Creative Software Design

5 – Compilation and Linkage, CMD Args

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Fall 2022

Midterm Exam

- Date & time: TBD, candidates are
  - Oct 18, about 1 hour between 09:00 - 11:00 am
  - Oct 20, about 1 hour between 11:00 am - 1:00 pm
- Place: TBD
- Scope: Lecture 2 ~ 7

- **You cannot leave until 30 minutes after the start of the exam** even if you finish the exam earlier.

- That means, **you cannot enter the room after 30 minutes from the start of the exam** (do not be late, never too late!).

- Please bring your student ID card to the exam.

Today's Topics

- Compilation and Linkage
  - C/C++ Build Stages
  - Header and Source Files
    - Function / Class Declaration and Definition
    - Include Guards
    - Inline Function
  - Preprocessor

- Command-line Arguments

- Building a Multi-file Project
  - Introduction to CMake

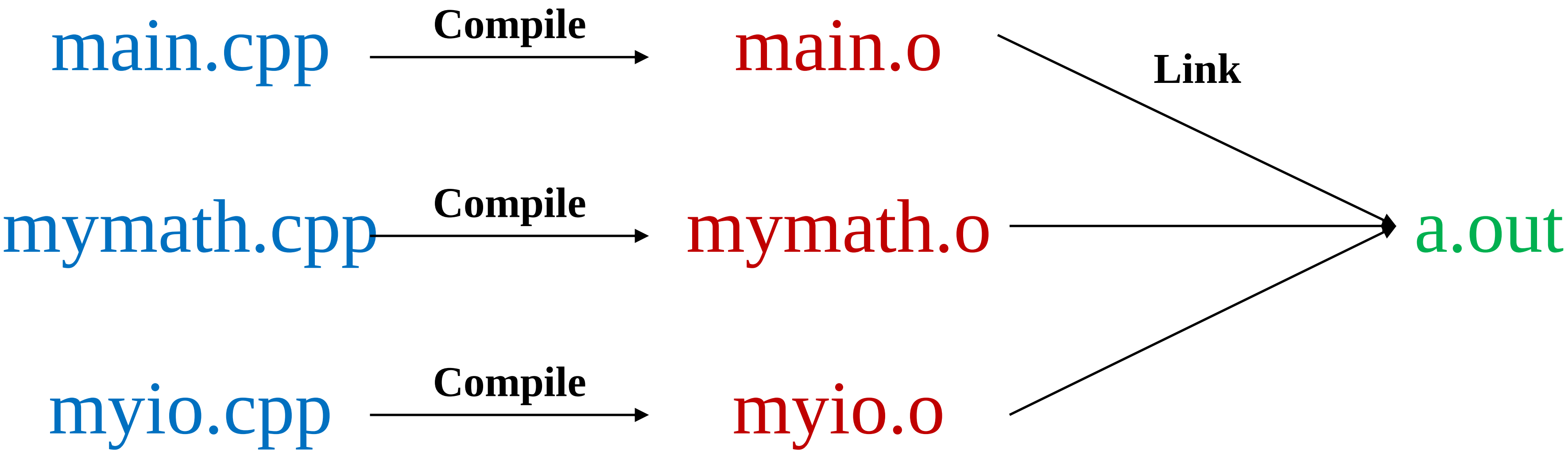
Compilation and Linkage

Compile & Link

- **Compile**
  - source code → machine code
  - ex) main.cpp (source file) → main.o (object file)
  - "compiler"

- **Link**
  - Create the final executable file (or library) by linking several object files (+libraries)
    - A library is just a collection of object files.
  - ex) main.o, ... → a.out, mylib.so
  - "linker"

Compile & Link Example



main.cpp

Compile

main.o

Link

mymath.cpp

Compile

mymath.o

a.out

myio.cpp

Compile

myio.o

C/C++ Build Stages

example.c

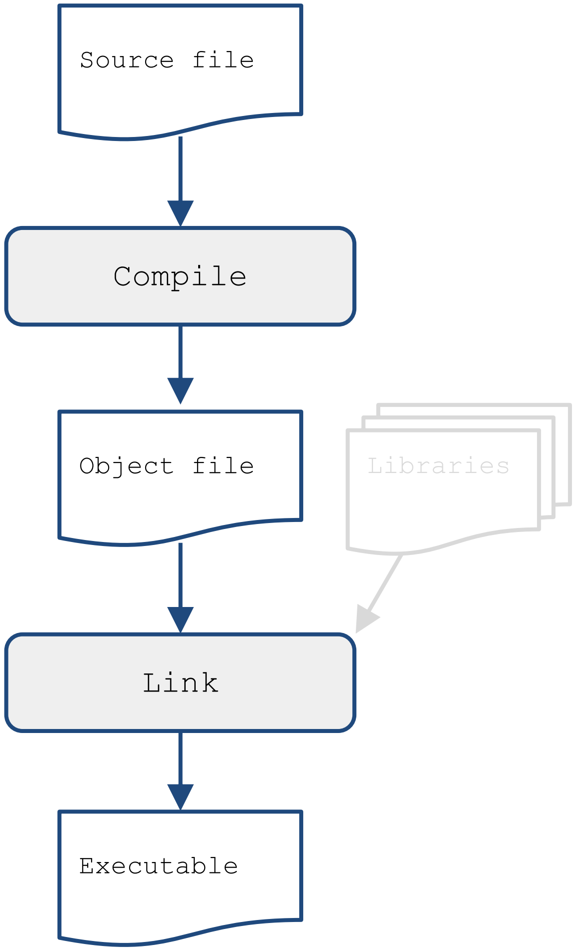
```
int FuncInt(int a, int b) {
  ...
}

int FuncDouble(double a, double b, double c) {
  ...
}

int main() { ... }
```

