PROFESSIONAL CMAKE

A PRACTICAL GUIDE

CRAIG SCOTT

Professional CMake: A Practical Guide

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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 There were some wikis and personal websites that had some useful contents, but there were also many that contained out-of-date or questionable advice and examples.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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I would also like to express my gratitude to the people behind Asciidoctor, the software used to compile and prepare this book. Despite the size, complexity and technical nature of the material, I have been constantly amazed at how it has made self-publishing not just a viable option, but also an enjoyable experience with surprisingly few practical limitations. The path from author to reader is now so much shorter and simpler than when I initially began work on this book. Thanks for the awesome tool!

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.

Part 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.

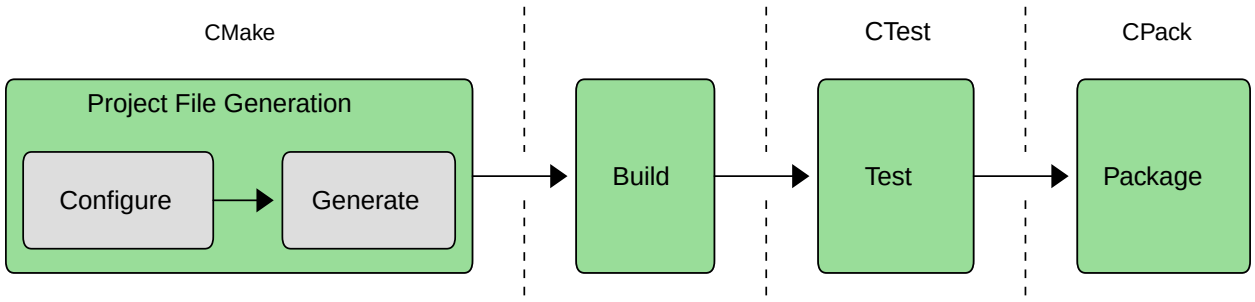
After completing this part of the book, the reader should continue on to the Part II, "Fundamentals" chapters. They go into more detail about key concepts and features that the rest of the book will rely on heavily.

Chapter 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.

Chapter 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.

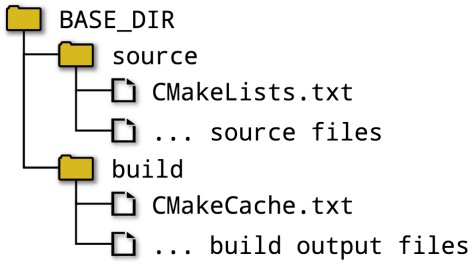
2.1. In-source Builds

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.

Chapter 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.

Chapter 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.

Chapter 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.

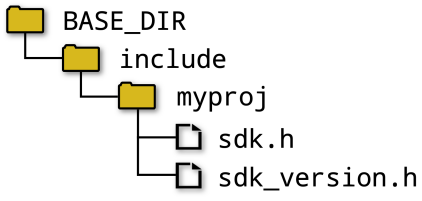
File sets are defined by the `target_sources()` command. Section 16.2.7, “File Sets”, Section 32.6, “File Sets Header Verification”, and Section 35.5.1, “File Sets” discuss the topic in detail, but for now, the following example shows how a public headers file set might be defined and installed:

```
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" --config 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 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.