Where are We Going?

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 management: Memory map & heap

Almost Half-Way

How are things going?

- From the staff perspective: things are going fine, and we know that the material is challenging and the assignments are time-consuming. If you feel behind: you probably aren't!
- What can we do better? Please give suggestions on the web page.
- We know you are working hard! We know this can seem overwhelming, but we also hope you are learning a ton, and also enjoying it!

gpio
timer
uart
printf
malloc
keyboard
fb
gl
console
shell

Good Modules

Decompose a system into smaller parts (modules)

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

A good interface

- An easy-to-understand abstraction that simplifies code
- Can be implemented easily and in different ways

Tested independently with unit tests

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

Example: printf

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

printf() does a lot of things

- Parses a format string
- Converts arguments into strings
- Concatenates format string and arguments into a longer string
- Outputs string to terminal/serial port

Example: printf

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

printf() does a lot of things

1. Outputs string to terminal/serial port
2. Concatenates format string and arguments into a longer string
3. Parses a format string
4. Converts arguments into strings

An example decomposition, recommended in the assignment, that breaks the problem into smaller, simpler parts.

Example: printf

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

printf() does a lot of things

1. `printf()`
2. `snprintf()`
3. `snprintf()`
4. `sign_to_base()`

An example decomposition, recommended in the assignment, that breaks the problem into smaller, simpler parts.

Linking

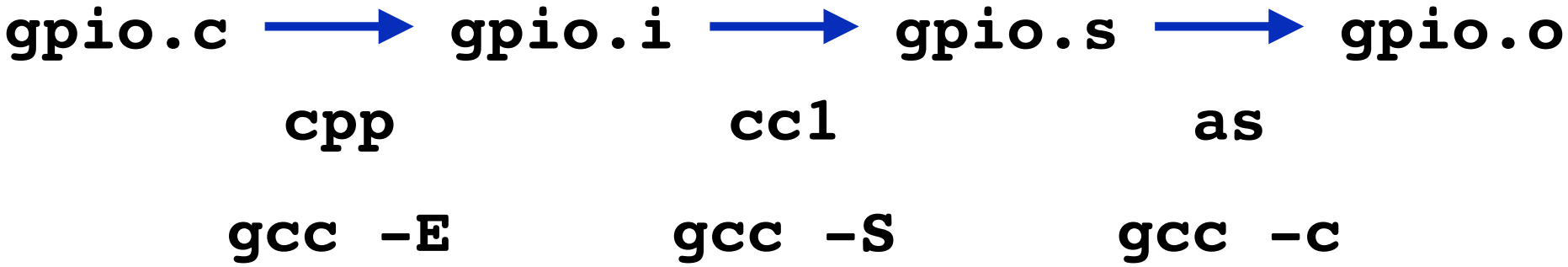
Your program uses multiple modules, each with its own abstraction and logic

Some modules call other modules: you need module A to be able to invoke a function in module B

Your tools *link* them together, somehow combining them into a single block of binary code

"The Build"