example.o

```
_FuncInt: ........
_FuncDouble: ........
_main: ........
```

example (example.exe)

```
........
```



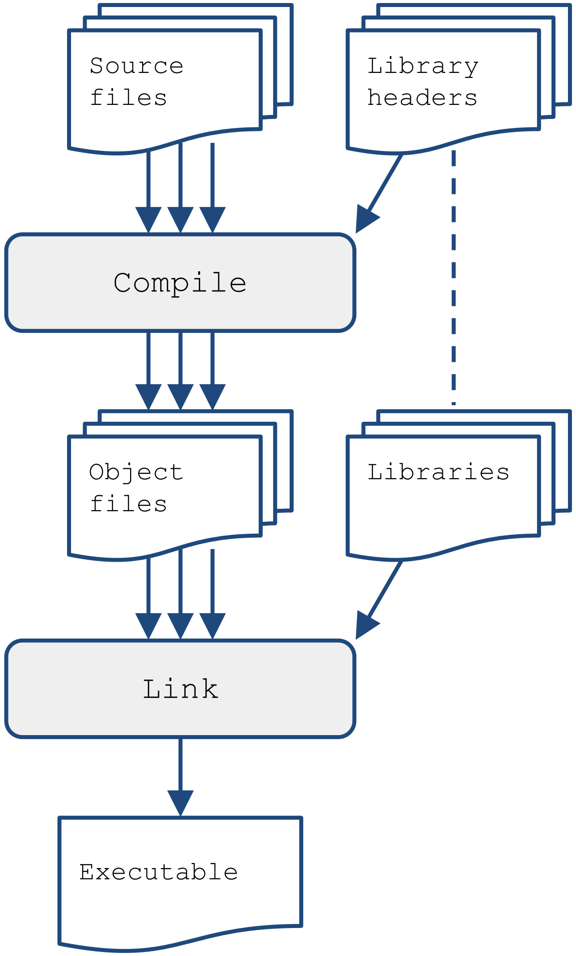
C/C++ Build Stages

example.c

```
#include <math.h>

int FuncInt(int a, int b) {
  ...
}

int FuncDouble(double a, double b, double c) {
  double d = sin(a) * b + cos(a) * c;
  ...
}

int main() { ... }
```

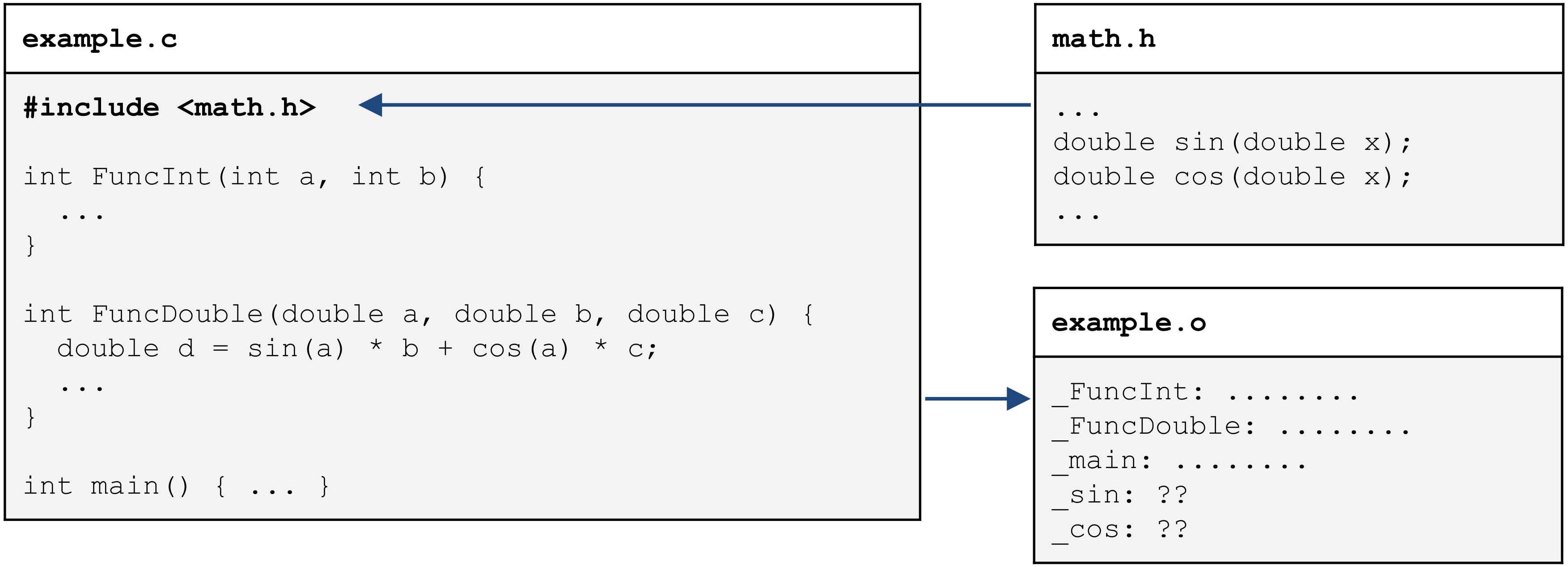
Compilers only need to know the declarations (types) of the functions or external variables.

How can the compiler know the type of the function `sin` and `cos`?


Source files
Library headers
Compile
Object files
Libraries
Link
Executable

C/C++ Compilation

- Compilers only need to know the declarations (types) of the functions or external variables.
- How can the compiler know the type of the function `sin` and `cos`?
- -> Including `math.h`
- The preprocessor just replaces `#include` statements with their file content.



example.c

```
#include <math.h>

int FuncInt(int a, int b) {
  ...
}

int FuncDouble(double a, double b, double c) {
  double d = sin(a) * b + cos(a) * c;
  ...
}

int main() { ... }
```

math.h

```
...
double sin(double x);
double cos(double x);
...
```

example.o

```
_FuncInt: ........
_FuncDouble: ........
_main: ........
_sin: ??
_cos: ??
```

C/C++ Build Stages

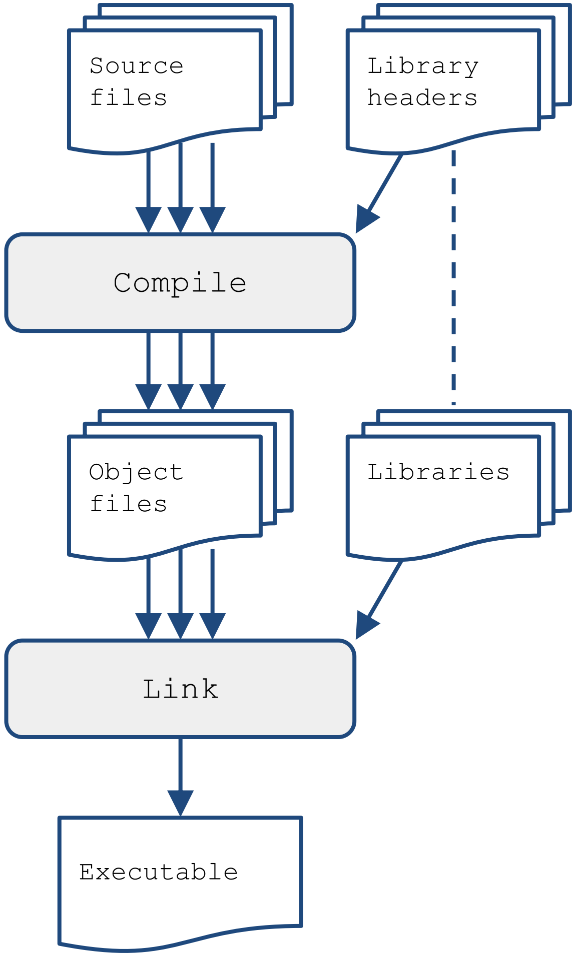
example.c

```
#include <math.h>

int FuncInt(int a, int b) {
   ...
}

int FuncDouble(double a, double b, double c) {
   double d = sin(a) * b + cos(a) * c;
   ...
}

int main() { ... }
```

example.o

```
_FuncInt: ........
_FuncDouble: ........
_main: ........
_sin: ??
_cos: ??
```

Where can we find the definition of the function `sin` and `cos`?



