Compiling Fundamentals

15-213/15-513/14-513: Introduction to Computer Systems

Questions that will be answered today

- What does it mean to compile code?
- What does compiling code look like?
- How can code be compiled?
- What are Makefiles?

Why is this important?

- It is important to understand how programs are compiled to have a better understanding of how different parts of a computer interact with each other.
- Fundamental aspect of how computers run code.

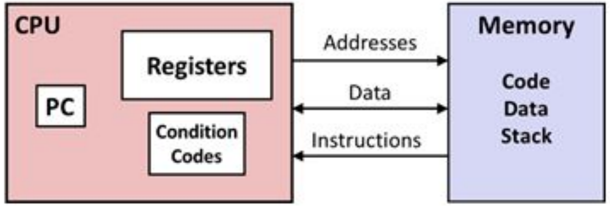
Levels of Abstraction

- C [and other high level languages] are easy for programmers to understand, but computers require lots of software to process them
- Machine code is just the opposite: easy for the computer to process, humans need lots of help to understand it
- Assembly language is a compromise between the two: readable by humans (barely), close correspondence to machine code

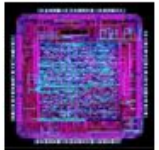
C programmer

```
#include <stdio.h>
int main(){
  int i, n = 10, t1 = 0, t2 = 1, nxt;
  for (i = 1; i <= n; ++i){
    printf("%d, ", t1);
    nxt = t1 + t2;
    t1 = t2;
    t2 = nxt; }
  return 0; }
```

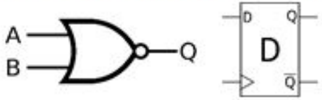
Assembly programmer



Computer designer

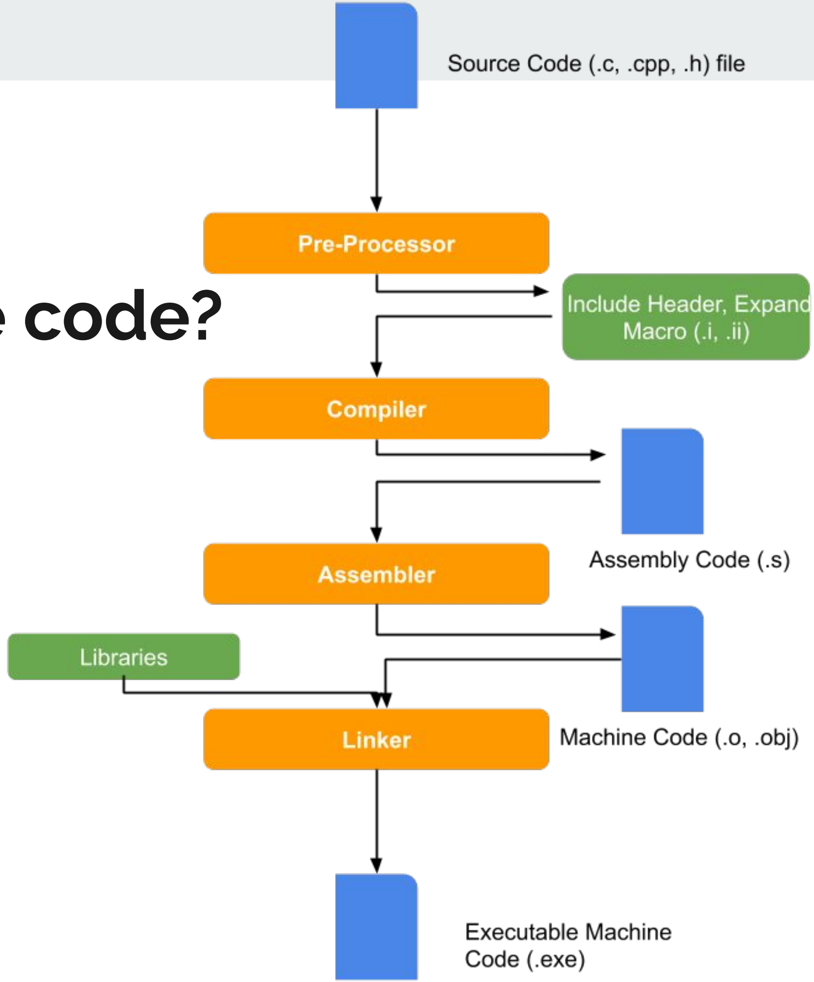


Gates, clocks, circuit layout, ...



