Admin

YEAH Repeat, today 2pm (🥰 Ishita)

Interest in `printf` code jam this weekend? When is best?

Today: Modules, Linking

Modules and libraries

- What makes for good design?

Build process

- How do source files become an executable?
- What does the linker do?
- Understanding and diagnosing build errors

How does a program begin executing?

Road map

Processor and memory architecture

Peripherals: GPIO, timers, UART

Assembly language and machine code

From C to assembly language

Function calls and stack frames

Serial communication and strings

Modules and libraries: Building and linking

Memory: Memory map, stack & heap

gpio ✓

timer ✓

uart ✓

strings

printf

malloc

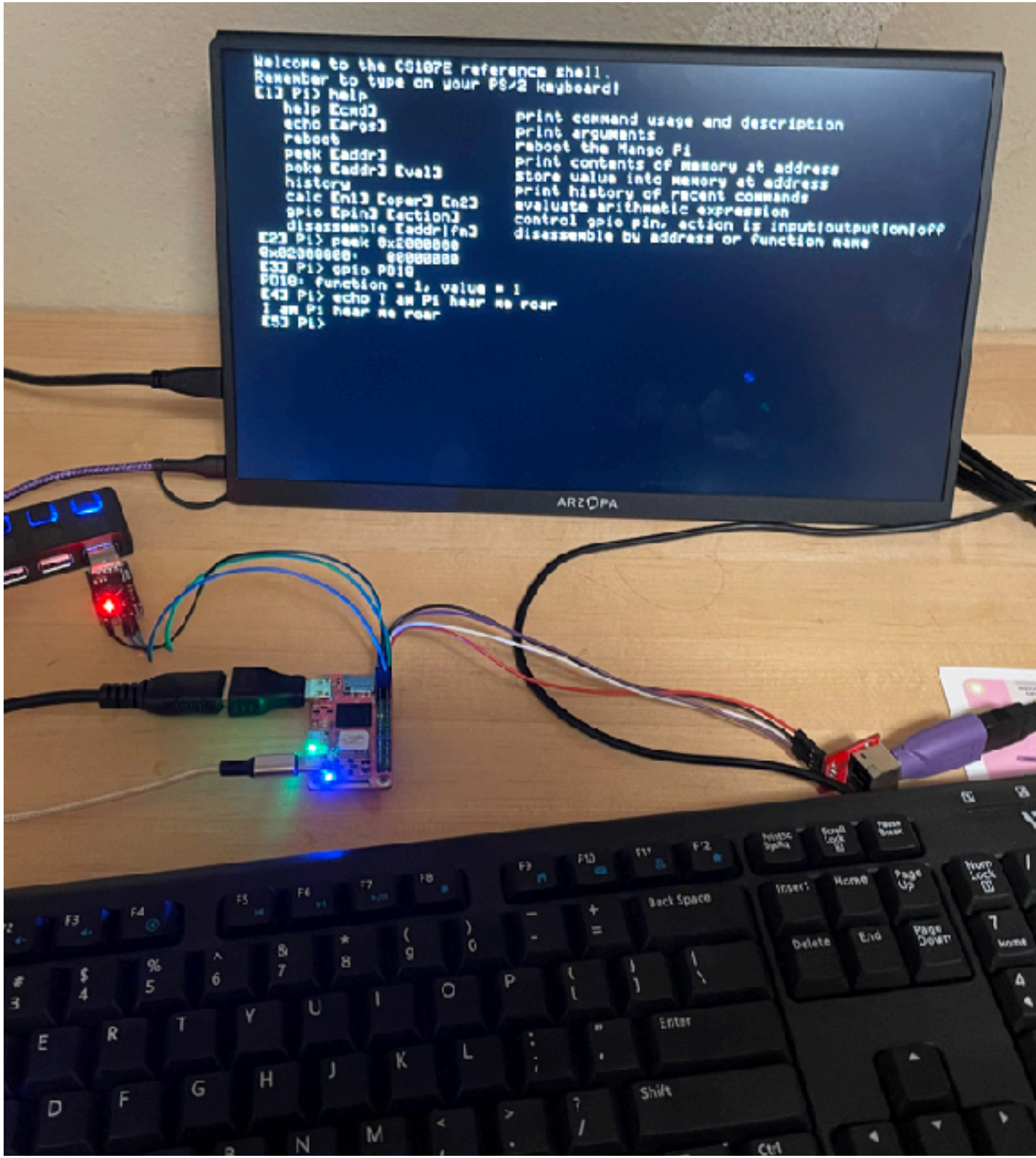
keyboard

fb

gl

console

shell



Good software design

Decompose a system into smaller parts (modules)

