# CS5416 Recitation 8

## C++ Compilation & Performance

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# How to write **good** system programs in C++

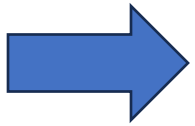
1. Clean and correct code

2. Develop efficient system

# Write clean and correct code

- Memory management in C++, RAII principle
- Smart pointers in C++
- C++ templates
- Standard containers – std::vector<T>, std::map<K,V>

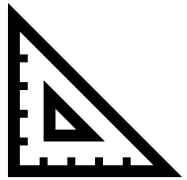
# Develop efficient systems



- Cmake for large system compilation management, gprof for program profiling
- Make efficient use of hardware
  - Hardware parallelism
  - Multithreading and synchronization

# Overview

- C++ compilation and linking
  - Linking review
  - Makefile and Cmake
- Performance optimization
  - Performance measurement
  - gprof



# C++ Compilation

- Linking
- Statically linked library vs dynamically linked library
- Makefile & CMake

# Linking

Linking is a technique that allows programs to be constructed from multiple object files.

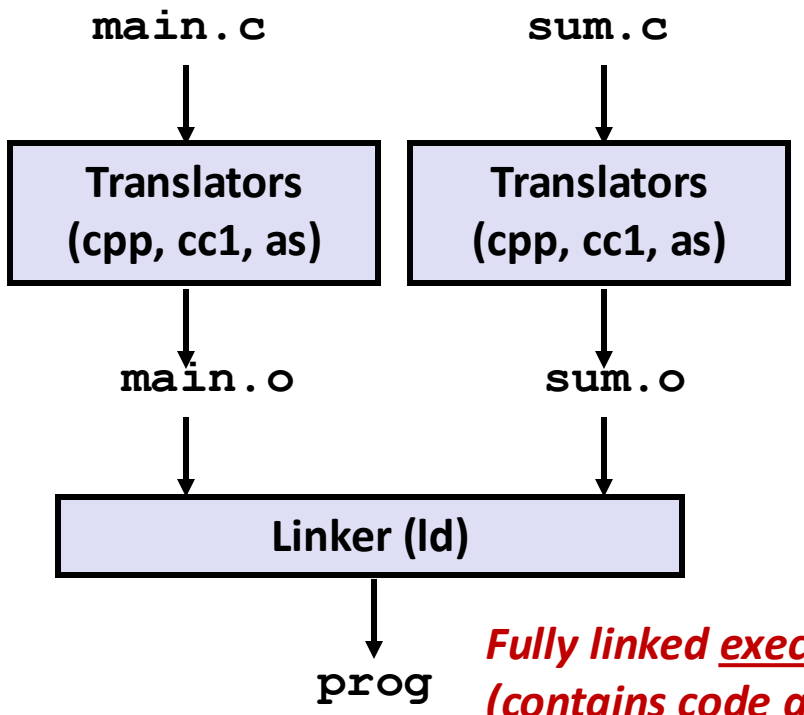
- Compile time (when a program is compiled)
- Load time (when a program is loaded into memory)
- Run time (while a program is executing)

# Linking


- A linker takes a collection of object files and combines them into an object file. But this object file will still depend on libraries.
- Next it cross-references this single object file against libraries, resolving any references to methods or constants in those libraries.
- If everything needed has been found, it outputs an executable image.

# Linking

- Gcc is really a "*compiler driver*": It launches a series of sub-programs
  - `linux> gcc -Og -o prog main.c sum.c`
  - `linux> ./prog`



# C++ libraries

- Why use libraries?
  - The C++ libraries are modular components of reusable code. Using class libraries, you can integrate blocks of code that have been previously built and tested.
- What are in C++ library?
  - A C++ library consists of header files and an object library.
  - The header files provide class and other definitions that the library **exposes** (offers) to the programs using it.
  - The object library(precompiled binary) contains **compiled implementation** of functions and data that are linked with your program to produce an executable program.