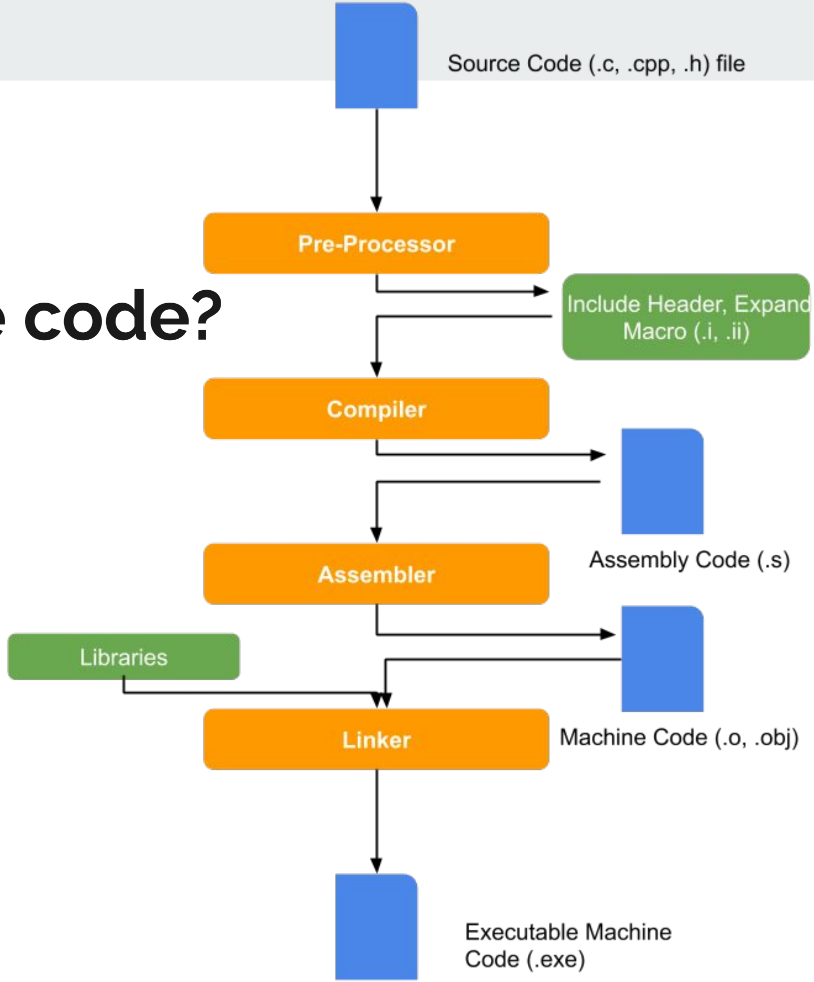
What does it mean to compile code?

- The computer only understands *machine code* directly
- All other languages must be either
  - *interpreted:* executed by software
  - *compiled:* translated to machine code by software



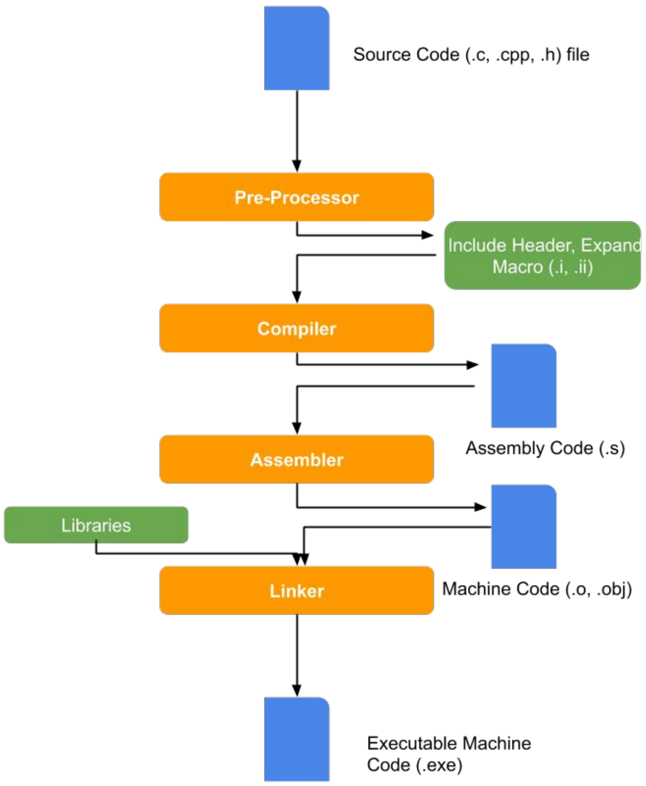
What does it mean to compile code?

- Computer follows steps to **translate** your code into something the computer can understand
- This is the process of **compiling** code [a compiler completes these actions]
- Four steps for C: preprocessing, compiling, assembling, linking
  - Most other compiled languages don't have the preprocessing step, but do have the other three



Stepping through the stages

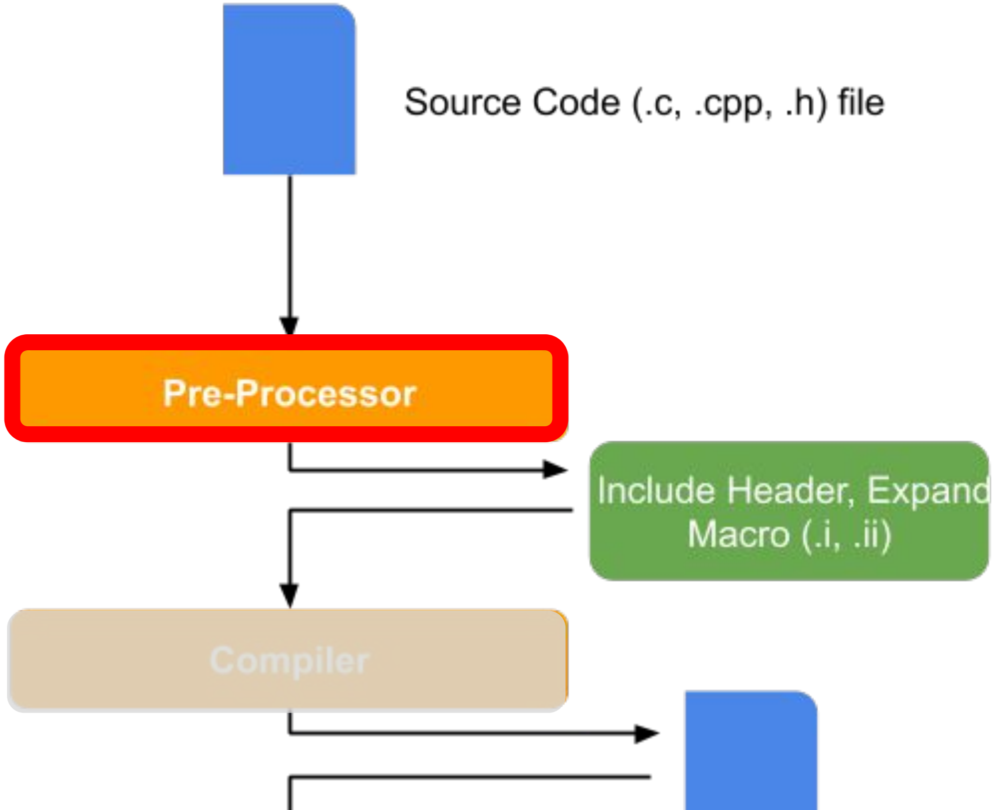
- Pre-Processor
  - $ gcc -E [flags] [filenames]
- Compiler
  - $ gcc -S [flags] [filenames]
- Assembler
  - $ gcc -c [flags] [filenames]
  - $ objdump -d [filenames]
- Linker
  - $ gcc -o [exename] [flags] [filenames]