Source files

Library headers

Compile

Object files

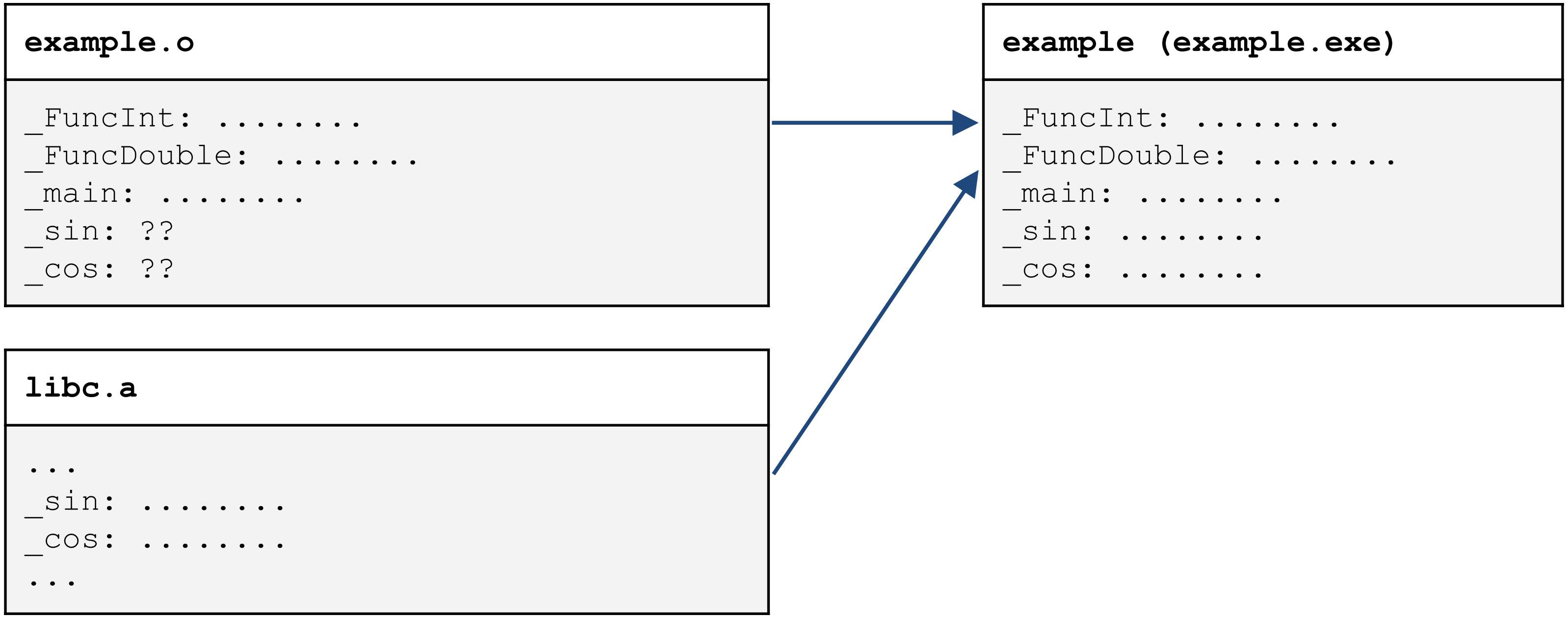
Libraries

Link

Executable

C/C++ Linking

- A library is just a collection of object files.
  - sin() and cos() are defined in C standard library (libc)
- Linker tries to find all unknown symbols in the object files and the libraries.



example.o

```
_FuncInt: ........
_FuncDouble: ........
_main: ........
_sin: ??
_cos: ??
```

libc.a

```
...
_sin: ........
_cos: ........
...
```

example (example.exe)

```
_FuncInt: ........
_FuncDouble: ........
_main: ........
_sin: ........
_cos: ........
```

Header and Source Files

In C++, a header file's extension is **'.h'** or '.hpp', and a source file's is **'.cpp'** or '.cc'.

C/C++ header files contain

- function and external variable declarations.
- struct and class (type) definition.
- enumeration definitions.
- macro definitions.
- inline function definitions (C++).
- ...

Headers show the interface of the entities in the source files.

Header & Source Files for Functions

- ***Function declaration*** which only specifies the function name, parameter profile, and the return type → in a **header file**

- ***Function definition*** which provides the actual implementation of the function body → in a **source file**

```
// myfunc.h - header file
int FuncInt(int a, int b);
double Norm(const double* array, int n);
```

```
// myfunc.cpp - source file
#include <math.h>
#include "myfunc.h"

int FuncInt(int a, int b) {
  return a * 10 + b * b;
}
double Norm(const double* array, int n) {
  double sqsum = 0;
  for (int i = 0; i < n; ++i) sqsum += array[i] * array[i];
  return sqrt(sqsum);
}
```

Header & Source Files for Classes

- ***Class definition*** which contains member variables and member functions declarations → in a **header file**

- ***Class member functions definition*** → in a **source file**

- Separating a class code into header & source files is important!
- If you do not understand, skip it. Classes will be covered in more detail next time.

```
// rectangle.h - header file
class Rectangle
{
private:
    int width, height;
public:
    void setValues(int x, int y);
};
```

```
// rectangle.cpp - source file
#include “rectangle.h”

void Rectangle::setValues (int x, int y)
{
    width = x;
    height = y;
}
```

Include Guard: Will this code compile?

