1.o: hi1.c
	cc -c hi1.c -o hi1.o
hi2.o: hi2.c
	cc -c hi2.c -o hi2.o
libhello.so: hello1.o hello2.o
	cc -shared -o libhello.so hello1.o hello2.o
hello1.o: hello1.c
	cc -fPIC -c hello1.c -o hello1.o
hello2.o: hello2.c
	cc -fPIC -c hello2.c -o hello2.o
```

3.3 Run Make Tool

Run `make` tool to drive build process:

```
$ make
cc -c hi1.c -o hi1.o
cc -fPIC -c hello1.c -o hello1.o
cc -fPIC -c hello2.c -o hello2.o
cc -shared -o libhello.so hello1.o hello2.o
cc hi1.o libhello.so -o hi1 -Wl,-rpath='$ORIGIN'
cc -c hi2.c -o hi2.o
cc hi2.o libhello.so -o hi2 -Wl,-rpath='$ORIGIN'
$ ./hi1
hello: world
$ ./hi2
hello: world
hello: world
```

The `make` tool checks timestamps, follows dependencies:

```
$ make
make: Nothing to be done for 'all'.
$ touch hello2.c
$ make
cc -fPIC -c hello2.c -o hello2.o
cc -shared -o libhello.so hello1.o hello2.o
cc hi1.o libhello.so -o hi1 -Wl,-rpath='$ORIGIN'
cc hi2.o libhello.so -o hi2 -Wl,-rpath='$ORIGIN'
$ make
make: Nothing to be done for 'all'.
```

3.4 Implicit Dependencies

Header files (*.h) are *implicit* dependencies of compilation:

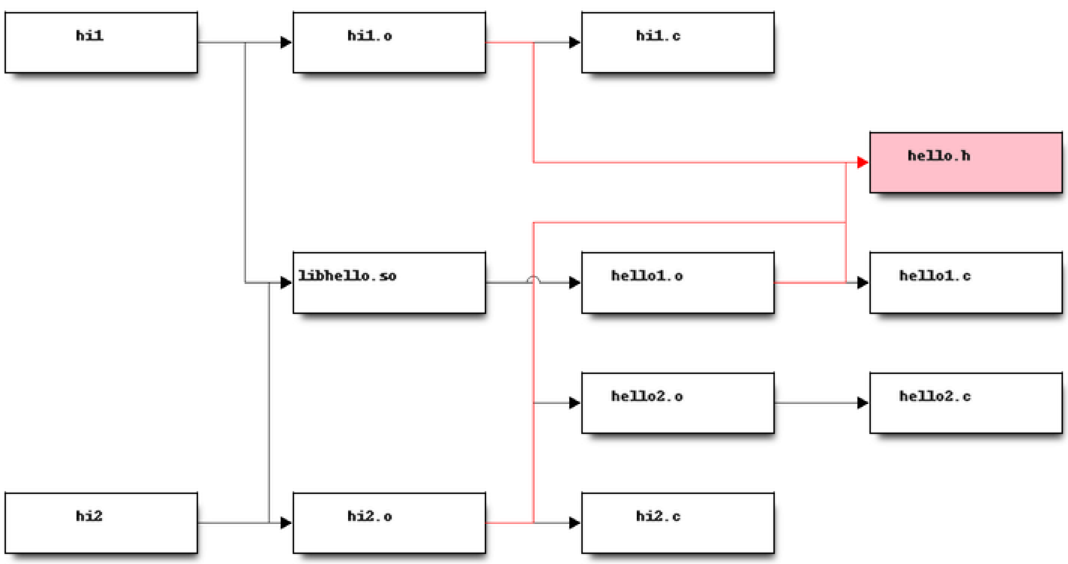
```
$ grep hello.h *.c
hello1.c:#include "hello.h"
hi2.c:#include "hello.h"
hi1.c:#include "hello.h"
```

The compiler can tell us about dependencies:

```
$ gcc -MM hello1.c -MT hello1.o
hello1.o: hello1.c hello.h
```

Implicit dependencies not yet expressed in our `Makefile`:

```
$ touch hello.h
$ make
make: Nothing to be done for 'all'.
```



3.5 Makefile: Implicit Dependencies

Extend our `Makefile` with implicit dependencies:

```
hi1.o: hello.h
hi2.o: hello.h
hello1.o: hello.h
```

```
$ make
cc -c hi1.c -o hi1.o
cc -fPIC -c hello1.c -o hello1.o
```

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```
cc -shared -o libhello.so hello1.o hello2.o
cc hi1.o libhello.so -o hi1 -Wl,-rpath='$ORIGIN'
cc -c hi2.c -o hi2.o
cc hi2.o libhello.so -o hi2 -Wl,-rpath='$ORIGIN'
```

Everything but `hello2.o` rebuilds when `hello.h` changes.

3.6 Build System: Make

- Features:
  - Dependencies enable efficient, concurrent (re-)builds.
- Limitations:
  - Tricky to maintain implicit dependencies.
  - Platform- and tool-specific tables of commands.
  - Build rules do not re-run when commands change.
  - Need manual rules for “install” and “clean” operations.
  - Not reusable with IDEs like Visual Studio and Xcode.

3.7 Build System: MSBuild

Underlies Visual Studio 2010+ builds.

```
<Project DefaultTargets="Build" ToolsVersion="12.0" ...>
  ...
  <ItemGroup>
    <ClCompile Include="hi1.c" />
  </ItemGroup>
  <ItemGroup>
    <ProjectReference Include="hello.vcxproj">
      <Project>158CE2ED-F99F-4D09-A981-CF4C46D9A63B</Project>
    </ProjectReference>
  </ItemGroup>
  ...
</Project>
```

- Features:
  - Create and update through Visual Studio IDE.
  - Handles implicit dependencies automatically.
  - Built-in “clean” operations.
- Limitations:
  - Platform- and tool-specific. Not portable.
  - Need manual rules for “install” operations.
  - Difficult to merge version control branches.

3.8 Example Build Systems

- Make: Canonical dependency-based build system.
- Ninja: An "assembly language for build systems". Designed to be generated.
- MSBuild: Underlies Visual Studio 2010+ builds.
- Waf, Scons: Python-based build system frameworks.