C Code to Machine Code

Pre-Processor

- Peculiar to the C family; other languages don't have this
- Processes #include, #define, #if, macros
  - Combines main source file with headers (textually)
  - Defines and expands macros (token-based shorthand)
  - Conditionally removes parts of the code (e.g. specialize for Linux, Mac, ...)
- Removes all comments
- Output looks like C still



Before and after preprocessing

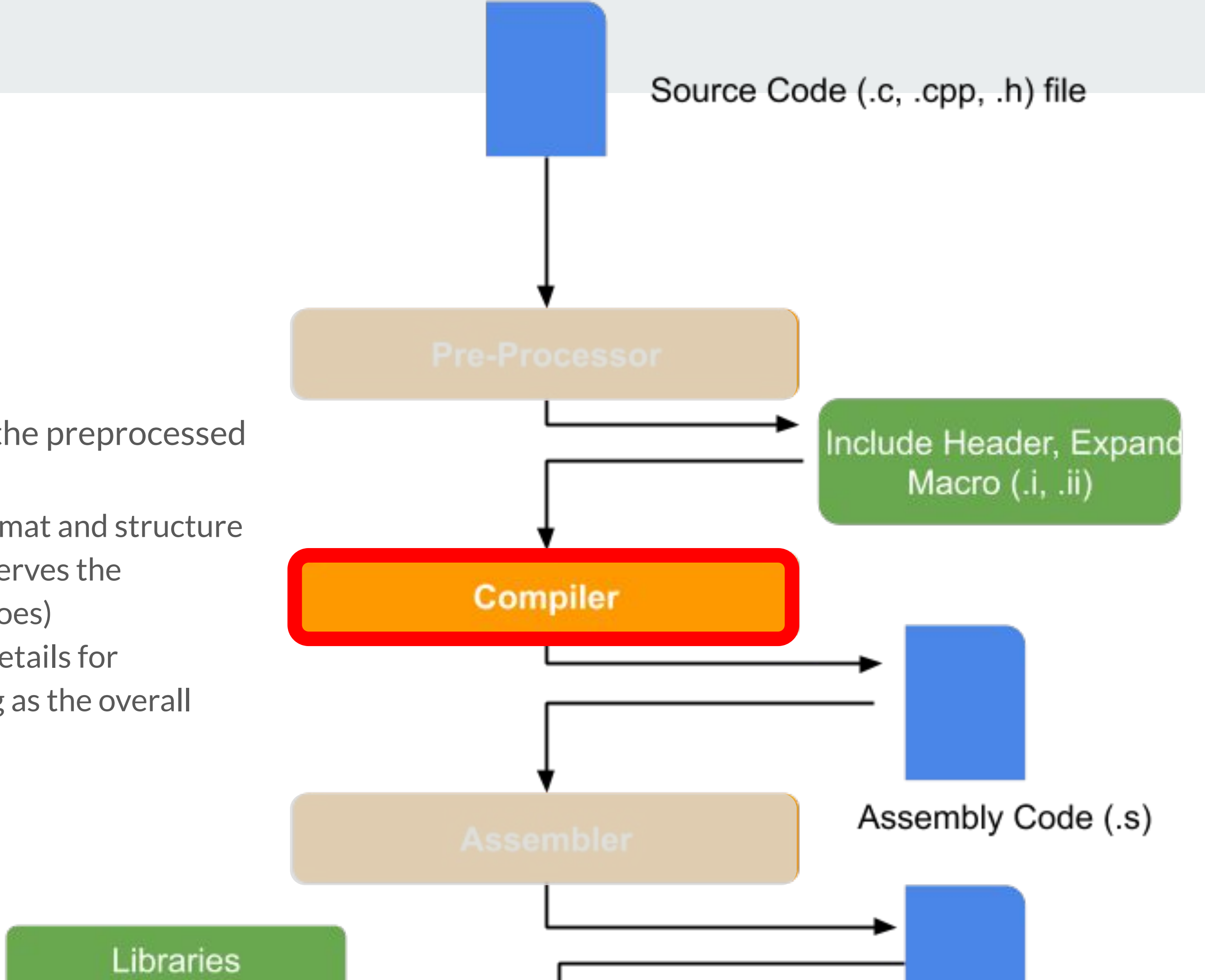
```c
#include <limits.h>
#include <stdio.h>

int main(void) {
    // Report the range of `char` on this system
    printf("CHAR_MIN = %d\n"
           "CHAR_MAX = %d\n",
           CHAR_MIN, CHAR_MAX);
    return 0;
}
```