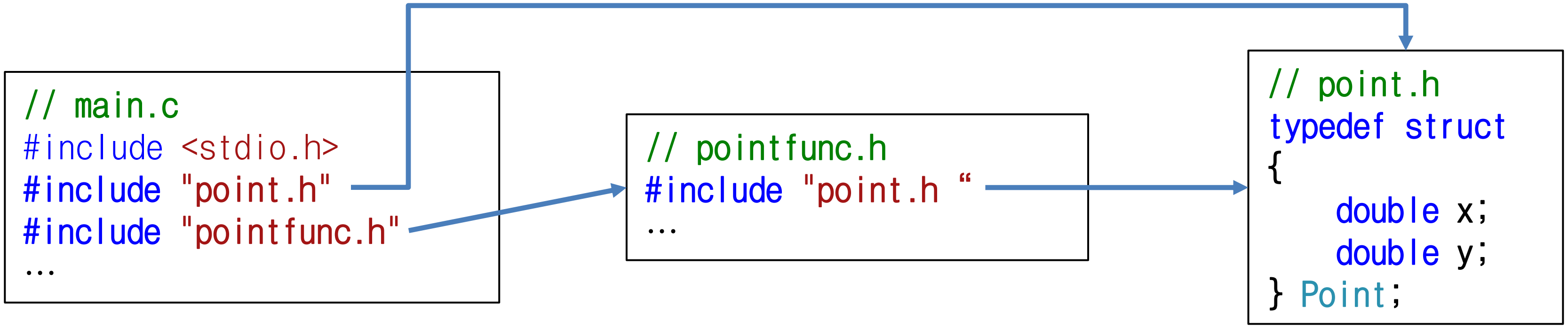
```c
// point.h
typedef struct
{
    double x;
    double y;
} Point;
```

```c
// pointfunc.h
#include "point.h"
double calcDist(Point p1, Point p2);
```

```c
// pointfunc.c
#include <math.h>
#include "pointfunc.h"

double calcDist(Point p1, Point p2)
{
    double xdiff = p2.x - p1.x;
    double ydiff = p2.y - p1.y;
    return sqrt(xdiff*xdiff + ydiff*ydiff);
}
```

```c
// main.c
#include <stdio.h>
#include "point.h"
#include "pointfunc.h"

int main()
{
    Point p1 = { 0,0 };
    Point p2 = { 1,1 };

    // print distance btwn two points
    printf("distance: %f₩n", calcDist(p1, p2));

    return 0;
}
```

No, because of double inclusion of point.h



```
// main.c
#include <stdio.h>
#include "point.h"
#include "pointfunc.h"
…
```

```
// pointfunc.h
#include "point.h “
…
```

```
// point.h
typedef struct
{
    double x;
    double y;
} Point;
```

- As a result, the definition of Point appears twice in main.c. → Generates a compile error
- Deleting `#include "point.h"` from main.c solves the problem, but

- The more files, the more complicated include dependencies, so it's not easy to check all the inclusions.

- We have a better way to handle this issue!

Include Guard: #pragma once

- Add **#pragma once** at the top of header files
  - Preprocessor directive to instruct that the file to be included only once

- Although it is not an official C / C++ standard, it is widely supported by most compilers.

Include Guard: #pragma once

```
// point.h
#pragma once

typedef struct
{
    double x;
    double y;
} Point;
```

```
// pointfunc.h
#pragma once

#include "point.h"
double calcDist(Point p1, Point p2);
```

```
// pointfunc.c
#include <math.h>
#include "pointfunc.h"

double calcDist(Point p1, Point p2)
{
    double xdiff = p2.x - p1.x;
    double ydiff = p2.y - p1.y;
    return sqrt(xdiff*xdiff + ydiff*ydiff);
}
```

```
// main.c
#include <stdio.h>
#include "point.h"
#include "pointfunc.h"

int main()
{
    Point p1 = { 0,0 };
    Point p2 = { 1,1 };

    // print distance btwn two points
    printf("distance: %f₩n", calcDist(p1, p2));

    return 0;
}
```

Another Include Guard: #ifndef

```
// point.h
#ifndef __POINT_H__
#define __POINT_H__

typedef struct
{
    double x;
    double y;
} Point;

#endif
```

- If the name __POINT_H__ is not already defined, define __POINT_H__ and include the later part in the compilation.

- If __POINT_H__ is defined, the entire file is not included in the compilation.

- When point.h is about to be included second time, __POINT_H__ is already defined. Therefore, entire point.h is not included in the compilation.

- Still used a lot.

Quiz #1

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers **in this format** to be counted as attendance.

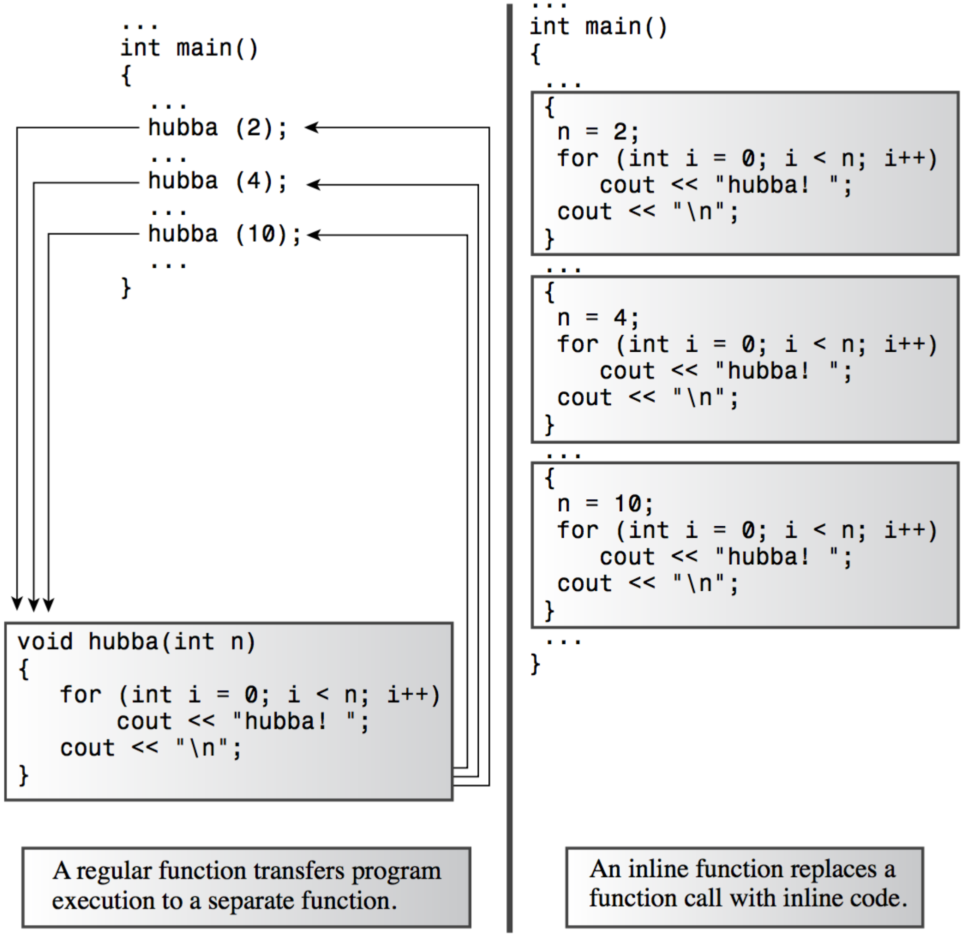
Inline Function

- Function definitions should not be in header files, except inline functions.
- Inline expansion : an inline function works as if the function call is replaced with the function body.
- Use with care : often executes faster but increases the size of the compiled binary code.

```cpp
#include <iostream>

inline int max(int a, int b) {
  return a > b ? a : b;
}

int main() {
  const int size = 5;
  int array[size] = { 2 3 1 5 3 };
  for (int i = 1; i < size; ++i)
    std::cout << max(array[i - 1], array[i]) << std::endl;
  return 0;
}
```