- **Interface**: what the module does
- **Implementation**: how it does it

A good interface is:

- Easy-to-understand abstraction that simplifies client use
- Can be implemented easily and in different ways, portable

Module is tested independently with unit tests

Designing good interface boundaries is the "art" of software engineering

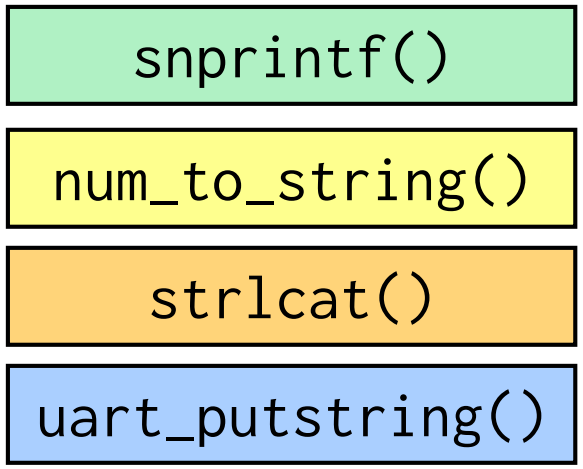
Module example: printf

Interface is single feature— make formatted string

```
int printf(const char* format, ...);
```

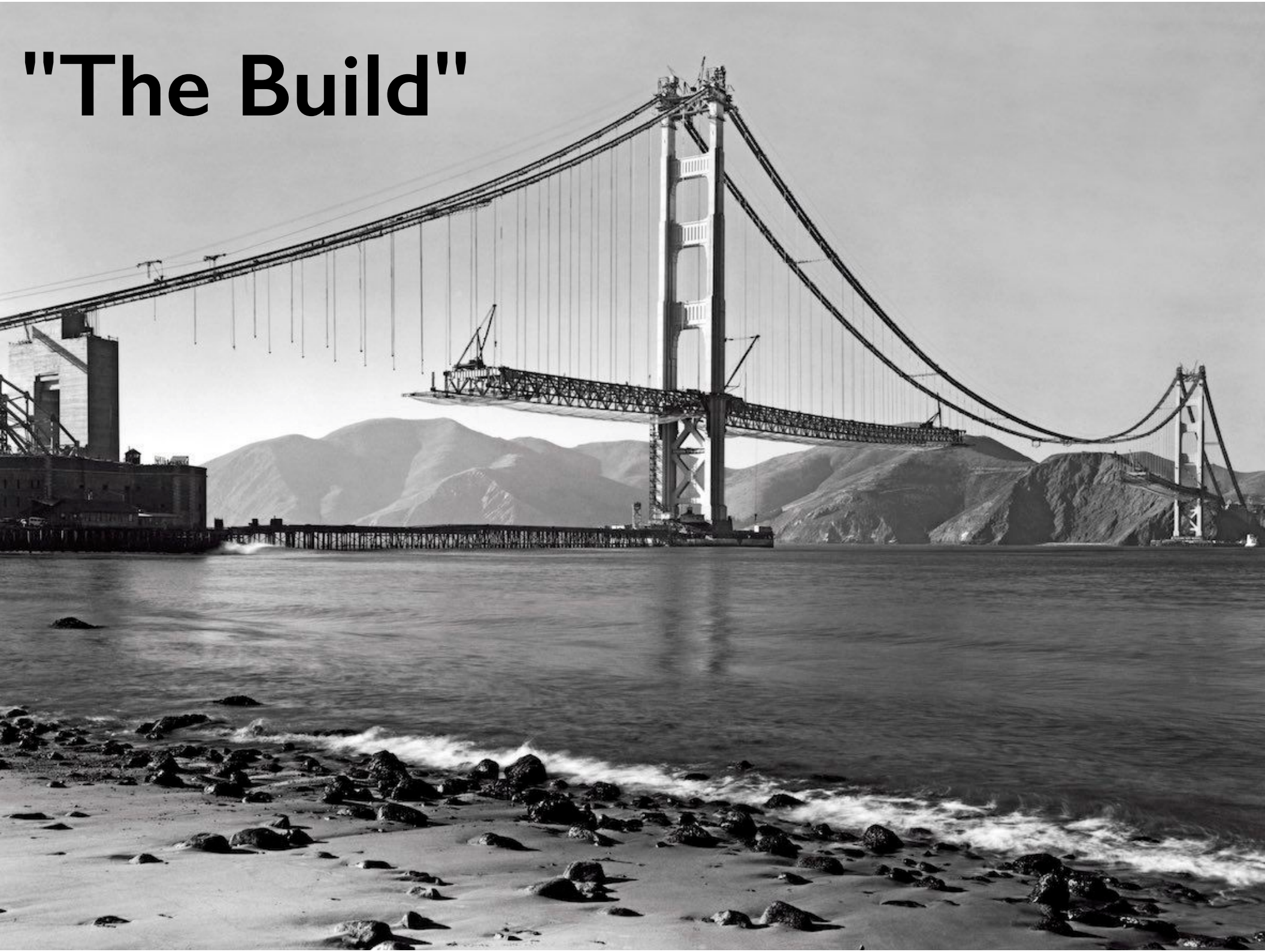
Implementation is complex, must:

- Parse format string
- Convert arguments into strings
- Concatenate conversions into one string
- Output string over uart



Decompose problem into smaller, simpler tasks, test independently, build up in layers

"The Build"



NASA Command Center during SpaceX mission

CS107e Command Center: Makefile

```
APPLICATION = clock
MY_MODULES = gpio.o timer.o

ARCH    = -march=rv64im -mabi=lp64
ASFLAGS = $(ARCH)
CFLAGS  = $(ARCH) -Og -g -Wall -ffreestanding
LDFLAGS = -nostdlib -T memmap.ld
LDLIBS  =

all : $(APPLICATION).bin

%.bin: %.elf
   riscv64-unknown-elf-objcopy $< -O binary $@

%.elf: %.o $(MY_MODULES) cstart.o start.o          LINKER
   riscv64-unknown-elf-ld $(LDFLAGS) $^ $(LDLIBS) -o $@

%.o: %.c                                          COMPILER
   riscv64-unknown-elf-gcc $(CFLAGS) -c $< -o $@

%.o: %.s                                          ASSEMBLER
   riscv64-unknown-elf-as $(ASFLAGS) $< -o $@
```

Build process

PREPROCESSOR: **`cpp`** `(code.c -> code.i)`

Input: C source file

Output: replace **`#include`** and **`#define`** with text expansions

COMPILER: **`cc1`** `(code.i -> code.s)`

Input: preprocessed C source file

Output: assembly file

ASSEMBLER: **`as`** `(code.s -> code.o)`

Input: assembly file

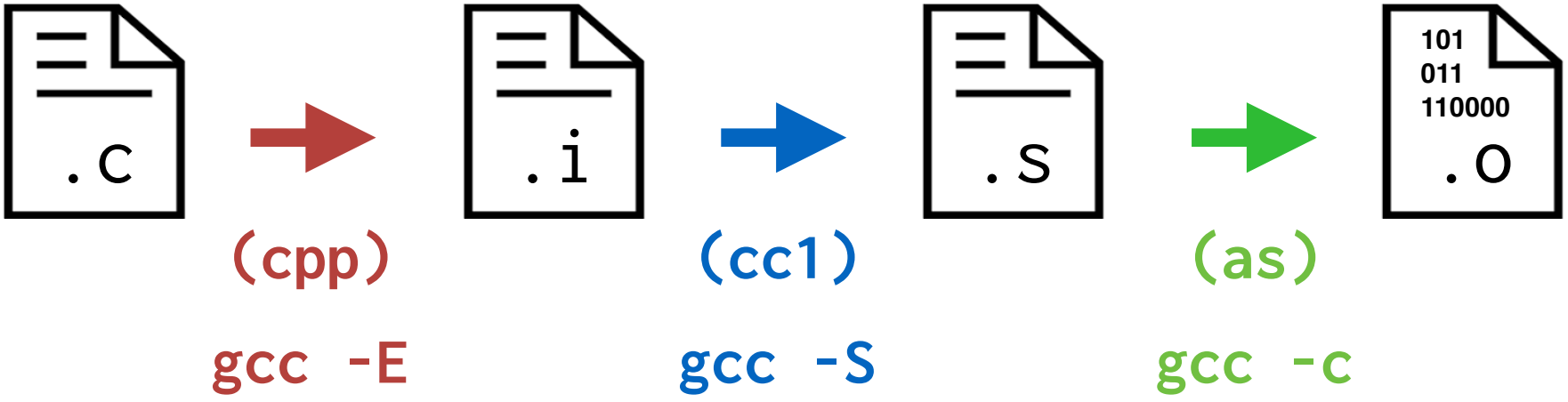
Output: machine code (binary-encoded)