- Contents of header files inserted inline
- Comments removed
- Macros expanded
- “Directive” lines (beginning with #) communicate things like original line numbers

```c
# 1 "test.c"
# 1 "/usr/lib/gcc/x86_64-linux-gnu/10/include/limits.h" 1 3 4
...
# 1 "/usr/include/stdio.h" 1 3 4
...
extern int fprintf (FILE *__restrict __stream,
        const char *__restrict __format, ...);
extern int printf (const char *__restrict __format, ...);
...
# 874 "/usr/include/stdio.h" 3 4
# 3 "test.c" 2

int main(void) {
    printf("CHAR_MIN = %d\n"
           "CHAR_MAX = %d\n",
# 6 "test.c" 3 4
           (-0x7f - 1)
# 6 "test.c"
                  , 0x7f);
    return 0;
}
```

Compiler

- The compiler translates the preprocessed code into assembly code
  - This changes the format and structure of the code but preserves the semantics (what it does)
  - Can change lots of details for optimization, as long as the overall effect is the same



Before and after compilation

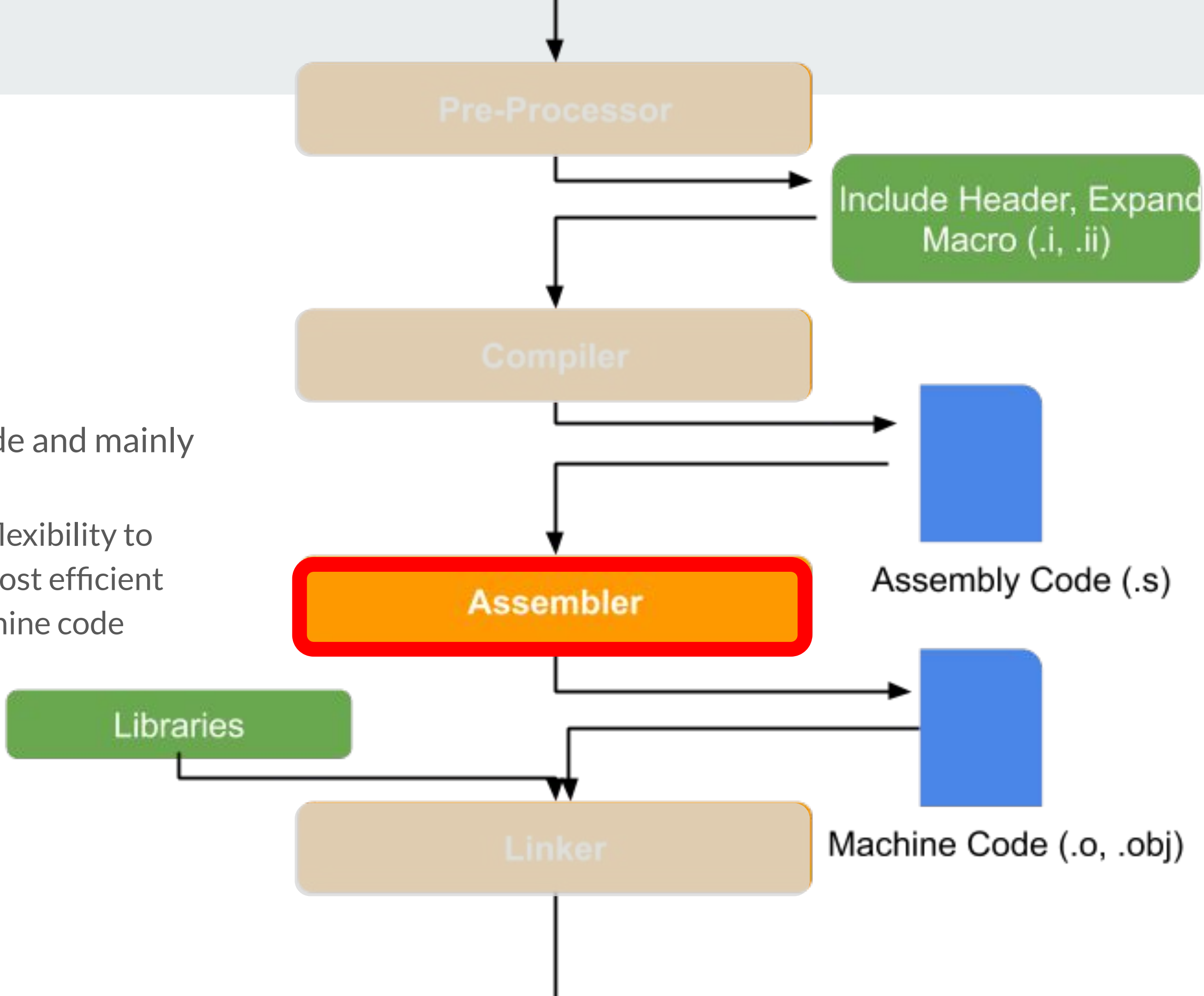
```
extern int printf (const char *__restrict
                         __format, ...);
int main(void) {
    printf("CHAR_MIN = %d\n"
           "CHAR_MAX = %d\n",
           (-0x7f - 1), 0x7f);
    return 0;
}
```

- C *source code* converted to *assembly language*
- Textual, but 1:1 correspondence to machine language
- String out-of-line, referred to by label (`.LC0`)
- `printf` just referred to, not declared

```
    .file     "test.c"
    .section    .rodata.str1.1,"aMS",@progbits,1
.LC0:
    .string     "CHAR_MIN = %d\nCHAR_MAX = %d\n"
    .text
    .globl     main
main:
    subq     $8, %rsp
    movl     $127, %edx
    movl     $-128, %esi
    leaq     .LC0(%rip), %rdi
    xorl     %eax, %eax
    call     printf@PLT
    xorl     %eax, %eax
    addq     $8, %rsp
    ret
    .size     main, .-main
```

