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# Build Systems

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RPI Open Source Software - Spring 2019

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Modifications by Wes Turner



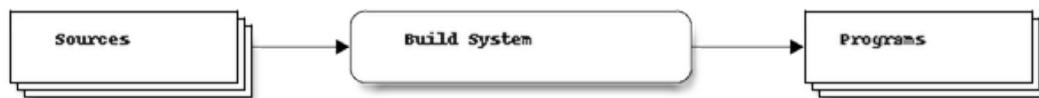
## INTRODUCTION

### 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/v3.13/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.





## 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.o
collect2 -o hi /tmp/tmp1.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.o
cc1 hello.c -o /tmp/tmp2.o
collect2 -o hi1 /tmp/tmp1.o /tmp/tmp2.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.o
cc1 hello.c -o /tmp/tmp2.o
collect2 -o hi1 /tmp/tmp1.o /tmp/tmp2.o -lgcc ...
$ gcc hi2.c hello.c -o hi2 -###
cc1 hi2.c -o /tmp/tmp1.o
cc1 hello.c -o /tmp/tmp2.o
collect2 -o hi2 /tmp/tmp1.o /tmp/tmp2.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 hello.o
$ gcc hi1.c hello.o -o hi1 -###
cc1 hi1.c -o /tmp/tmp1.o
collect2 -o hi1 /tmp/tmp1.o hello.o -lgcc ...
$ gcc hi2.c hello.o -o hi2 -###
cc1 hi2.c -o /tmp/tmp1.o
collect2 -o hi2 /tmp/tmp1.o hello.o -lgcc ...
```

- 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

.. nextslide::
+ 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 RPATH
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)

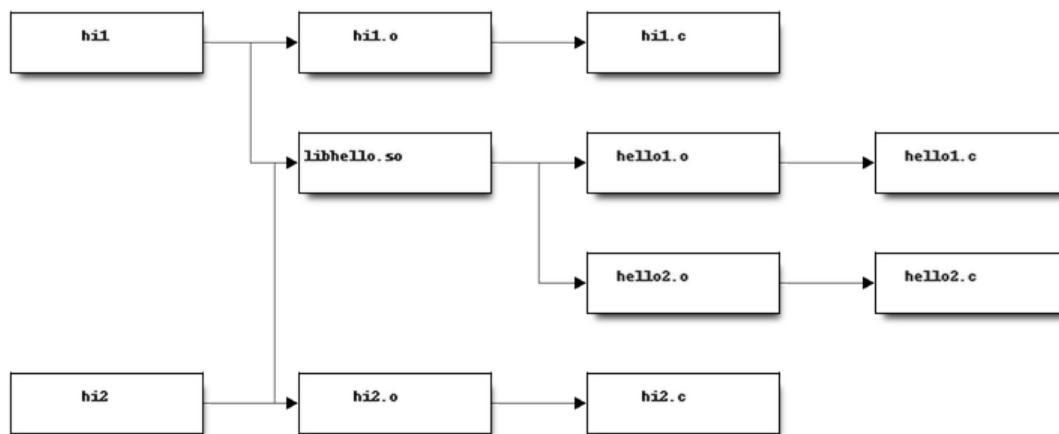
- Objects linked together into libraries loaded by programs at runtime.
- A subset of symbols with “extern linkage” exposed publicly via explicit markup.
- On Windows, associated “import library” (`.lib`).

## 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.

## 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
hi1: hi1.o libhello.so
    cc hi1.o libhello.so -o hi1 -Wl,-rpath='$$ORIGIN'
hi2: hi2.o libhello.so
```