gcc is all powerful



gcc –save-temps

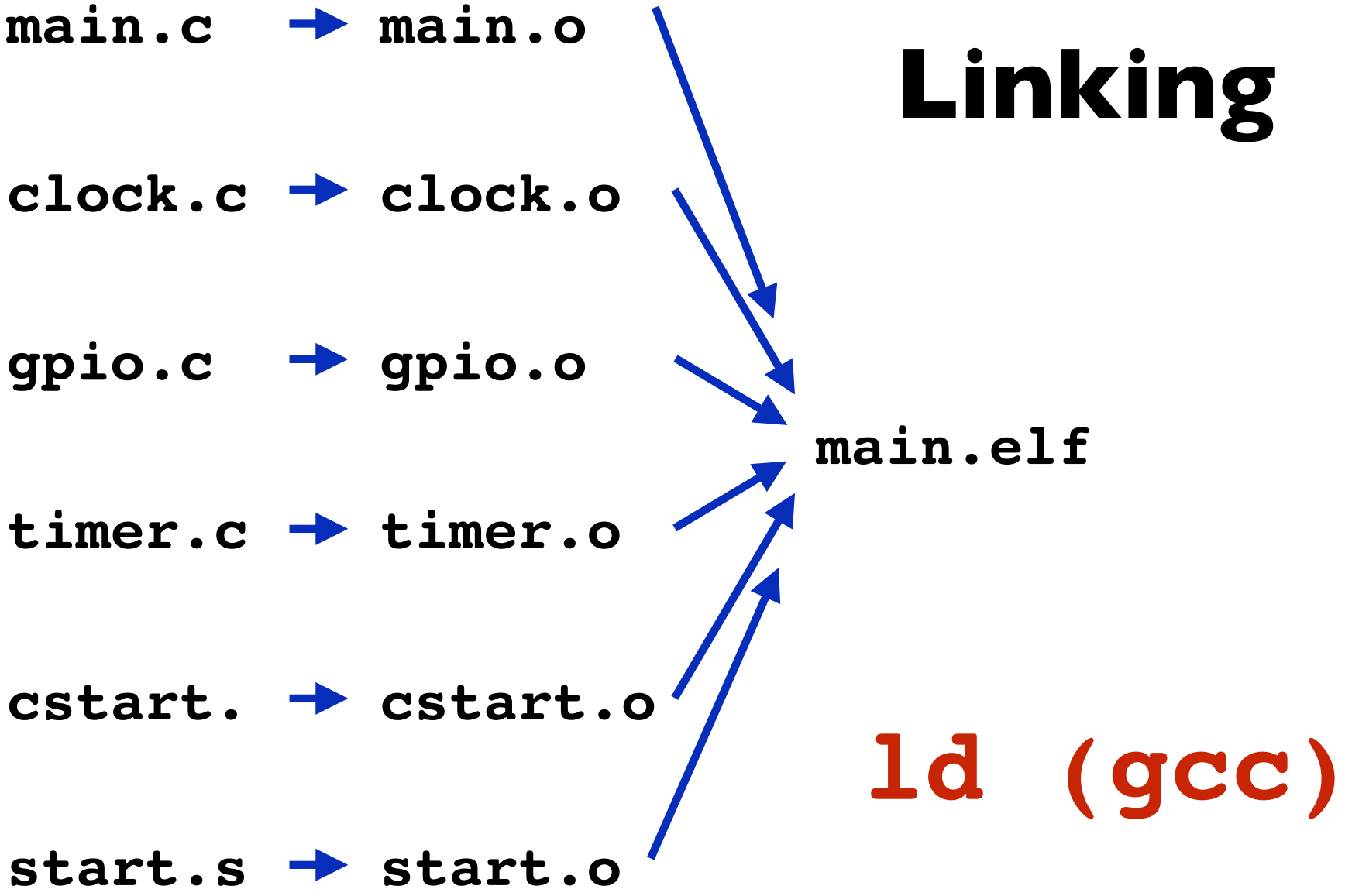
Object Files (.o = ELF)
and
Symbols

```
// nm - display names (symbols)
$ arm-none-eabi-nm blink.o
         U gpio_init
         U gpio_set_function
         U gpio_write
         U timer_delay
         U timer_init
00000000 T main

// T - text symbol (function)
// U - undefined symbol
```

```
$ arm-none-eabi-nm -n gpio.o
00000000 T gpio_init
00000004 T gpio_set_function
00000008 T gpio_get_function
00000010 T gpio_set_input
00000014 T gpio_set_output
00000018 T gpio_write
0000001c T gpio_read

$ vi gpio.o.list
```


main.c
main.o
clock.c
clock.o
gpio.c
gpio.o
timer.c
timer.o
cstart.
cstart.o
start.s
start.o
main.elf
Linking
ld (gcc)

```
$ arm-none-eabi-nm -n blink.elf
00008000 T _start  // start must be here!!
0000800c t hang
00008010 T main
00008060 T timer_init
00008064 T timer_get_ticks
0000806c T timer_delay_us
00008078 T timer_delay_ms
00008094 T timer_delay
000080b4 T gpio_init
000080b8 T gpio_set_function
000080bc T gpio_get_function
000080c4 T gpio_set_input
000080c8 T gpio_set_output
000080cc T gpio_write
000080d0 T gpio_read
000080d8 T _cstart
00008130 T __bss_end__
00008130 T __bss_start__

$ vi blink.elf.list
```