Assembler

- Parses assembly code and mainly translates into bits
  - There is some flexibility to generate the most efficient version of machine code



Before and after assembling

```
    .file    "test.c"
    .section    .rodata.str1.1,"aMS",@progbits,1
.LC0:
    .string    "CHAR_MIN = %d\nCHAR_MAX = %d\n"
    .text
    .globl    main
main:
    subq    $8, %rsp
    movl    $127, %edx
    movl    $-128, %esi
    leaq    .LC0(%rip), %rdi
    xorl    %eax, %eax
    call    printf@PLT
    xorl    %eax, %eax
    addq    $8, %rsp
    ret
    .size    main, .-main
```

- Everything is now binary
- “Relocations” for addresses not yet known

```
$ objdump -s -r test.o
test.o: file format elf64-x86-64

RELOCATION RECORDS FOR [.text]:
OFFSET           TYPE              VALUE
0000000000000011 R_X86_64_PC32     .LC0-0x0000000000000004
0000000000000018 R_X86_64_PLT32   printf-0x0000000000000004

Contents of section .rodata.str1.1:
 0000 43484152 5f4d494e 203d2025 640a4348  CHAR_MIN = %d.CH
 0010 41525f4d 4158203d 2025640a 00        AR_MAX = %d..

Contents of section .text:
 0000 4883ec08 ba7f0000 00be80ff ffff488d  H.............H.
 0010 3d000000 0031c0e8 00000000 31c04883  =....1......1.H.
 0020 c408c3                               ...
```

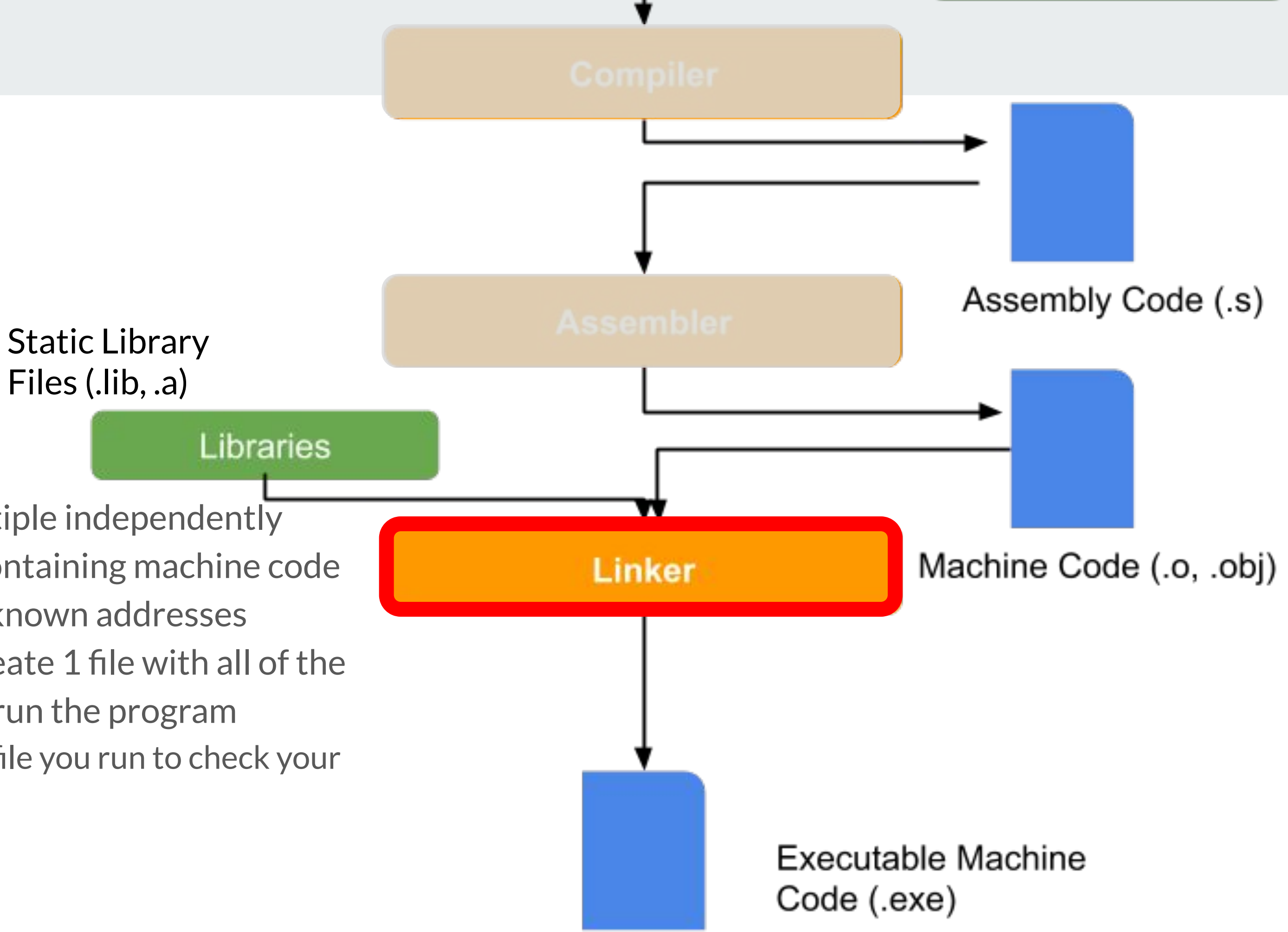
Before and after assembling

```
    .file    "test.c"
    .section    .rodata.str1.1,"aMS",@progbits,1
.LC0:
    .string    "CHAR_MIN = %d\nCHAR_MAX = %d\n"
    .text
    .globl    main
main:
    subq    $8, %rsp
    movl    $127, %edx
    movl    $-128, %esi
    leaq    .LC0(%rip), %rdi
    xorl    %eax, %eax
    call    printf@PLT
    xorl    %eax, %eax
    addq    $8, %rsp
    ret
    .size    main, .-main
```