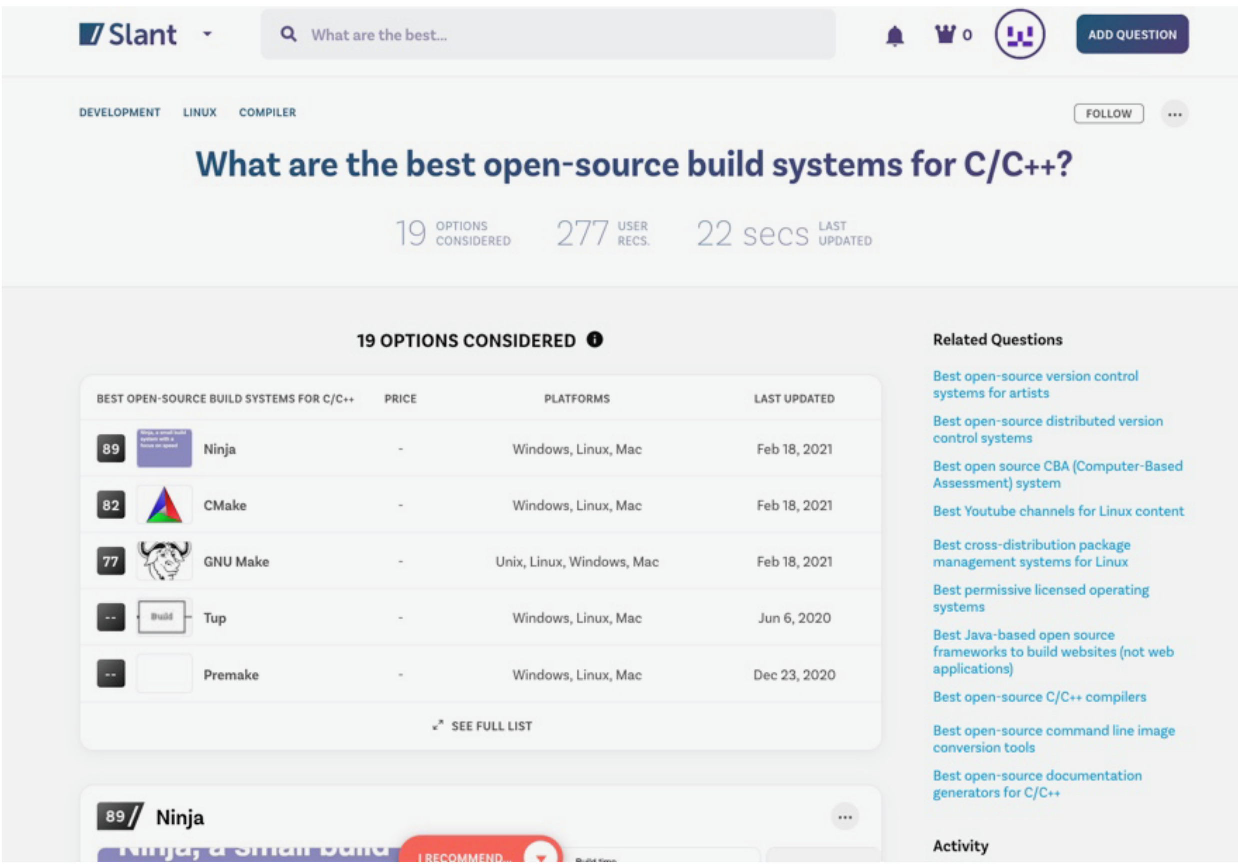
CHAPTER

FOUR

GENERATING BUILD SYSTEMS

4.1 Where Do We Go From Here?

- https://www.slant.co/topics/4263/~open-source-build-systems-for-c-c



4.2 Build System Generators

Transform a common input specification into platform- and tool-specific build files. Examples:

- GNU Build System (autotools): Generates `configure` script for distribution with source code to generate GNU make build files for local system.
- CMake: Generates for Make, Ninja, Visual Studio, or Xcode build files for local system.
- Premake, GYP: Generate re-distributable GNU Make, Visual Studio, and Xcode build files.

4.3 CMake

- Created by Kitware in 2000 to support cross-platform builds for the Insight Toolkit. Sponsored originally by the US NLM.
- Generalized incrementally over time.
- KDE (K Desktop Environment) switched to CMake in 2006; kicked off widespread adoption.
- How to: https://community.kde.org/Guidelines_and_HOWTOs/CMake
- Now de-facto standard for cross-platform `C`, `C++`, and `Fortran` projects.
- Homepage: https://cmake.org
- Documentation: https://cmake.org/cmake/help/latest/

4.4 CMake Example Code

Create a `CMakeLists.txt` file for our example:

```
cmake_minimum_required(VERSION 3.0)
project(Hello C)

add_library(hello SHARED hello1.c hello2.c hello.h)

add_executable(hi1 hi1.c)
target_link_libraries(hi1 hello)

add_executable(hi2 hi2.c)
target_link_libraries(hi2 hello)
```

4.5 Running CMake

Make an *out-of-source* build directory and run `cmake` tool:

```
$ mkdir build && cd build
$ cmake ..
...
-- Build files have been written to: /.../build
$ ls
CMakeCache.txt
```

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```
CMakeFiles/
cmake_install.cmake
Makefile
```

Run `make` tool to drive the actual build:

```
$ make
Scanning dependencies of target hello
[ 14%] Building C object CMakeFiles/hello.dir/hello1.c.o
[ 28%] Building C object CMakeFiles/hello.dir/hello2.c.o
[ 42%] Linking C shared library libhello.so
[ 42%] Built target hello
Scanning dependencies of target hi1
[ 57%] Building C object CMakeFiles/hi1.dir/hi1.c.o
[ 71%] Linking C executable hi1
[ 71%] Built target hi1
Scanning dependencies of target hi2
[ 85%] Building C object CMakeFiles/hi2.dir/hi2.c.o
[100%] Linking C executable hi2
[100%] Built target hi2
```

Inspect results:

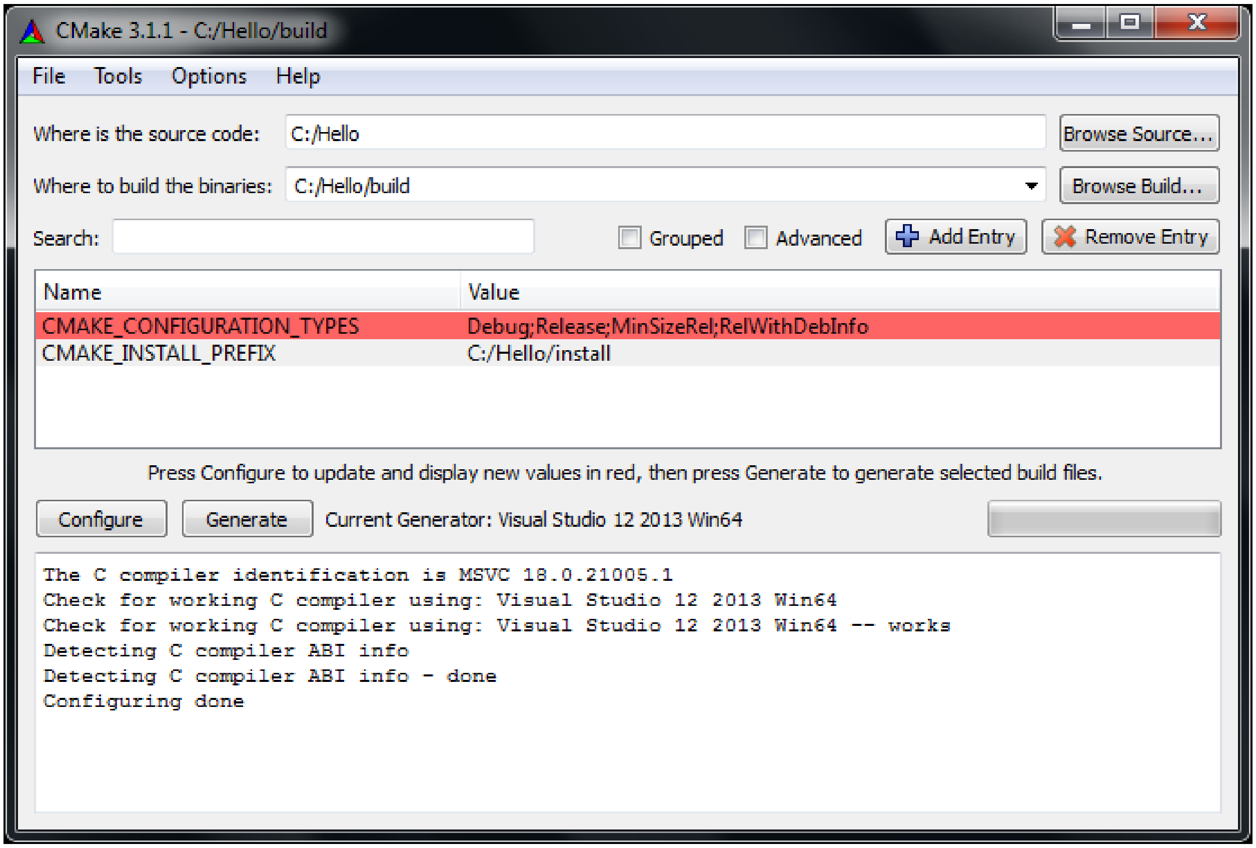
```
$ ls
CMakeCache.txt
CMakeFiles/
cmake_install.cmake
hi1
hi2
libhello.so
Makefile
$ ./hi1
hello: world
$ ./hi2
hello: world
hello: world
```

4.6 CMake-generated Makefiles

- Use platform- and tool-specific commands.
- Handle implicit dependencies automatically.
- Provide rules for “install” and “clean” operations.
- Display description of each step with progress percentage.