# Static-linked libraries

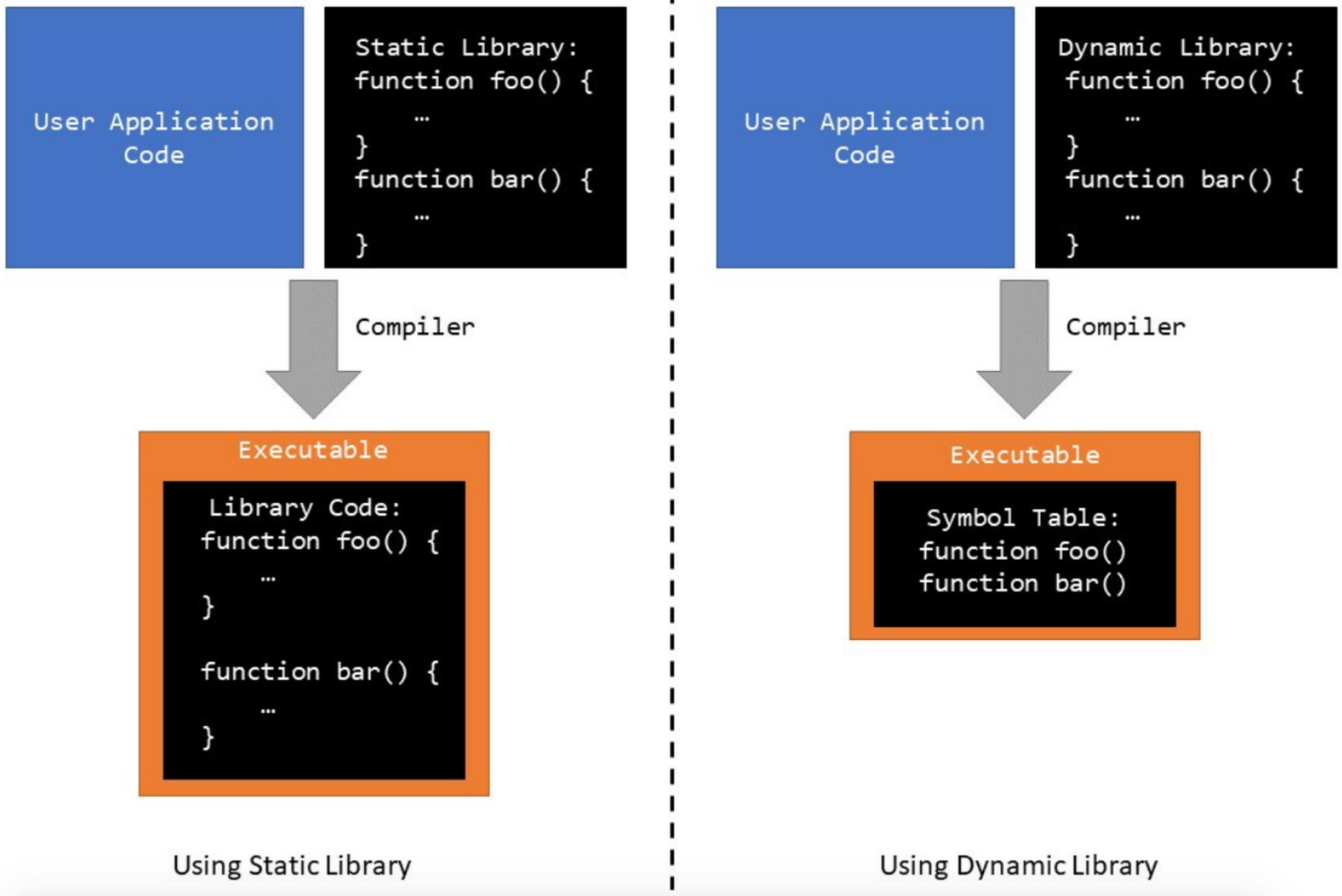
- contains code that is linked to users' programs at compile time. (.a(archive) in linux, or .lib in windows)
- Compiled and linked directly into the program
- a copy of the library becomes part of every executable that uses it, this can cause a lot of wasted space. (Suppose building 100 executables, each one of them will contain the whole library code, which increases the code size overall)

# Dynamic(shared) library

- contains code designed to be shared by multiple programs. (.so in linux, or .dll in wondows, .dylib in OS X files)
- Loaded into your application at run time
- many programs can share one copy, which saves space. (All the functions are in a certain place in memory space, and every program can access them, without having multiple copies of them)