- Just to emphasize that 1:1 correspondence between assembly and machine instructions

```
$ objdump -d -r test.o
test.o: file format elf64-x86-64
Disassembly of section .text.startup:

0000000000000000 <main>:
   0:    48 83 ec 08              sub     $0x8,%rsp
   4:    ba 7f 00 00 00           mov     $0x7f,%edx
   9:    be 80 ff ff ff           mov     $0xffffff80,%esi
   e:    48 8d 3d 00 00 00 00     lea     0x0(%rip),%rdi
                   11: R_X86_64_PC32 .LC0-0x4
  15:    31 c0                    xor     %eax,%eax
  17:    e8 00 00 00 00           call    1c <main+0x1c>
             18: R_X86_64_PLT32    printf-0x4
  1c:    31 c0                    xor     %eax,%eax
  1e:    48 83 c4 08              add     $0x8,%rsp
  22:    c3                       ret
```

Linker



- Aggregates multiple independently compiled files containing machine code
- Fills in those unknown addresses
- The goal is to create 1 file with all of the needed code to run the program
    - This is the file you run to check your code!

How to Use The Compiler (gcc)

GCC - What is it?

- GNU Compiler Collection
  - GCC is a set of compilers for various languages. It provides all of the infrastructure for building software in those languages from source code to assembly.
- The compiler can handle compiling everything on its own, but you can use various flags to breakdown the compilation steps
- Example:

```
gcc [flags] [infile(s)]
```

Common GCC Flags

-o [EXECUTABLE NAME] : names executable file

-Ox : Code optimization

- **-O0** : Compile as fast as possible, don’t optimize [this is the default]
- **-O1**, **-O2**, **-O3**: Optimize for reduced execution time [higher numbers are more optimized]
- **-Os** : Optimize for code size instead of execution time.
- **-Og** : Optimize for execution time, but try to avoid making interactive debugging harder.

-g : produce “debug info”: annotate assembly so gdb can find variables and source code

-Wall : enable many “warning” messages that *should* be on by default, but aren’t

- Does *not* turn on all of the warning messages GCC can produce.
- See https://gcc.gnu.org/onlinedocs/gcc-4.8.0/gcc/Warning-Options.html for many more

-Werror : turns all warnings into errors

-std=c99 : use the 1999 version of the C standard and disable some (not all!) extensions

Makefiles

What is a makefile?

- Automates the process of creating files (using a compiler)
- For example, create **`bomb`** from `bomb.c`, `phases.c`, and `util.c`
- Running `make bomb` will update bomb
  - *Only* if any of the source files have changed;
    avoids unnecessary work
  - Remembers complicated compiler commands for you
- Can also store recipes for automating development tasks
  - `make format` to reformat source files

Makefiles are lists of *rules*

- There are two kinds of rules: **normal** and **phony**
  - Normal rules create files
  - Phony rules don't directly create files
- Each rule has a **target**.
  - For **normal** rules, the target is the name of the file that the rule will create
  - For **phony** rules, the target is an arbitrary name for what the rule does
- Rules may have **prerequisites** (also known as **dependencies**)
  - Prerequisites are the files that are needed to create the target
  - If any of the prerequisites doesn't exist, it must be created first
  - If any of the prerequisites is newer than the target, the target is "out of date" and must be re-created
- Rules may have **commands**.
  - One or more shell commands that create the target from its prerequisites
  - For phony rules, just some commands to be run

Normal rule example

```
bomb: bomb.o phases.o util.o
	$(CC) -o bomb bomb.o phases.o util.o
```

Normal rule example

If this file
doesn't exist…

… or if it is older than any of these files…

```
bomb: bomb.o phases.o util.o
    $(CC) -o bomb bomb.o phases.o util.o
```

… then run this command.

Normal rule example

If this file doesn't exist…

… or if it is older than any of these files…

```
bomb: bomb.o phases.o util.o
    $(CC) -o bomb bomb.o phases.o util.o
```

This refers to the value of a *variable*, named CC, that holds the name of a C compiler.

… then run this command.

Normal rule without prerequisites

```
output_dir:
    mkdir output_dir
```

- Run `mkdir output_dir` if `output_dir` does not exist
- If it does exist, no action

Normal rule without commands

```
bomb.o: bomb.c support.h phases.h
```

- Re-create bomb.o if any of bomb.c, support.h, phases.h is newer
- The commands to do this are given somewhere else
  - A *pattern rule* elsewhere in the Makefile
  - An *implicit rule* built into Make

Pattern and implicit rules

```
%.o: %.c
    $(CC) $(CFLAGS) -c -o $@ $<
```

- To create an .o file from a .c file with the same base name, use this command
- Special variables $@ and $< give the name of the .o and .c files respectively
- Variables CC and CFLAGS can be set to customize behavior

- This rule is *implicit* — built into Make — you don't have to write it yourself