Symbols

Symbols represent the address of functions or data

Single global name space

- need `gpio_` prefix to distinguish names
- e.g. `gpio_init` versus `timer_init`

Local variables in functions are not symbols

Defined vs. undefined (`extern`) symbols

Definitions: global vs local (`static`)

- by default symbols are local in `.s` files
- by default symbols are global in `.c` files

Question

C doesn't support polymorphic functions.

You can't have both

- `itoa`(char *buf, int bufsize, short val);
- `itoa`(char *buf, int bufsize, int val);
- There can be only one symbol `itoa` in object files

C++ *does* support polymorphic functions

- `ostream& operator<< (short val);`
- `ostream& operator<< (unsigned short val);`
- How does this work?

Symbol Resolution

Set of defined symbols D

Set of undefined symbols U

Moving left to right, for each .o file, the linker updates U and D and proceeds to next input file.

Problems

- If two files try to define the same symbol, an error is reported***
- After all the input arguments are processed, if U is found to be not empty, the linker prints an error report and terminates.

Common Errors

1. Symbol undefined
2. Symbol multiply defined

data/

```
// uninitialized global and static variables
int i;
static int j;

// initialized global and static variables
int k = 1;
int l = 0;
static int m = 2;

// initialized global and static const
variables
const int n = 3;
static const int o = 4;
```

```
% arm-none-eabi-nm -S tricky.o
00000004 00000004 C i
00000000 00000004 b j
00000000 00000004 D k
00000004 00000004 B l
00000004 00000004 d m
00000000 00000004 R n
00000004 00000004 r o
00000000 000000d8 T tricky

# The global uninitialized variable i
# is in common (C).

# If you compile with -Og, some variables
# are optimized out -- which?
```

Guide to Symbols

T/t - text

D/d - read-write data

R/r - read-only data

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

C - common (instead of B)

lower-case letter means `static`

Data Symbols

Types

- global vs static
- read-only data vs data
- initialized vs uninitialized data
- common (shared data)

Combining Multiple Modules (`.o`) into a Single Executable (`.elf`)

`memmap`

```
SECTIONS
{
    .text 0x8000 : {
        start.o(.text*)
        *(.text*)
    }
    .data : { *(.data*) }
    .rodata : { *(.rodata*) }
    __bss_start__ = .;
    .bss : { *(.bss*)  *(COMMON) }
    __bss_end__ = ALIGN(8);
}
```

Sections

Instructions go in `.text`

Data goes in `.data`

`const` data (read-only) goes in `.rodata`

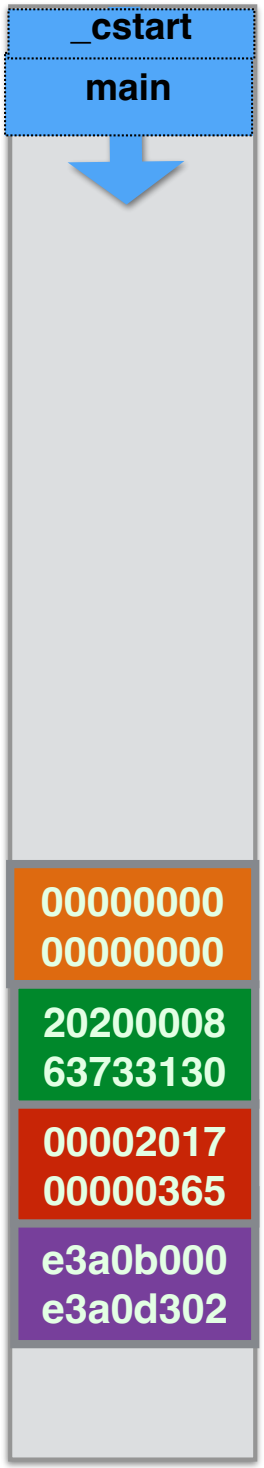
Uninitialized data goes in `.bss`

+ other information about the program

- symbols, relocation, debugging, …

```
SECTIONS
{
  .text 0x8000 :  { start.o(.text*)
                    *(.text*) }
  .data :         { *(.data*) }
  .rodata :       { *(.rodata*) }

  __bss_start__ = .;
  .bss :          { *(.bss*)
                    *(COMMON) }
  __bss_end__ = ALIGN(8);
}
```