Inline Function

- The difference between normal functions and inline functions is how the c ompiler incorporates them into a program.



```
...
int main()
{
    ...
    hubba (2);
    ...
    hubba (4);
    ...
    hubba (10);
    ...
}
```

```
void hubba(int n)
{
   for (int i = 0; i < n; i++)
       cout << "hubba!  ";
   cout << "\n";
}
```

A regular function transfers program execution to a separate function.

```
...
int main()
{
 ...
 {
  n = 2;
  for (int i = 0; i < n; i++)
     cout << "hubba!  ";
  cout << "\n";
 }
 ...
 {
  n = 4;
  for (int i = 0; i < n; i++)
     cout << "hubba!  ";
  cout << "\n";
 }
 ...
 {
  n = 10;
  for (int i = 0; i < n; i++)
     cout << "hubba!  ";
  cout << "\n";
 }
 ...
}
```

An inline function replaces a function call with inline code.

Inline Function in Classes

- Member functions defined in a class definition (in a header file) are inline functions.

- Again, if you do not understand, skip it for now.

```
// rectangle.h - header file
class Rectangle
{
private:
    int width, height;
public:
    void setValues(int x, int y)
    {
        width = x;
        height = y;
    }
};
```

C/C++ Preprocessor

- When compilation begins, the preprocessor replaces the # directives in the source.

```
#include <math.h>
#include <iostream>
#include "my_header.h"

#pragma once

#define PI 3.141592
#define PI_2 (PI/2)

#define MAX(a, b) ((a) > (b) ? (a) : (b))

int main() {
  const double angle = PI / 3;
  int n, min_iter = 10;
  std::cin >> n;
  const int num_iter = MAX(n, min_iter);
  // What happens if we use MAX(++n, min_iter);
  for (int i = 0; i < n; ++i) {
    ...
  }
  return 0;
}
```

Command-line Arguments

Command-line Arguments

- C/C++ main function may take additional input parameters.

```
int main();                         // OR int main(void);
int main(int argc, char **argv);    // OR int main(int argc, char *argv[]);
```

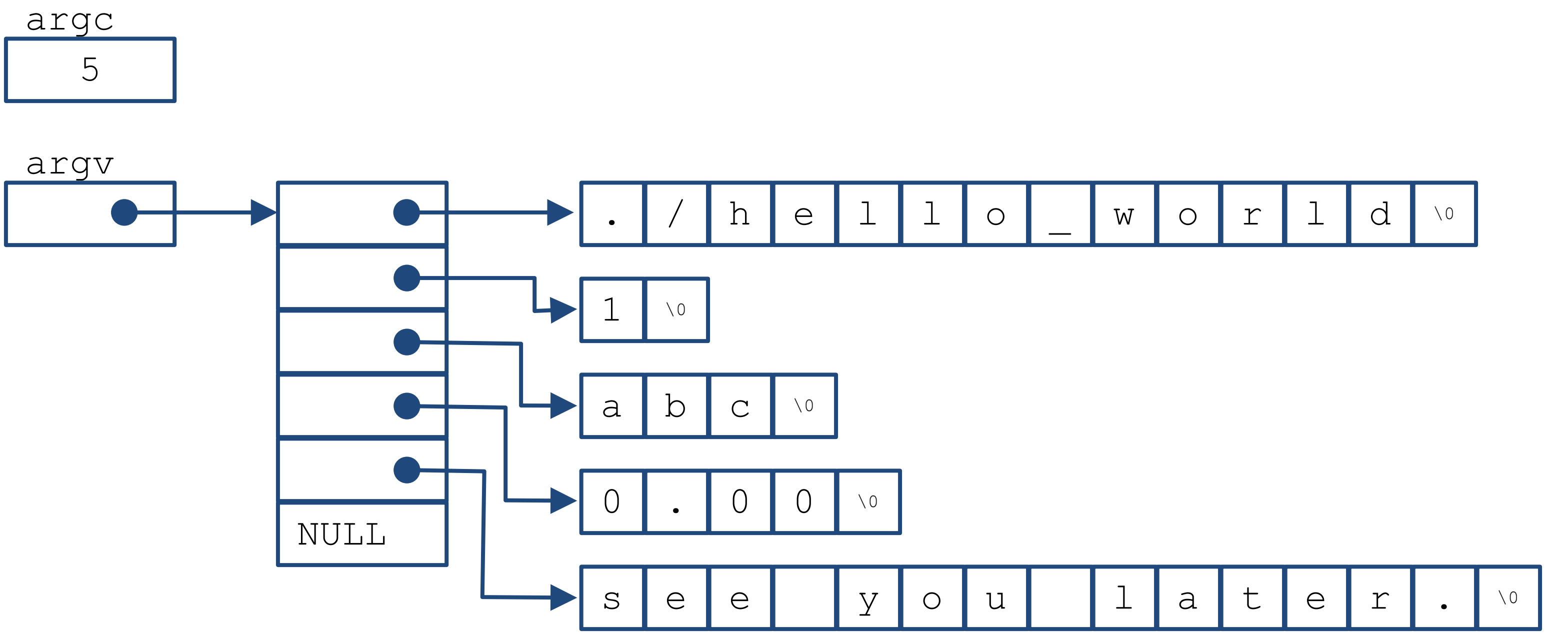
- When the program is executed, the *command-line arguments* are passed.

```
$ ./hello_world 1 abc 0.00 "see you later."

-> argc: 5
   argv[0]: "./hello_world"   argv[3] = "0.00"
   argv[1]: "1"               argv[4] = "see you later."
   argv[2]: "abc"             argv[5] = NULL
```

Command-line Arguments

```
int main(int argc, char **argv);
```

```
$ ./hello_world 1 abc 0.00 "see you later."

-> argc: 5
   argv[0]: "./hello_world"   argv[3] = "0.00"
   argv[1]: "1"               argv[4] = "see you later."
   argv[2]: "abc"             argv[5] = NULL
```



Review: Double Pointer (Pointer to Pointer)

- A string array: const char* strArr[] = {"aaa", "bbb", "ccc"};

- Recall: Passing an Array to a Function:
  - Pass the **start address** of the array as a pointer parameter

- Example 1: A function to print an int array:
- void printArray(int* arr, int len)

- Example 2: A function to print an char* array:
- void printArray(char** strArr, int len)

Command-line Arguments

- A simple program to print all command-line arguments.

```
#include <stdio.h>

int main(int argc, const char **argv) {
  for (int i = 0; i < argc; ++i) printf("%s\n", argv[i]);
  return 0;
}
```

- You may need string-to-number conversion.

```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, const char **argv) {
  for (int i = 1; i < argc; ++i) printf("%d\n", atoi(argv[i]));
  return 0;
}
```

Return value of main()

- The return value of the main function is the program's exit status.
    - EXIT_SUCCESS (typically 0) or EXIT_FAILURE.