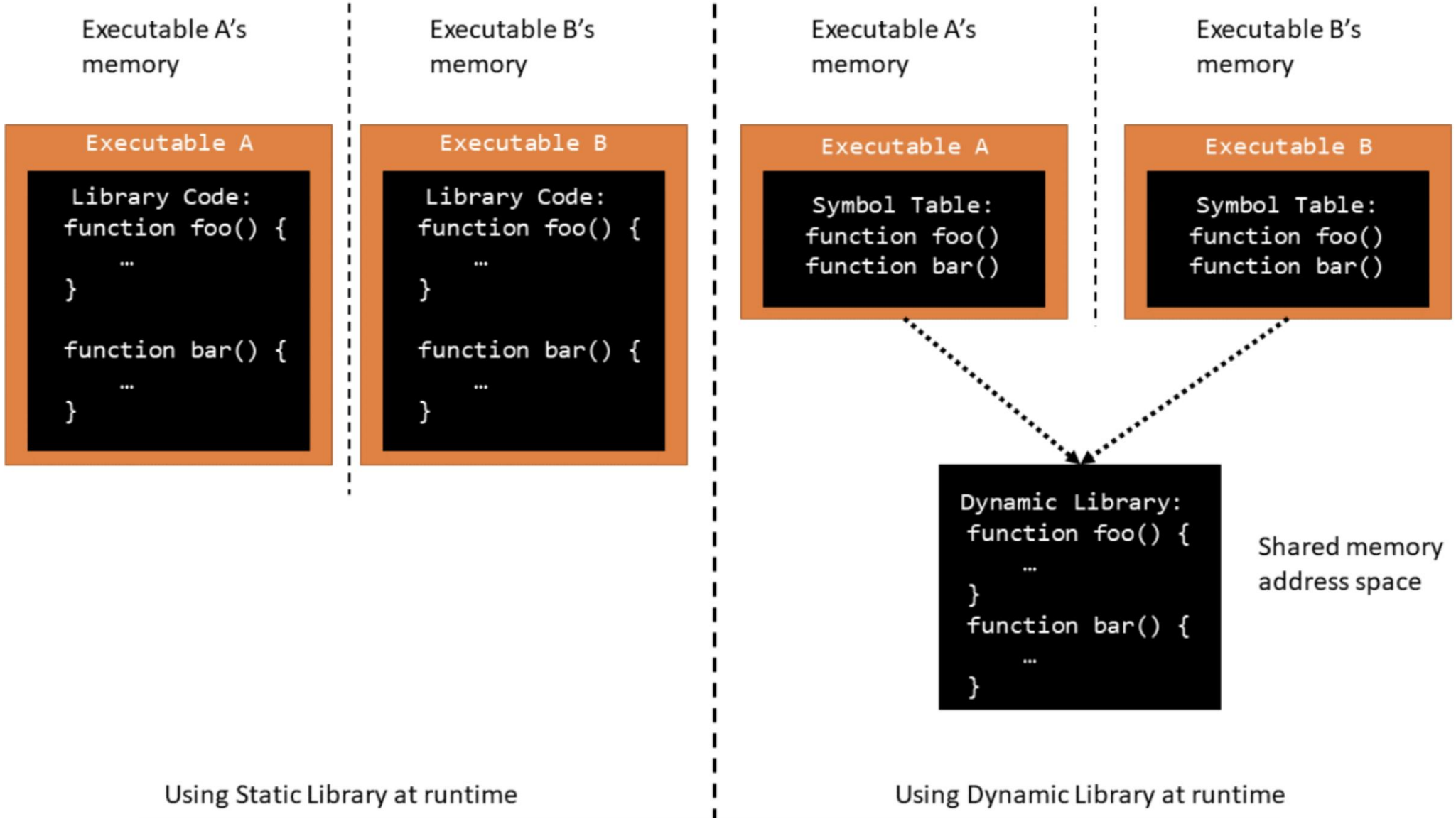
# Library Types in C++

--- compile time



# Library Types in C++

--- run time



# When to use **static linking** vs. dynamic linking

- Static linking disadvantages
  - **Duplication** in the **stored** executables
  - **Duplication** in the **running** executables
  - Minor bug fixes in system libraries?  Must **rebuild** everything!