Phony rule example

```
all: bomb bomb-solve
.PHONY: all
```

- When asked to create “all”, create `bomb` and `bomb-solve`
- Does **not** create a file named “all”
- The `.PHONY` annotation can be anywhere in the makefile

Phony rule example 2

```
clean:
    rm -f bomb bomb-solve *.o
.PHONY: clean
```

- When asked to create “clean”, run this command
  - Which deletes `bomb`, `bomb-solve`, and all object files
- Does **not** create a file named “clean”

The `make` command

- Running **`make`** in the shell will cause the shell to look for a Makefile in the current directory. If it finds one, it will attempt to create the first target listed in the Makefile.
- You can also run **`make`** <target_name> to indicate exactly which target you want to create.
- By convention, the first target is a phony target named `all`
  - so `make` and `make all` do the same thing
  - as the name implies, this is to create everything that the makefile knows how to create
- Phony rules serve as entry points into the Makefile
  - `make all` creates everything, `make clean` deletes all generated files, `make check` runs tests, …
  - But you can also `make bomb.o` if that's the only thing you want

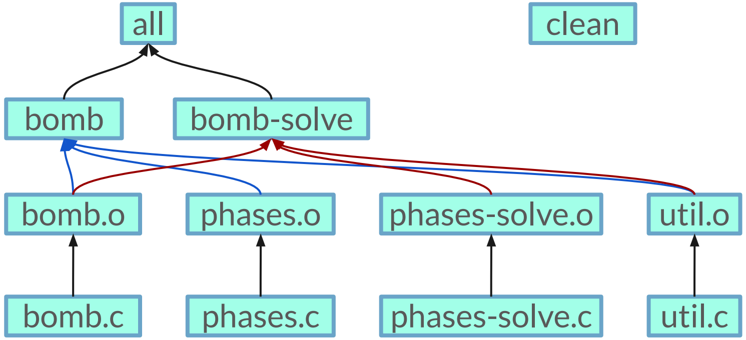
A complete Makefile

```
CC = gcc
CFLAGS = -std=c99 -g -O2 -Wall -Werror

all: bomb bomb-solve
bomb: bomb.o phases.o util.o
	$(CC) $(LDFLAGS) -o $@ $^ $(LIBS)

bomb-solve: bomb.o phases-solve.o util.o
	$(CC) $(LDFLAGS) -o $@ $^ $(LIBS)

bomb.o: bomb.c phases.h support.h
phases.o: phases.c phases.h support.h
phases-solve.o: phases-solve.c phases.h support.h
util.o: util.c support.h

clean:
	rm -f bomb bomb-solve *.o

.PHONY: all clean
```

- OK to use undefined variables
  - LDFLAGS, LIBS
  - Found in environment or treated as empty
- Don't need to give commands to create object files from C source
  - But do need to list header file dependencies for each object file
- *Do* need to give commands to create executables (missing feature)
- `all` rule at the top, `clean` rule at the bottom
- One `.PHONY` annotation for all phony rules

Rules form a graph

```
CC = gcc
CFLAGS = -std=c99 -g -O2 -Wall -Werror

all: bomb bomb-solve
bomb: bomb.o phases.o util.o
	$(CC) $(LDFLAGS) -o $@ $^ $(LIBS)

bomb-solve: bomb.o phases-solve.o util.o
	$(CC) $(LDFLAGS) -o $@ $^ $(LIBS)

bomb.o: bomb.c phases.h support.h
phases.o: phases.c phases.h support.h
phases-solve.o: phases-solve.c phases.h support.h
util.o: util.c support.h

clean:
	rm -f bomb bomb-solve *.o

.PHONY: all clean
```



- Make avoids unnecessary work
  - If `bomb.c` changes, make all will re-create `bomb.o`, `bomb`, `bomb-solve`
  - If `phases.c` changes, make all will only re-create `phases.o` and `bomb`
- Make can see through missing targets
  - If `bomb.o` does not exist, `make bomb` creates it from `bomb.c`

Practice!

https://www.cs.cmu.edu/~213/bootcamps/lab3_handout.pdf

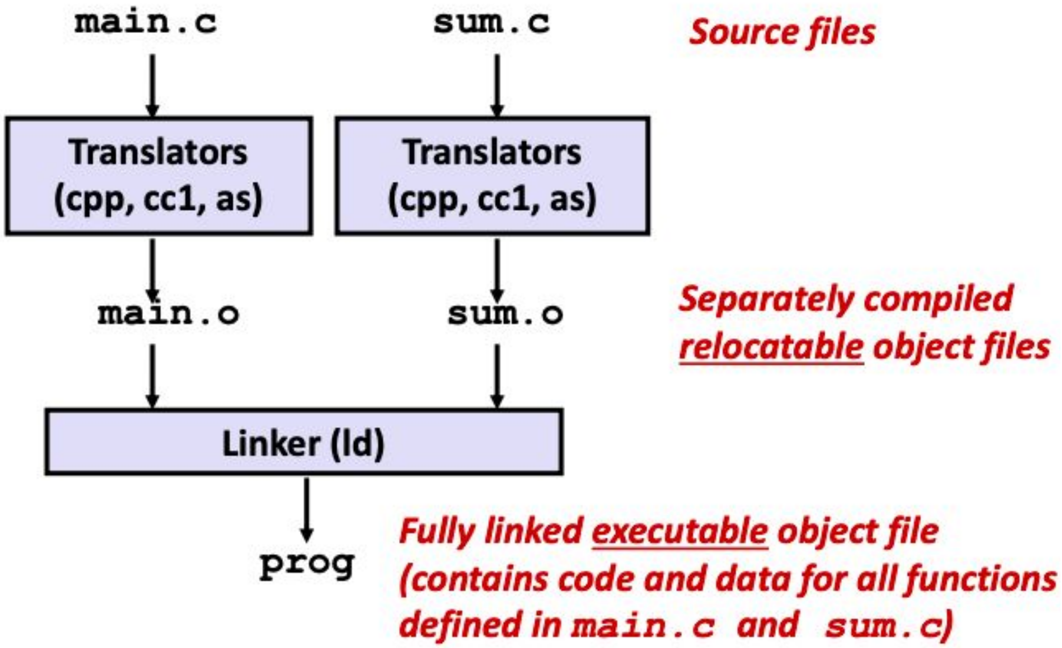
Feedback:
https://tinyurl.com/213bootcamp2

Appendix

Linking Files

Why are we learning about linking files?