- Where is this return value used?

```
$ command_a ; command_b                 # Execute command_a then command_b.

$ command_a && command_b      # Execute command_a AND IF IT IS SUCCESSFUL
                                                            # execute command_b.

$ command_a || command_b      # Execute command_a AND IF IT FAILS
                                                            # execute command_b.
```

Quiz #2

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

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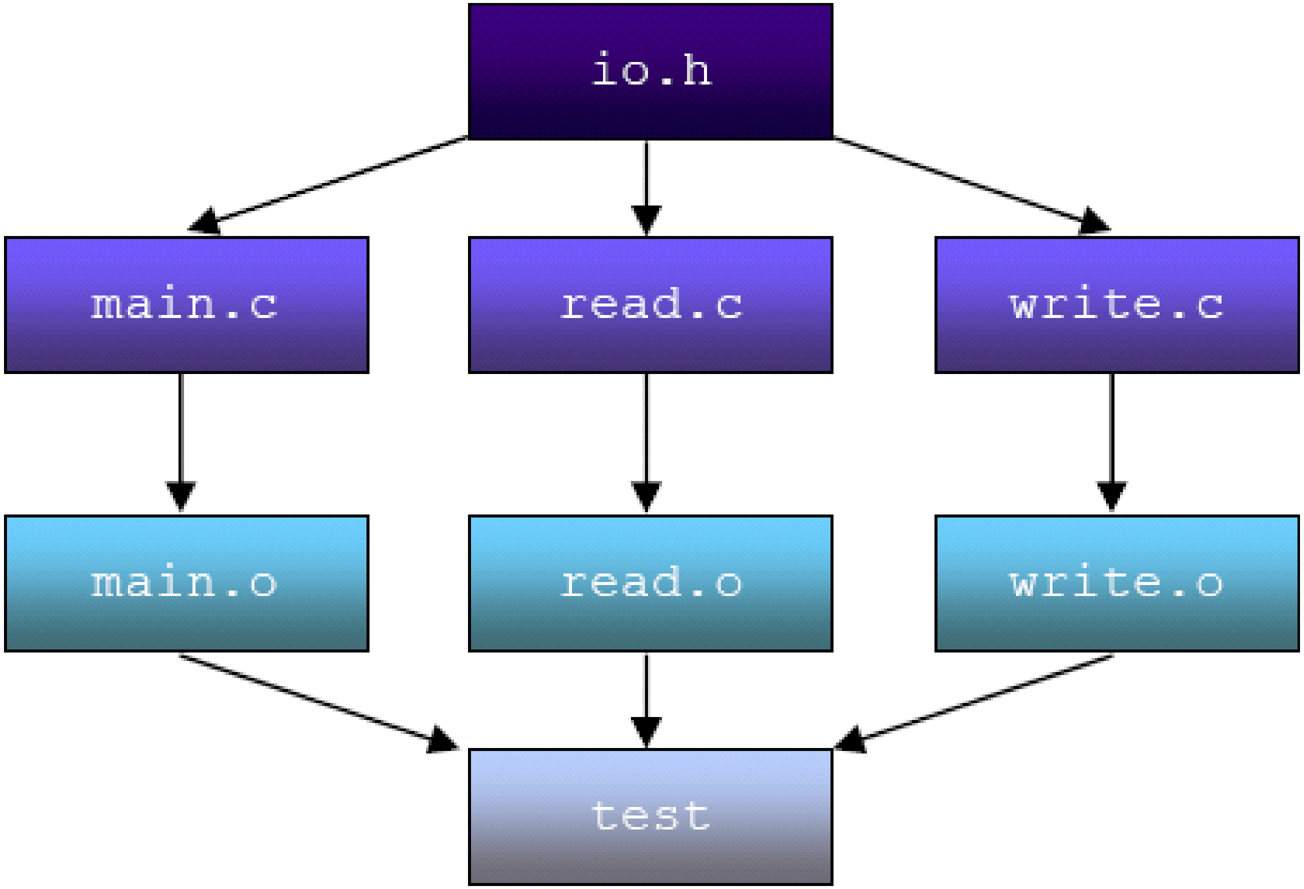
Building a Multi-file Project

Building a Multi-file Project

- How to build this project effectively?

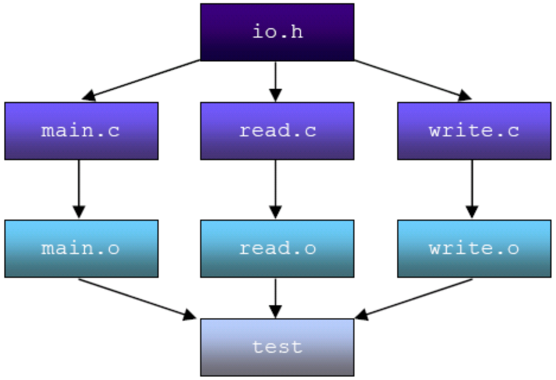


1) Using g++ directly

(Shell)

```
g++ -c test read.c write.c main.c  # compile and link

# or
g++ -c read.c write.c main.c       # compile
g++ -o test read.o write.o main.o  # link
```



- Typing these lines every time is cumbersome!

- How about putting these commands into a shell script?
- → Cannot use dependency information
  - It means you need to recompile main.c and write.c even if you only modify read.c

- Using dependency information is essential for building large projects
  - Because it takes too long to compile and link all files every time

2) Make

- A Makefile contains dependency information

Makefile

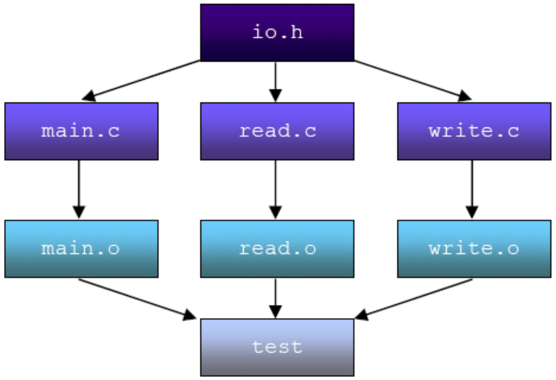
```
test : read.o write.o main.o
    gcc -o test read.o write.o main.o

main.o : io.h main.c
    gcc -c main.c

read.o : io.h read.c
    gcc -c read.c

write.o: io.h write.c
    gcc -c write.c
```