LINKER: **`ld`** `(code.o -> code.elf)`

Input: multiple .o files, libraries

Output: executable

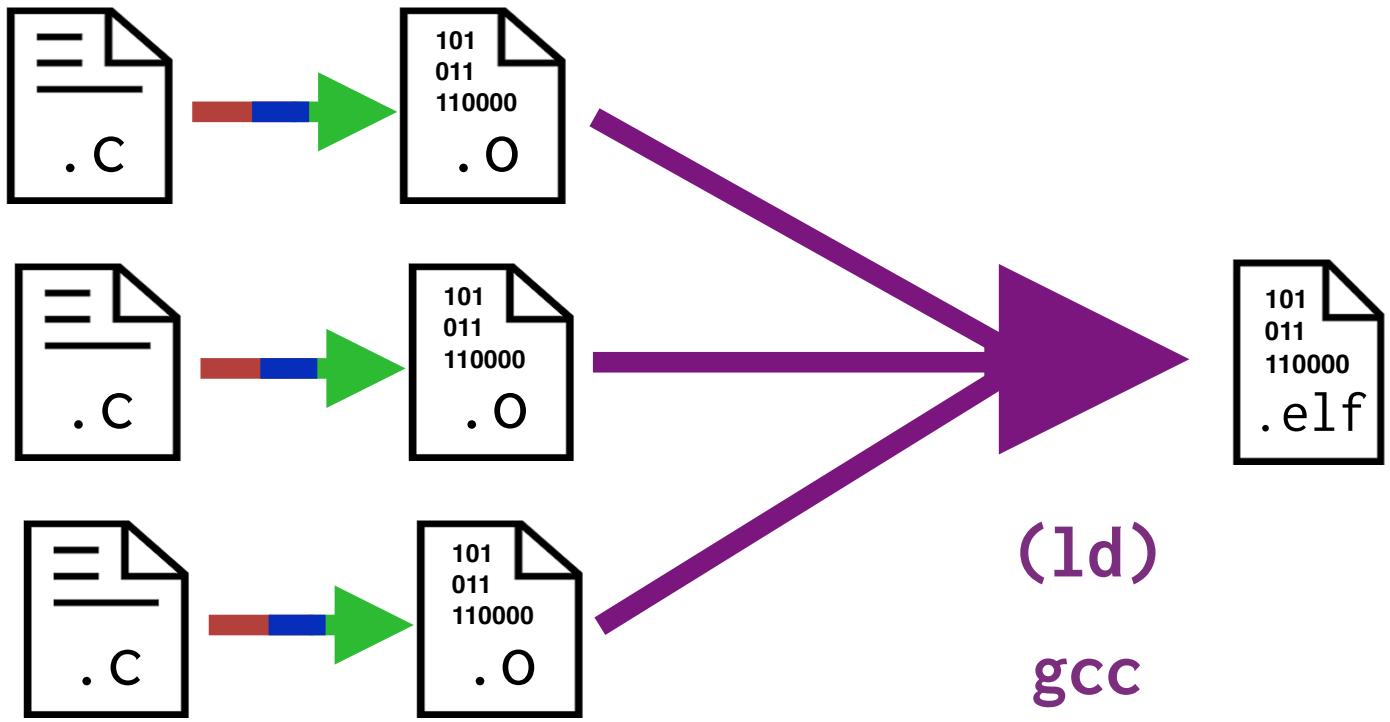
Compiling a single module



want to see intermediate files?

```
gcc --save-temps
```

Link modules into executable



`Combines clock.o timer.o gpio.o start.o cstart.o`

What does the linker do?