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```
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"
```

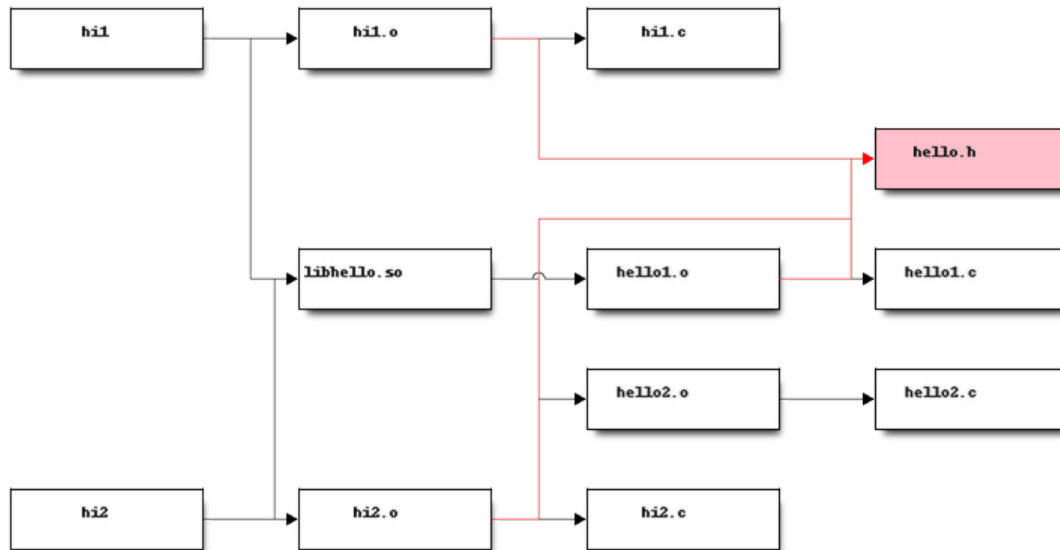


The compiler can tell us about dependencies:

```
$ 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
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.

## GENERATING BUILD SYSTEMS

### 4.1 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.

### 4.2 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.
- Now de-facto standard for cross-platform C, C++, and Fortran projects.
- Homepage: <https://cmake.org>
- Documentation: <https://cmake.org/documentation>

### 4.3 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)
```

## 4.4 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
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
```