- Linker is a computer system program that object files (generated by a compiler or an assembler) and combines them into a single executable file, library file, or another object file.
- Programs are translated and linked using a compiler driver:
  - `linux> gcc -Og -o prog main.c sum.c`
  - `linux> ./prog`
- More in future lecture!



What does a linker do?

- Symbol resolution
  - Programs define and reference *symbols* (global variables and functions)
  - Linker associates each symbol reference with exactly 1 symbol definition
- Relocation
  - Merges separate code and data sections into single sections
  - Relocates symbols from relative locations in .o files to final memory locations
  - Updates all references to symbols to reflect new positions

Linker symbols

- Global symbols
  - Symbols defined by module m that can be referenced by other modules.
    - e.g., non-static C functions and non-static global variables.
- External symbols
  - Global symbols that are referenced by module m but defined by some other module.
- Local symbols
  - Symbols that are defined and referenced exclusively by module m.
    - e.g., C functions and global variables defined with the static attribute.
  - Local linker symbols are not local program variables

Symbols

Definitions

```c
int sum(int *a, int n);

int array[2] = {1, 2};

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
```

main.c

```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

sum.c

Reference

Why do you need linkers?

- Modularity
  - Program can be written as a collection of smaller source files, rather than one monolithic mass.
- Efficiency
  - Time: Separate compilation
    - Change one source file, compile, and then relink. No need to recompile other source files.
  - Space: Libraries
    - Common functions can be aggregated into a single file...

Static vs Dynamic Linking

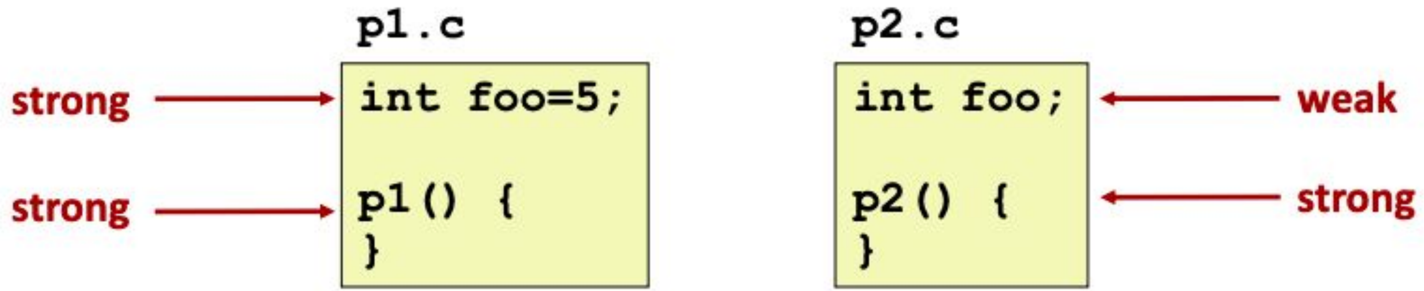
- Static Linking
  - Executable files and running memory images contain only the library code they actually use
- Dynamic linking
  - Executable files contain no library code
  - During execution, single copy of library code can be shared across all executing processes

Types of object files

- Relocatable object file (.o file)
    - Code and data that can be combined with other relocatable object files to form executable object file
        - Each .o file is produced from exactly one source (.c) file
- Executable object file (a.out file)
    - Code and data that can be copied directly into memory and then executed
- Shared object file (.so file)
    - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time

How Linker resolves duplicate symbol definitions

- Program symbols are either *strong* or *weak*
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals
    - Or one's declared with specifier `extern`



Symbol rules

1. Multiple strong symbols are not allowed
    - Each item can be defined only once
2. Given a strong symbol and multiple weak symbols, choose the strong symbol
    - References to the weak symbol resolve to the strong symbol
3. If there are multiple weak symbols, pick an arbitrary one

LD_LIBRARY_PATH

- If you are using dynamic libraries, you need to tell the compiler where to look for the library!
- It is easiest to use dynamic libraries with makefiles, just include this line:

```
LD_LIBRARY_PATH = "~/my/path"
```

- If you are interested in creating a dynamic library, follow the steps here:
  - Shared Libraries: https://tldp.org/HOWTO/Program-Library-HOWTO/shared-libraries.html
  - Dynamic Libraries: https://tldp.org/HOWTO/Program-Library-HOWTO/dl-libraries.html

Resources

https://missing.csail.mit.edu/2020/metaprogramming/
https://www.cs.cmu.edu/~15131/f17/topics/makefiles/
https://www.gnu.org/software/make/manual/html_node/Phony-Targets.html
https://makefiletutorial.com/
https://www.oreilly.com/library/view/programming-embedded-systems/0596009836/ch04.html
https://gcc.gnu.org/onlinedocs/gcc/
https://daveparillo.github.io/cisc187-reader/build-tools/make.html