# When to use **static linking** vs. dynamic linking

- Static linking advantages
  - Executable is **complete** and **self-contained**. **No runtime dependencies**
  - **Predictable** behavior
  - Requires **minimal** operating system
- When to use
  - Commonly used by embedded systems, like microcontroller, IoT devices, …

# When to use static linking vs. **dynamic linking**

- Dynamic linking disadvantages
  - **Runtime dependency**: at execution, the dynamic linker does need to be able to find the library file (a ".so" file) If a dynamically linked executable is launched on a machine that lacks the DLL, you will get an error message (usually, on startup, but there are some obscure cases where it happens later, when the DLL is needed)
  - **Compatibility issues**: version conflict

# When to use static linking vs. **dynamic linking**

- Dynamic linking advantages
  - Reduced memory usage, smaller executable size: a single copy is shared
  - Easier for update and maintenance
  - Version flexibility. If the library updates, simply only need update the library itself (if the APIs remain the same)
- When to use it
  - Commonly used for open-sourced libraries (boost, opencv, grpc..)

# Linking

- Linking is the process of combining various object files (and libraries) into a single executable or library.
- Linking happens either at **compile time** (**static linking**) or at **runtime** (dynamic linking).

$ **ldd** my_exec

# Loading

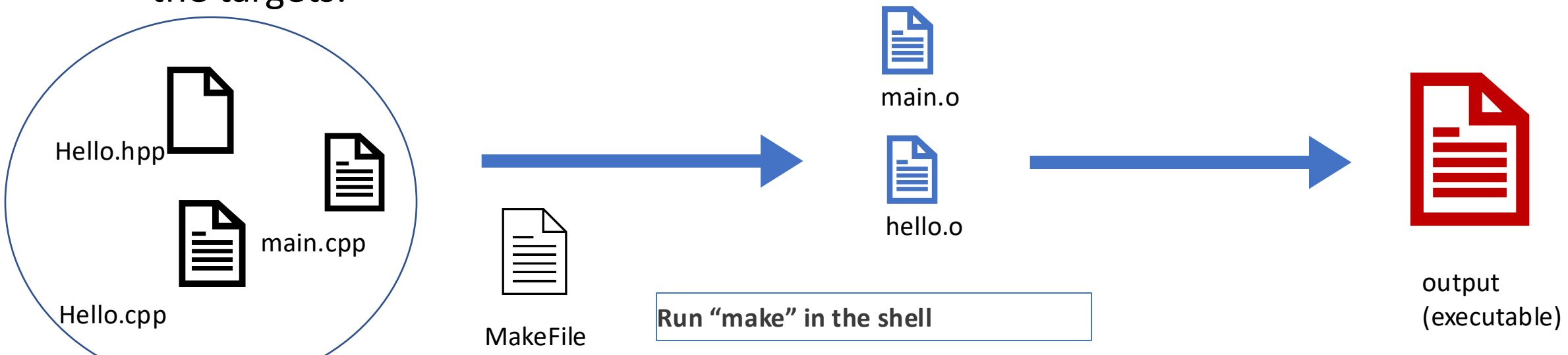
- Loading is the process of bringing an executable (and its dependencies) into memory to run it.
- Loading happens at runtime
  - For **statically linked** programs: the operating system **directly loads** the entire binary into memory. No loading or dynamic linking involved.
  - For **dynamically linked** programs: dynamic linker(part of OS) **finds**, **loads**, and **links** shared libraries into memory.

# Makefile & Cmake

- What is Makefile and CMake
- Simple CMake
- CMake with linked libraries
- CMake with flags

# Build Files & Generate Executables --- MakeFile

- Makefile is just a text file that is used or referenced by the ‘make’ command to build the targets.



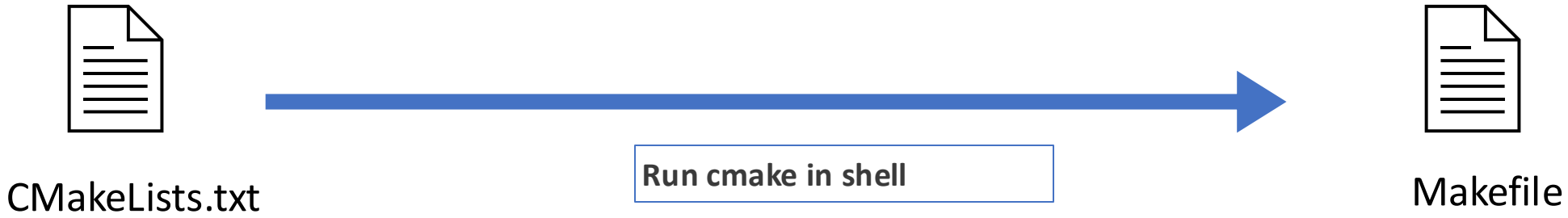

```
CC = g++
CFLAGS = -g -Wall
TARGET = output
all: $(TARGET)
$(TARGET): main.o hello.o
		$(CC) $(CFLAGS) -o $(TARGET) main.o hello.o
main.o: main.cpp hello.hpp
		$(CC) $(CFLAGS) -c main.cpp
hello.o: hello.hpp hello.cpp
		$(CC) $(CFLAGS) -c hello.cpp
```