- Maintain pristine source with *out-of-source* builds.

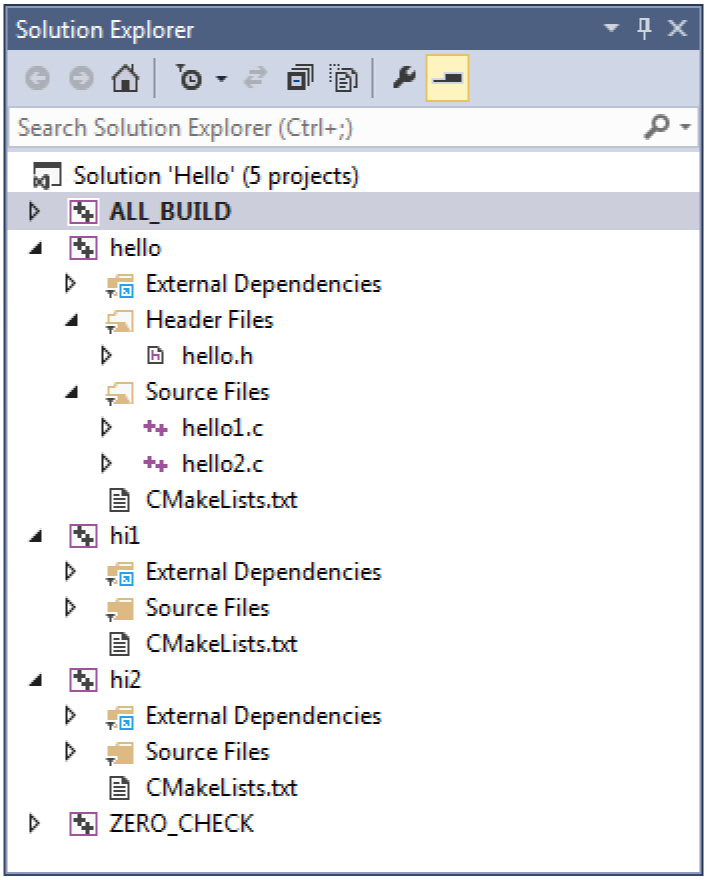
4.7 CMake GUI

Optionally use a GUI instead of a command prompt:



4.8 CMake-generated VS Project

Generated Visual Studio IDE project:



4.9 CMake Syntax Primer

- See the cmake-language(7) manual.
- `CMakeLists.txt` files denote source directories.
- `*.cmake` files implement modules and scripts.

```
# line comment
#[[bracket comment]]
set(VAR1 a)  # "a"
set(VAR2 a b c)  # "a;b;c"
message(${VAR2} "\n" # "abc" (unquoted)
        "${VAR2}" "\n" # "a;b;c" (quoted)
        [[${VAR2}]] "\n" # "${VAR2}" (bracket)
        )
```

CHAPTER

FIVE

CONCLUSION

5.1 Build Systems Summary

- Turn sources into programs.
- Organize code to share among programs.
- Encode build dependencies.
- Generated for portability and scale.
- CMake used widely for `C`, `C++`, and `Fortran`.

- Your next lab session will focus on Make and CMake.
- Thank You