Dependency information



2) Make

- More sophisticated one

Makefile

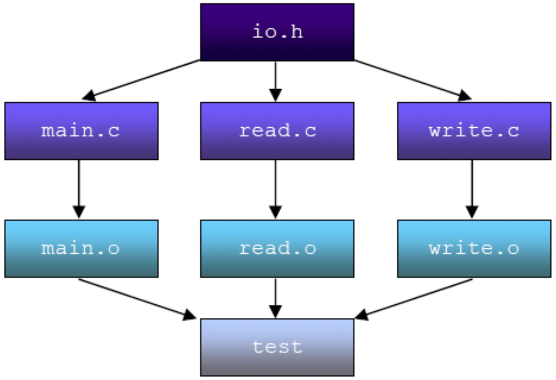
```
CC=g++
SRCS=main.c read.c write.c
OBJS=$(SRCS:%.c=%.o)
TARGET=test

.SUFFIXES : .c .o

$(TARGET): $(OBJS)
    $(CC) -o $(TARGET) $(OBJS)

main.o: io.h main.c
read.o: io.h read.c
write.o: io.h write.c
```

Dependency information



Quiz #3

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
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  - **e.g. 2017123456: 4)**

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2) Make

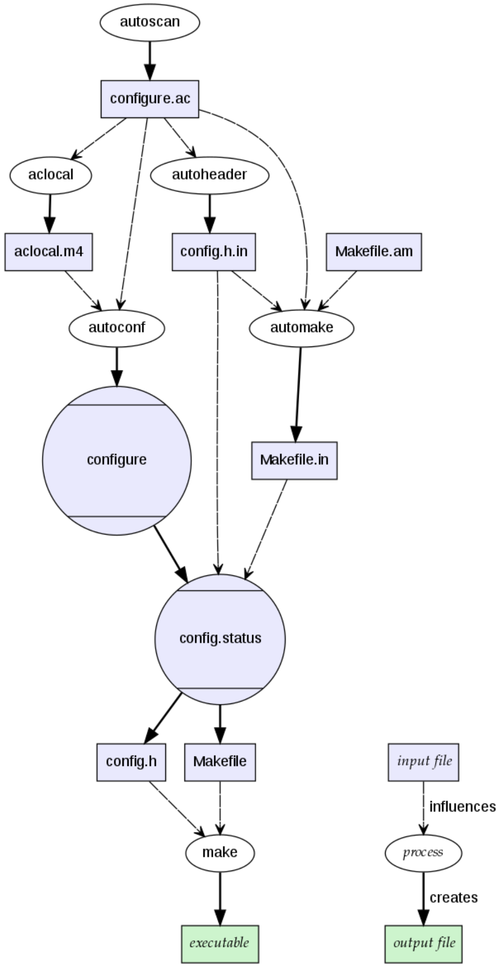
- The larger and more complex the project, the more difficult it is to...
  - Keep track of vast dependency information
  - Specify additional tasks before / after build
  - Adjust build options for different target platforms

- So, pure Makefiles are rarely used in the field. All serious projects on Unix/Linux use "Makefile generators" or alternatives.

3) Autotools

- Traditional Makefile generator
  - Many GNU tools are built using it

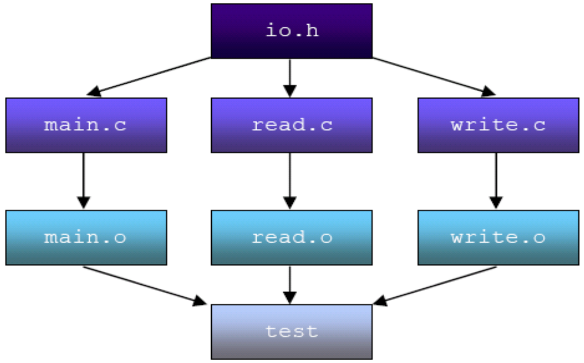
- Too complicated!
  - Main tools (autoconf, automake, libtool) are separate but highly dependent on each other
  - Need to know how to use other languages: bash script, m4
  - "autohell"



4) CMake

- Much easier to use with relatively simple syntax
- Cross-platform
  - On Unix/Linux: Generates Makefile
  - On Windows: Generates Visual Studio project file (.vcxproj)
- Some large open source projects has moved to CMake
  - KDE, https://lwn.net/Articles/188693/
  - https://gitlab.kitware.com/cmake/community/wikis/doc/cmake/Projects
- **Starting from Assignment 5-1, you should use CMake** instead of Make.

Example using Makefile



Makefile

```
test : read.o write.o main.o
    gcc -o test read.o write.o main.o

main.o : io.h main.c
    gcc -c main.c

read.o : io.h read.c
    gcc -c read.c

write.o: io.h write.c
    gcc -c write.c
```

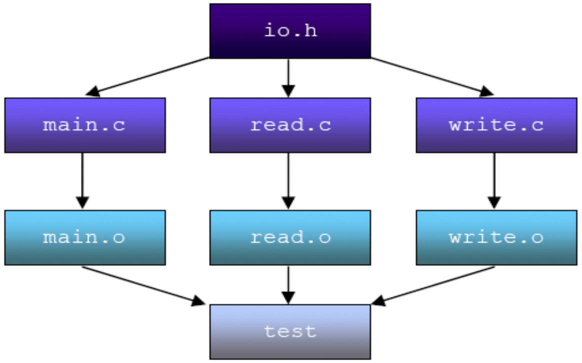
Makefile

```
CC=g++
SRCS=main.c read.c write.c
OBJS=$(SRCS:%.c=%.o)
TARGET=test

.SUFFIXES : .c .o

$(TARGET): $(OBJS)
    $(CC) -o $(TARGET) $(OBJS)

main.o: io.h main.c
read.o: io.h read.c
write.o: io.h write.c
```