# CMake

- Why CMake?
  - Makefiles are low-level, clunky creatures
  - **CMake** is a higher-level language to automatically **generate Makefiles**
  - CMake contains **more features**, such as finding library, files, header files; it **makes the linking process easier**, and gives **readable errors**
- What is CMake?
  - CMake is an extensible, open-source system that manages the build process in an operating system and in a compiler-independent manner.

# CMake

CMakeLists.txt files in each source directory are used to generate Makefiles



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4.x | 6 Branches | 126 Tags | Go to file t | Add file | Code

asmorkalov Merge pull request #26281 from kallaballa:clgl_device_discovery e026a5a · 2 hours ago 34,601 Commits

| | | |
|---|---|---|
| .github | Force contributors to define Apache 2.0 license for the n... | 4 months ago |
| 3rdparty | Merge pull request #26216 from hanliutong:rvv-hal-mer... | last week |
| apps | Merge pull request #25582 from fengyuentau:dnn/dump... | 5 months ago |
| cmake | Merge pull request #26234 from zachlowry:apply-gcc6-... | last week |
| data | Merge pull request #22727 from su77ungr:patch-1 | 2 years ago |
| doc | Merge pull request #26260 from sturkmen72:upd_doc_... | last week |
| include | exclude opencv_contrib modules | 4 years ago |
| modules | Merge pull request #26281 from kallaballa:clgl_device_d... | 2 hours ago |
| platforms | Merge pull request #25901 from mshabunin:fix-riscv-aa... | last month |
| samples | Merge pull request #26212 from jamacias:feature/TickM... | 4 days ago |
| .editorconfig | add .editorconfig | 6 years ago |
| .gitattributes | cmake: generate and install ffmpeg-download.ps1 | 6 years ago |
| .gitignore | Merge pull request #17165 from komakai:objc-binding | 4 years ago |
| CMakeLists.txt | build: set cmake policy for if(IN_LIST) support | 2 days ago |
| CONTRIBUTING.md | migration: github.com/opencv/opencv | 8 years ago |

## About

Open Source Computer Vision Library

opencv.org

opencv | c-plus-plus | computer-vision | deep-learning | image-processing

Readme
Apache-2.0 license
Security policy
Activity
Custom properties
78.6k stars
2.7k watching
55.8k forks
Report repository

## Releases 63

OpenCV 4.10.0 Latest
on Jun 3

+ 62 releases

## Sponsor this project

opencv OpenCV

Sponsor

# Why CMake?

- Compilation tool that helps to **generate build file** in a standard way
  - specify build order and dependencies
  - prevent creating cyclic dependencies and common bugs
  - Good at scaling to **large projects**

# Cmake with one simple file

demo

- Helloworld demo example

cmakelists.txt

```
cmake_minimum_required(VERSION 3.12) # set the project name project(MyProject) # add the executable add_executable(output main.cpp)
```

- Build and Run
  - Navigate to the source directory, and create a build directory

    $ cd ./myproject & $ mkdir build
  - Navigate to the build directory, and run Cmake to configure the project and generate a build system

    $ cd build &. $ cmake ..
  - Call build system to compile/link the project

    either run. $ make

    or run. $ cmake –build .

# Cmake with libraries

- Demo: main.cpp with hello library

- add_executable:
  - create an executable target from source files
  - generate the final program that can be run on the system

cmakelists.txt

```
cmake_minimum_required(VERSION 3.12)
project(MyProject VERSION 1.0.0)

add_library{
        say-hello [library type](optional)
        hello.hpp
        hello.cpp
}

target_include_directories(say-hello
PUBLIC ${CMAKE_SOURCE_DIR})

add_executable(output main.cpp)

target_link_libraries(output PRIVATE say-
hello)
```