(zeroed data) **.bss**

(read-only data) **.rodata**

(initialized data) **.data**

.text

```
// _start must be declared global,
//   by default symbols in .s are local.

// Identify this section as the one
// to go first in binary image
.section ".text.start"

// initialize sp and fp
.globl _start
_start:
    mov sp, #0x8000000
    mov fp, #0
    bl _cstart
hang: b hang
```

`_start must be located at 0x8000!!`

Raspberry Pi loads kernel.img starting at 0x8000 when booting

```
$ cd ../data
$ arm-none-eabi-nm -S -n main.elf
00008000 T _start
0000800c t hang
00008010 00000038 T main
00008048 00000040 T tricky
00008088 00000058 T _cstart
000080e0 00000004 D k
000080e4 00000004 R n
000080e8 R __bss_start__
000080e8 00000004 b j
000080ec 00000004 B l
000080f0 00000004 B i
000080f8 B __bss_end__
```

Relocation

```
// start.s

.globl _start
start:
    mov sp, #0x8000000
    mov fp, #0
    bl _cstart
hang:
    b hang
```

```
// Disassembly of start.o (start.list)

0000000 <_start>:
   0:   mov sp, #0x8000000
   4:   mov fp, #0
   8:   bl  0 <_cstart>

0000000c <hang>:
   c:   b   c <hang>

// Note: the address of _cstart is 0
// Why?
//   _start doesn't know where c_start is!

// Note it does know the address of hang
```

```
// Disassembly of clock.elf.list

00008000 <_start>:
    8000: mov     sp, #134217728  ; 0x8000000
    8004: bl      8088 <_cstart>

00008008 <hang>:
    8008: b       8008 <hang>

00008088 <_cstart>:
    8088:   push    {r3, lr}

// Note: the address of _cstart is #8088
// Now _start knows where _cstart is!
```

Libraries

An archive `.a` is just a collection of `.o` files.

The linker scans the library for any `.o` files that contain definitions of undefined symbols. If a file in the library contains an undefined symbol, the whole file and all its functions are linked in.

Adding the `.o` file from the library may result in more undefined symbols; the linker searches for the definition of these symbols in the library and includes the relevant files; this search is repeated until no more definitions of undefined symbols are found.

Libraries

class library: `blink-cs107e`

your library: `blink-libpi`

Questions?

Suppose you add more functions to the clock interface (**e.g.** `clock_start()`, `clock_tick()`, `clock_end()`) what source files would need to be modified? rebuilt?

What happens if you link with

```
ld … -lpi gpio.o?
```

Triggering a Rebuild

When to Rebuild?

Change to implementation (`clock.c`)?

- Must recompile implementation (`clock.o`)

Change to interface (`clock.h`)?

- Should (must) recompile clients of the interface (`main.c`)
- Add recipe that `main.o` depends on `clock.h`

Change to `Makefile`

- Adding a file to `OBJECTS` may require rebuilding executable `main.elf`
- **Modify recipe for** `main.elf` to depend on `Makefile`
- BEWARE: This is typical of a hidden dependency

Builds

Automate the build! Manual builds are error prone

Needs to be fast and reliable

- Fast means compile modules only when necessary
- Reliably means keeping track of dependencies between files

Separate system into small modules with minimal dependencies

Ensure `Makefile` contains all dependencies

Summary

Decomposing software into modules is a critical skill

- Like organizing an essay into sections, paragraphs, sentences

The linker combines modules into a larger binary

- Resolves undefined symbols to modules that define them
- Lays out data and code
- Relocation when needed

Makefiles designed to only compile modules that need recompilation

- If F changes, recompile everything that depends on F