(Shell)

```
make
```

Example using CMake



CMakeLists.txt

```
add_executable( test main.c read.c write.c )
```

command

target name

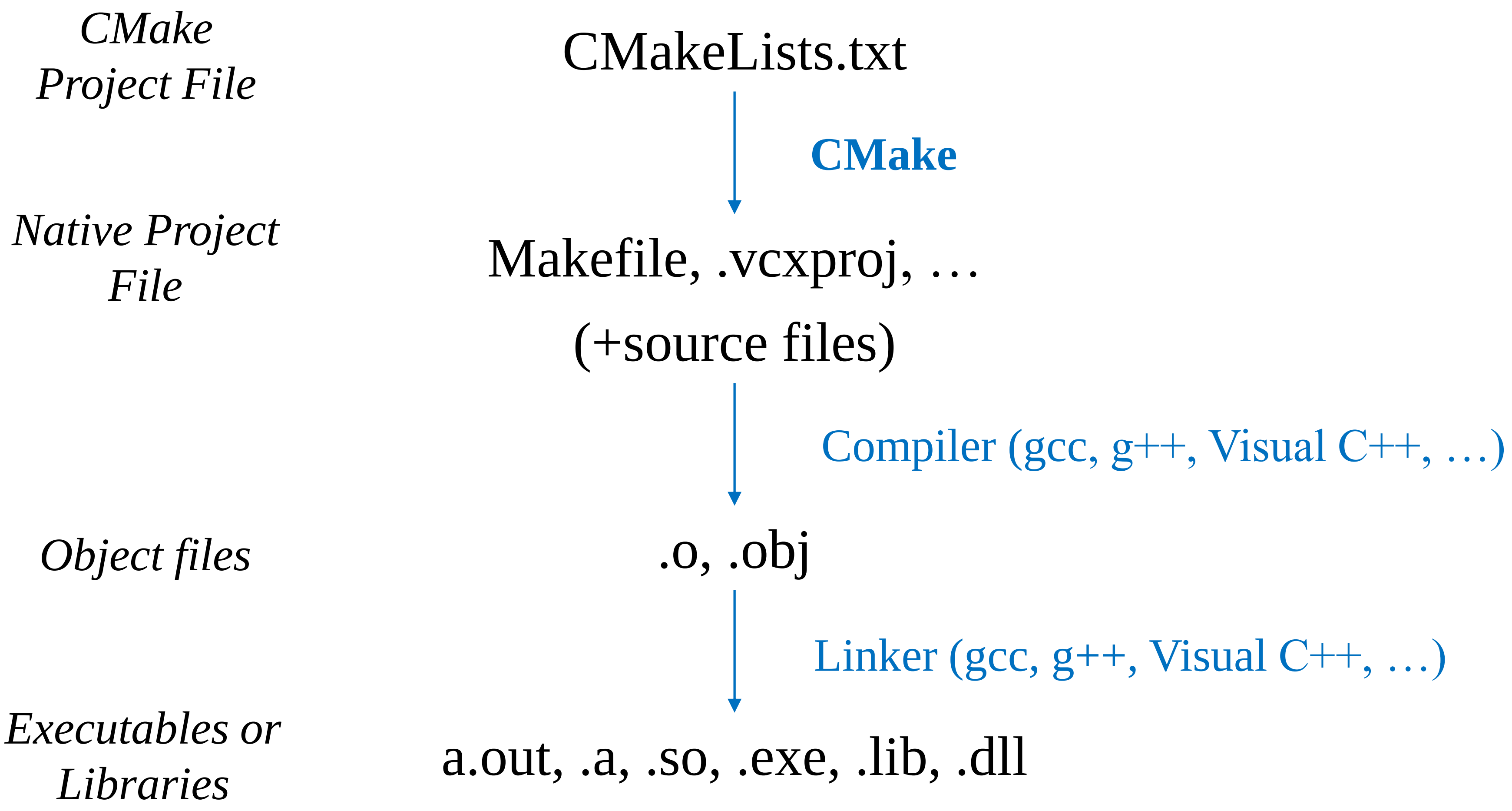
source files

arguments

(Shell)

```
cmake
make
```

Build Process using CMake



CMake Project File

CMakeLists.txt

CMake

Native Project File

Makefile, .vcxproj, …

(+source files)

Compiler (gcc, g++, Visual C++, …)

Object files

.o, .obj

Linker (gcc, g++, Visual C++, …)

Executables or Libraries

a.out, .a, .so, .exe, .lib, .dll

[Practice] CMake

- Install CMake

(Shell)

```
sudo apt-get install cmake
```

[Practice] CMake

- Create these files somewhere

myprint.h

```
#pragma once
void myprint(const
std::string& s, int n);
```

main.cpp

```
#include <string>
#include "myprint.h"

int main()
{
    myprint("hello world", 5);

    return 0;
}
```

myprint.cpp

```
#include <iostream>
#include <string>

void myprint(const std::string& s,
int n)
{
    for(int i=0; i<n; ++i)
        std::cout << s << std::endl;
}
```

CMakeLists.txt

```
add_executable(test main.cpp myprint.cpp)
```

[Practice] CMake

- Create a build directory & cd
  - The name does not have to be “build”.

(Shell)

```
mkdir build
cd build
```

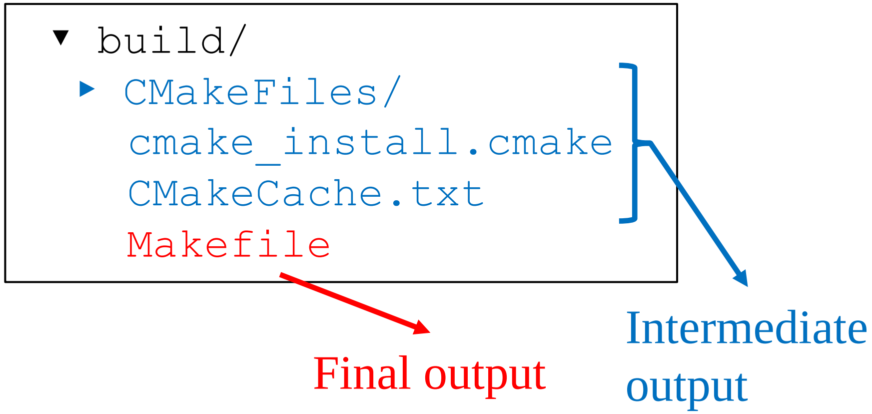
```
▼ test/
      build/
      CMakeLists.txt
      main.cpp
      myprint.h
      myprint.cpp
```

[Practice] CMake

- Run CMake
  - “Generate Makefile using CMakeLists.txt in the parent directory(../)”

(Shell)

```
cmake ../
```



```
▼ build/
  ▸ CMakeFiles/
    cmake_install.cmake
    CMakeCache.txt
    Makefile
```

Final output

Intermediate output

- Run Make
  - “Compile & link the project using Makefile in the current directory(./)”

(Shell)

```
make
```

(Shell)

```
./test # run the final executable
```

More about CMake

- We’ve just covered very basic usage of CMake

- The real power of CMake comes from more complicated projects using a bunch of libraries, subdirectories, etc.
  - add_library(), target_link_libraries(), add_subdirectory(), target_include_directories(), find_package(), ...

- More resource
  - https://cmake.org/cmake-tutorial/
  - https://cmake.org/cmake/help/v3.12/#reference-manuals

Next Time

- Labs for this lecture:
  - Lab1 (next Tue): Assignment 5-1
  - Lab2 (next Thur): Assignment 5-2

- Next lecture (next Fri):
  - 6 - Class