# Cmake with libraries

- Demo: main.cpp with hello library

- Declare a new library
  - Library name : say-hello
  - Source files: hello.hpp, hello.cpp
  - Can add library type: STATIC (default), SHARED

cmakelists.txt

```
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project(MyProject VERSION 1.0.0)

add_library{
        say-hello [library type](optional)
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target_include_directories(say-hello
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add_executable(output main.cpp)

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# C++ libraries

- What are in C++ library?
  - A C++ library consists of header files and an object library.
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# Cmake with libraries

demo

- Demo: main.cpp with hello library

- Tell cmake to link the library to the executable(output)
  - Private link
  - Public link
  - interface

cmakelists.txt

```
cmake_minimum_required(VERSION 3.12)
project(MyProject VERSION 1.0.0)

add_library{
        say-hello [library type](optional)
        hello.hpp
        hello.cpp
}

target_include_directories(say-hello
PUBLIC ${CMAKE_SOURCE_DIR})

add_executable(output main.cpp)

target_link_libraries(output PRIVATE say-hello)
```

# Cmake

## Target_link_libraries

- target_link_libraries(<target>

  <PRIVATE|PUBLIC|INTERFACE> <lib> ...])

- The PUBLIC, PRIVATE and INTERFACE keywords can be used to specify both the link dependencies and the link interface in one command.
  - PUBLIC: Libraries and targets following PUBLIC are linked to, and are made part of the link interface.
  - PRIVATE: Libraries and targets following PRIVATE are linked to, but are not made part of the link interface.
  - INTERFACE: Libraries following INTERFACE are appended to the link interface and are not used for linking <target>

# Cmake

## Target_include_libraries

```
target_include_directories(<target> [SYSTEM] [AFTER|BEFORE]
                           <INTERFACE|PUBLIC|PRIVATE> [items1...]
                           [<INTERFACE|PUBLIC|PRIVATE> [items2...] ...])
```

- Specifies include directories to use when compiling a given target.
- Tells the compiler where to look for header files (e.g., .h, .hpp files) that define functions, classes, or other declarations.

# Example of PRIVATE PUBLIC INTERFACE link libraries

```
add_library(my_lib STATIC my_lib.cpp)

target_include_directories(my_lib
    PRIVATE ${CMAKE_SOURCE_DIR}/include/private
    PUBLIC ${CMAKE_SOURCE_DIR}/include/public
    INTERFACE ${CMAKE_SOURCE_DIR}/include/interface )

target_link_libraries(my_lib PRIVATE private_lib PUBLIC public_lib INTERFACE
interface_lib )

add_executable(my_app main.cpp)
target_link_libraries(my_app my_lib)
```

# Setting include directories for my_lib

# Link libraries for my_lib

# Only my_lib will use this

# Add the executable

# Link my_app to my_lib

# Cmake with Flags

- C++ standard (equivalent to -std=c++20)

  CMAKE_CXX_STANDARD

cmakelists.txt

```
cmake_minimum_required(VERSION 3.12)
project(MyProject VERSION 1.0.0)

set(CMAKE_CXX_STANDARD 20)

set(CMAKE_BUILD_TYPE Release)
if(CMAKE_BUILD_TYPE STREQUAL "Release")
   set(CMAKE_CXX_FLAGS_RELEASE
"${CMAKE_CXX_FLAGS_RELEASE} –O3")
   set(CMAKE_C_FLAGS_RELEASE
"${CMAKE_C_FLAGS_RELEASE} –O3")
endif()

add_executable(output main.cpp)
```

# Cmake with Flags

- Build Type

```
set(CMAKE_BUILD_TYPE Release)
set(CMAKE_BUILD_TYPE Debug) // gdb
```

- Optimization level

```
set(CMAKE_CXX_FLAGS_RELEASE
"${CMAKE_CXX_FLAGS_RELEASE} -O1")
set(CMAKE_CXX_FLAGS_RELEASE
"${CMAKE_CXX_FLAGS_RELEASE} -O3")
```

demo

cmakelists.txt