Combines one or more object files into executable

Resolve inter-module references

Consolidate code, data sections across all modules

Arrange sections in output file in proper order

Symbols

C has single global namespace

- Each name can have only one definition
- Need conventions to avoid name clashes
  - e.g. `gpio_init` versus `timer_init`

Qualifier dictates symbol visibility and link behavior

- `static` private to module, not visible outside, no linking needed
- `extern` public, visible to other modules, cross-module references need link

Linker only concerned with extern symbols

Symbol resolution

Rule: Every symbol referenced must be defined once and exactly once

Linker errors during symbol resolution:

Multiply-defined: two definitions for same symbol

Undefined: needed symbol never defined

Linker resolution process

Set D (symbols that have been defined)

Set U (symbols that have been referenced, but not yet defined)

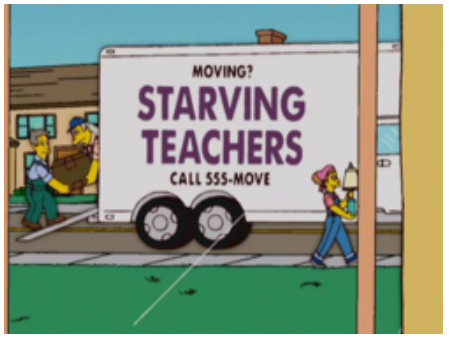
Linker processes .o files in order from left to right

Process each .o updates **Set U** and **Set D**

Continue until all .o processed

If end with **Set U** empty and **Set D** has no duplicates, link successful!

Symbol relocation



In .o file:

each symbol assigned a temporary address (offset within module)

reference to symbols within same module is PC-relative

In executable file:

modules consolidated into one file, laid out end to end

first module starts at address `0x40000000`

base for each subsequent module is offset by size of previous modules

final address of each symbol =

module_base + symbol_offset_within_module

start.s

```
.globl _start
_start:
    lui     sp,0x50000
    jal     _cstart
hang: j hang
```

start.o disassembly

```
   0:  lui    sp,0x50000
   4:  jal    0
   8:  j      8 <hang>
```

Target address for `j hang` is 8, encoded as PC-relative offset (in this case, `pc+0`)

Target address for `jal _cstart` is 0 (placeholder!).
File `start.s` doesn't know where `_cstart` is! (Why not?)

```
// Disassembly of clock.elf

0000000040000000 <_start>:
    40000000:  lui sp,0x5000
    40000004:  jal 400000e4 <_cstart>

0000000040000008 <hang>:
    4000000c:  j  40000008 <hang>
```

All addresses have been relocated/finalized

Address of **`_cstart`** is now known — **`400000e4`**

The linker worked it out and replaced target placeholder with function's actual address

```
0000000040000000 T _start
0000000040000008 t hang                    start.o
000000004000000c t blink
0000000040000050 T main                    clock.o
0000000040000150 T _cstart                 cstart.o
00000000400001a8 T gpio_init
00000000400001ac T gpio_set_input
00000000400001b0 T gpio_set_output
00000000400001b4 T gpio_set_function
00000000400001b8 T gpio_get_function
00000000400001c0 T gpio_write
00000000400001c4 T gpio_read               gpio.o
00000000400001cc T timer_get_ticks
00000000400001d4 T timer_init
00000000400001d8 T timer_delay_us
0000000040000210 T timer_delay
0000000040000234 T timer_delay_ms          timer.o
0000000040000288 R __bss_end
0000000040000288 R __bss_start
```

Handling of global data

Variable declared outside functions have global scope and program lifetime
(can be extern/static, read-only, initialized/not)

```
                              // uninitialized
int gNum;
static int sgNum;

                              // initialized
int iNum = 1;
static int siNum = 2;

                              // const
const int cNum = 3;
static const int scNum = 4;
```

```
$ riscv64-unknown-elf-nm -U -n data.o
0000000000000004 R cNum
0000000000000004 B gNum
0000000000000004 D iNum
000000000000002c T main
0000000000000000 r scNum
0000000000000000 b sgNum
0000000000000000 t show_var
0000000000000000 d siNum
```

LEGEND

T/t = text (code)

D/d = read-write data

R/r = read-only data (**const**)

B/b = bss (*Block Started by Symbol*)

C = common (instead of B)

lowercase letter means **static**, uppercase **extern**

Libraries

An archive .a is just a collection of modules (.o files)

Linker looks in library to find definitions for symbols in **Set U** (undefined). When symbol is found, entire module is linked in.