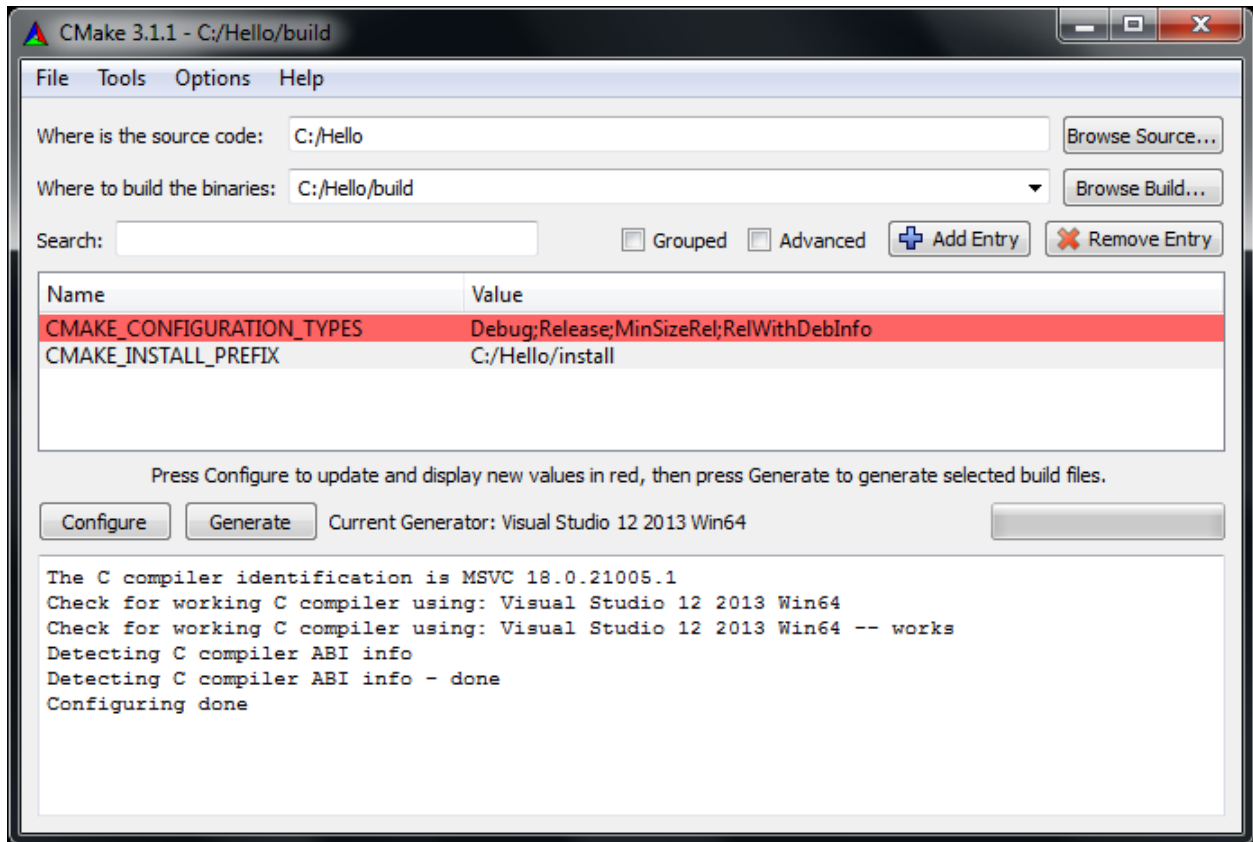
## 4.5 CMake-generated Makefiles

- 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.

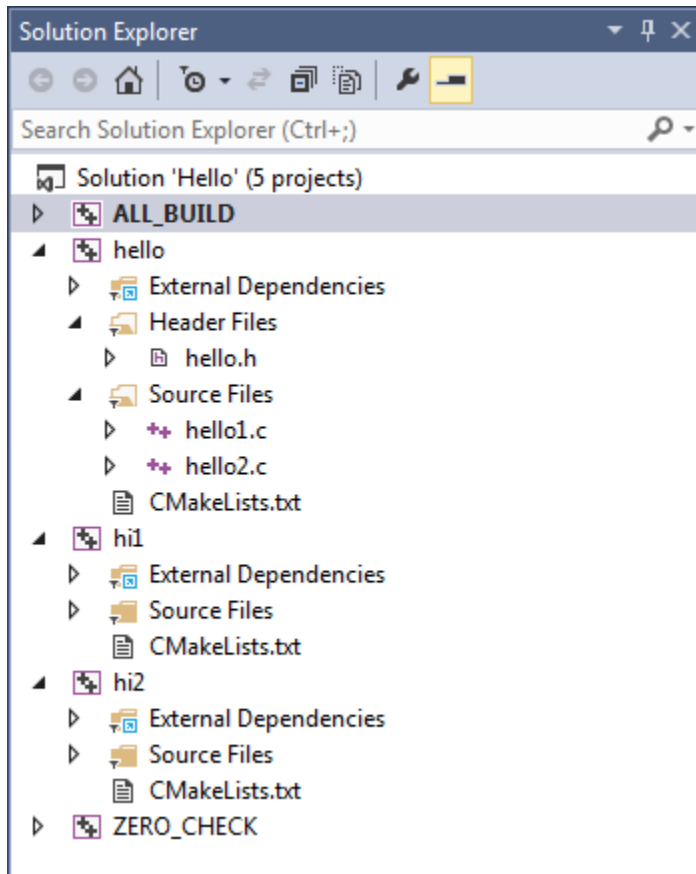
## 4.6 CMake GUI

Optionally use a GUI instead of a command prompt:



## 4.7 CMake-generated VS Project

Generated Visual Studio IDE project:



## 4.8 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)
)
```

## 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 CMake.
  - Thank You