```
cmake_minimum_required(VERSION 3.12)
project(MyProject VERSION 1.0.0)

set(CMAKE_CXX_STANDARD 20)

set(CMAKE_BUILD_TYPE Release)
if(CMAKE_BUILD_TYPE STREQUAL "Release")
   set(CMAKE_CXX_FLAGS_RELEASE
"${CMAKE_CXX_FLAGS_RELEASE} –O3")
   set(CMAKE_C_FLAGS_RELEASE
"${CMAKE_C_FLAGS_RELEASE} –O3")
endif()

add_executable(output main.cpp)
```

# Cmake commands

demo

cmakelists.txt

```
cmake_minimum_required(VERSION 3.12)
project(MyProject VERSION 1.0.0)

set(CMAKE_CXX_STANDARD 20)

set(CMAKE_BUILD_TYPE Release)


add_subdirectory(src/rectangle)
add_subdirectory(src/test)


add_executable(output main.cpp)
```

- Scope of execution

Additional files can be run (added to the scope) using the add_subdirectory() command

# Performance Optimization

- 5 steps to improve runtime efficiency
- Time study
- How to use gprof
- Demo

# Improve Execution Time Efficiency

1. Performance measurement (timing breakdown analysis)
2. Identify hot spots
3. Use a better algorithm or data structure
4. Enable compiler speed optimization
5. Tune the code

# Time the program

--- Unix 'time' command

- Run $ time ./output

```
real    0m12.977s
user    0m12.860s
sys     0m0.010s
```

- Real: Wall-clock time between program invocation and termination
- User: CPU time spent executing the program
- System: CPU time spent within the OS on the program's behalf

# Identify hot spots

- Gather statistics about your program's execution
- Runtime profiler: gprof (GNU Performance Profiler)
- How does gprof work?
  - By randomly sampling the code as it runs, gprof check what line is running, and what function it's in

# Gprof

- Compile the code with flag –pg
  - g++ **-pg** helloworld.cpp -o output
- Run the program
  - $ ./output
  - Running the application produce a profiling result called gmon.out
- Create the report file
  - **gprof output** > myreport
- Read the report
  - vim myreport

# Gprof by CMake

- Compile the code with flag –pg set in CMakeLists
- Run the program
  - $ ./output
- Create the report file
  - gprof output > myreport
- Read the report
  - vim myreport

cmakelists.txt

```
cmake_minimum_required(VERSION 3.12)
project(MyProject VERSION 1.0.0)

# Enable gprof profiling
set(CMAKE_CXX_FLAGS
"${CMAKE_CXX_FLAGS} -pg")
set(CMAKE_EXE_LINKER_FLAGS
"${CMAKE_EXE_LINKER_FLAGS} -pg")

add_executable(output main.cpp)
```

# Flat Profile

```
Each sample counts as 0.01 seconds.
 %   cumulative   self              self     total
time   seconds   seconds    calls  us/call  us/call  name
13.22      0.28     0.28 50045000     0.01     0.01  void std::__cxx11::basic_string<char, std::char_traits<char>, ...
10.39      0.50     0.22 100000000     0.00     0.00  std::vector<Entity, std::allocator<Entity> >::operator[](unsigned long)
6.85       0.65     0.15 50005000     0.00     0.00  __gnu_cxx::__normal_iterator<Entity const*,std::vector<Entity,...
5.67       0.77     0.12 100030000     0.00     0.00  __gnu_cxx::__normal_iterator<Entity const*, std::vector<Entity, ...
5.67       0.89     0.12 50045000     0.00     0.01  std::iterator_traits<char*>::difference_type std::distance<char*>(char*,...
5.43       1.00     0.12 50005000     0.00     0.00  __gnu_cxx::__normal_iterator<Entity const*,std::vector<Entity, ...
...
...
```

- name: name of the function
- %time: percentage of time spent executing this function
- cumulative seconds: This is the cumulative total number of seconds the computer spent executing this functions, plus the time spent in all the functions above this one in this table.
- self seconds: time spent executing this function
- calls: number of times function was called (excluding recursive)
- self s/call: average time per execution (excluding descendents)
- total s/call: average time per execution (including descendents)

# Improve Execution Time Efficiency

demo

1. Performance measurement (timing breakdown analysis)
2. Identify hot spots
3. Use a better algorithm or data structure
4. Enable compiler speed optimization. (Compile with -O3)
5. Tune the code

# Where to find the resources?

- Linking and Compilation
  - https://www.cs.cornell.edu/courses/cs4414/2024fa/Schedule.htm Lecture 13
  - CPPCON linker and loaders: https://www.youtube.com/watch?v=_enXuIxuNV4
- Makefile & Cmake
  - https://cmake.org/cmake/help/book/mastering-cmake/chapter/Converting%20Existing%20Systems%20To%20CMake.html
- Gprof
  - GNU gprof manual: https://ftp.gnu.org/old-gnu/Manuals/gprof-2.9.1/html_mono/gprof.html