If linking this module results in new undefined symbols, they are added to **Set U**. Process repeats until no additional undefined symbols, move on to next library

Building with libmango

```
ARCH    = -march=rv64im -mabi=lp64
CFLAGS  = $(ARCH) -Og -I$$CS107E/include -Wall -ffreestanding
LDFLAGS = -nostdlib -L$$CS107E/lib -T memmap.ld
LDLIBS  = -lmango

%.bin: %.elf
    riscv64-unknown-elf-objcopy $< -O binary $@

%.elf: %.o
    riscv64-unknown-elf-gcc $(LDFLAGS) $^ $(LDLIBS) -o $@

%.o: %.c
    riscv64-unknown-elf-gcc $(CFLAGS) -c $< -o $@
```

Diagnosing build errors

Which tool detects/reports… ?

mismatched type

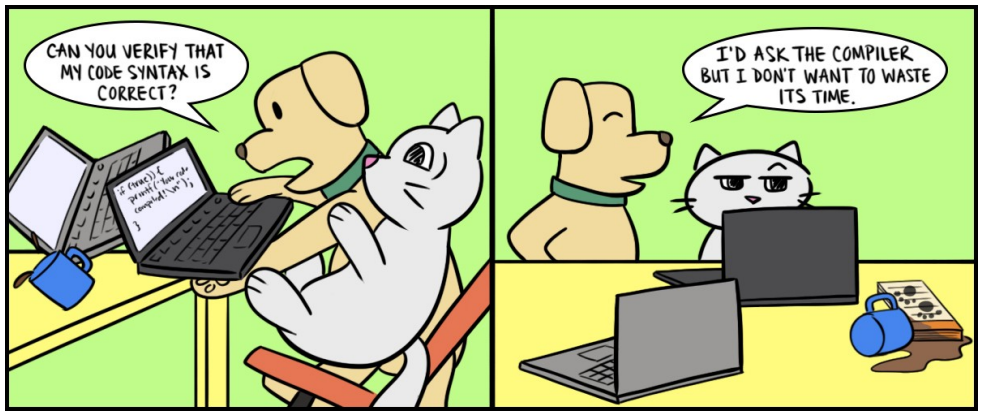
function call with wrong arguments

forgot #include

forgot to link with library

use variable uninitialized

two functions with same name



Modules and build process

Decompose into modules is skill to cultivate

- Separate system into coherent modules, minimize dependencies
- Clean abstractions, tidy interface
- Develop and test independently

Automate the build process

- Makefile is your command center
  - **Fast**: re-compile only what has changed
  - **Reliable**: track dependencies between modules
    - If file F changes, recompile everything that depends on F

Program start sequence

How is a program loaded into memory?

What must happens to start executing a program?

What is known about state of registers or contents of memory?

Does execution actually start at `main()`

👀 **Read our files!** 👀

`$CS107E/src/start.s`

`$CS107E/src/cstart.c`

`$CS107E/lib/memmap.ld`

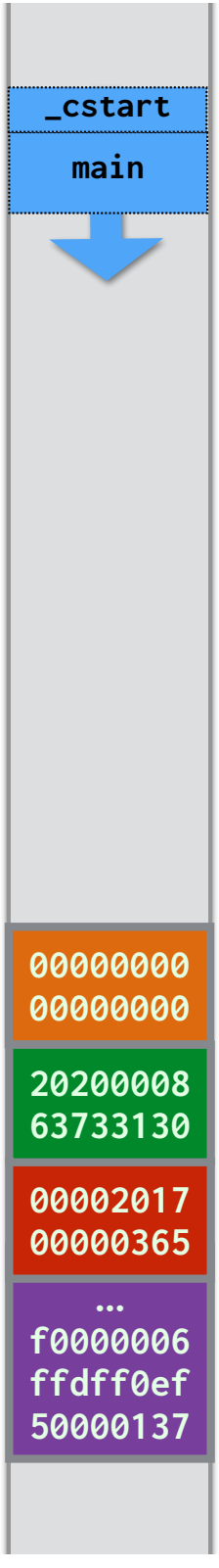
`memmap.ld` (linker script)

```
SECTIONS
{
    .text 0x40000000  :  { *(.text.start) *(.text*) }
    .rodata           :  { *(.rodata*) }
    .data             :  { *(.sdata*) }
    __bss_start       = .;
    .bss              :  { *(.bss*) }
    __bss_end         = .;
}
```

What is special about `.text.start` and why must it go first

What is the significance of `0x40000000`?

```
SECTIONS
{
   .text 0x40000000 :{ *(.text.start)
                       *(.text*)}
   .rodata :          { *(.rodata*) }
   .data :            { *(.data*) }
   __bss_start        = .;
   .bss :             { *(.bss*) }
   __bss_end          = . ;
}
```



(zeroed data) .bss

(initialized data) .data

(read-only data) .rodata

.text

```
$ xfel write 0x40000000 clock.bin
```