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

gpio
timer
uart
strings
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 and easy-to-use abstraction**
- **Can be implemented in different ways**

Designing good interfaces: THE 'art' of software engineering

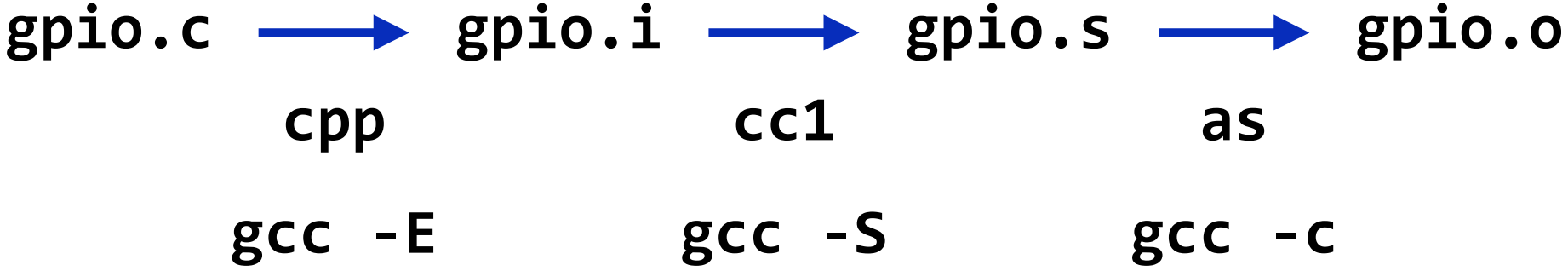
Modules tested independently with unit tests

"The Build"

NASA Command Center during SpaceX Mission

cs107e Command Center: `Makefile`

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
```

Symbols

Single global name space

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

Defined vs. undefined symbols

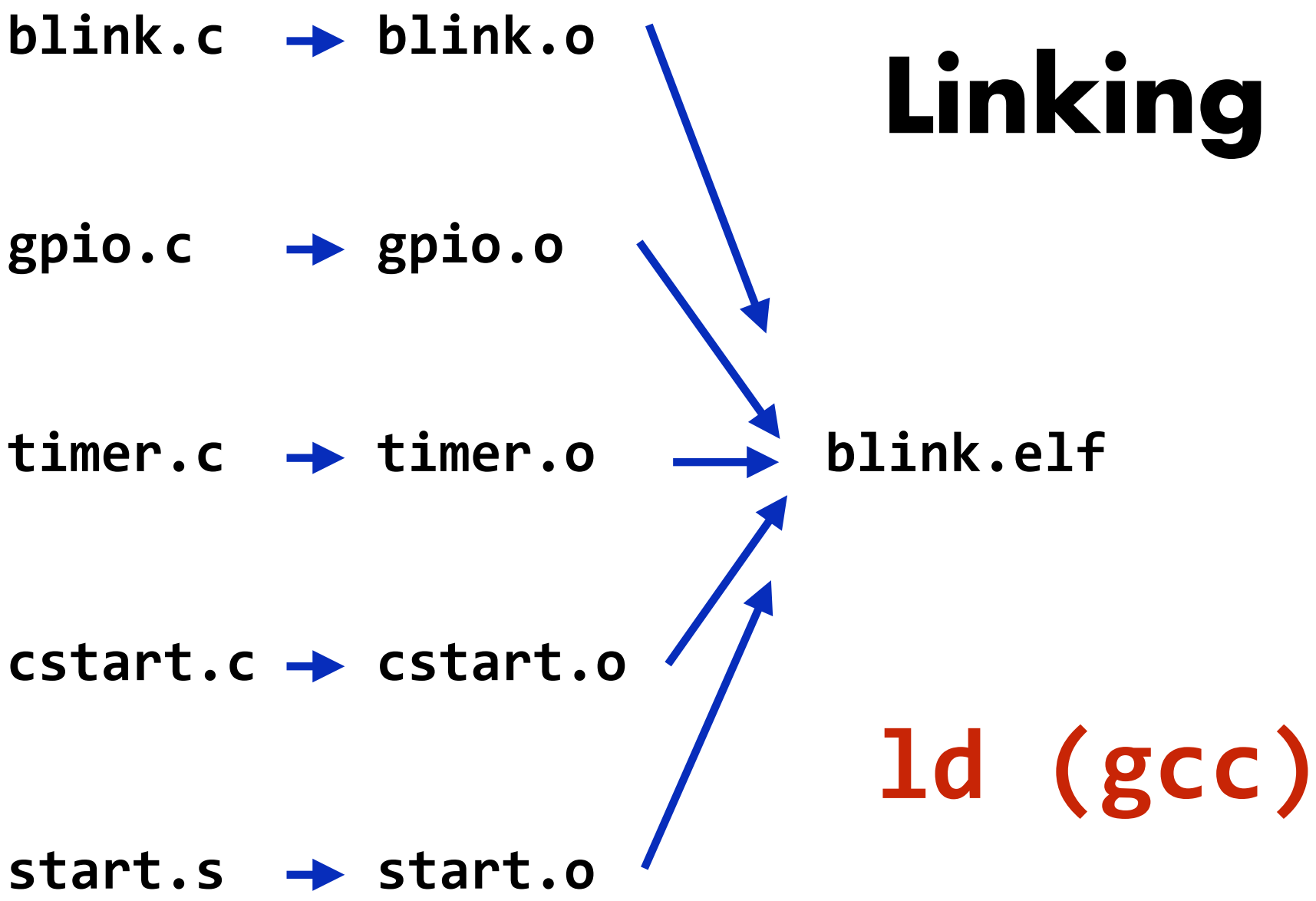
Definitions: global vs local (`static`**)**

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

Local variables in functions are not symbols

Linking

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


blink.c
blink.o
gpio.c
gpio.o
timer.c
timer.o
blink.elf
cstart.c
cstart.o
start.s
start.o
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__
```

```
// size reports the size of the text
$ arm-none-eabi-size blink.elf
   text data    bss  dec    hex   filename
    304    0      0  304    130   blink.elf
$ arm-none-eabi-size *.o
   text data    bss  dec    hex   filename
     80    0      0   80     50   blink.o
     88    0      0   88     58   cstart.o
     36    0      0   36     24   gpio.o
     16    0      0   16     10   start.o
     84    0      0   84     54   timer.o

// The size of blink.elf is equal to
// sum of the sizes of the .o's
```

Symbol Resolution

Set of defined symbols D

Set of undefined symbols U

Moving left to right, for each .o file:

- **D' = D union D(file)**
- **U' = U difference D(file)**

Note: Adding a symbol from a file, causes all the symbols in that file to be added

Common Errors

1. "undefined reference"
2. "multiple definitions"

```
// _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
```

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

Libraries

class library: `blink-cs107e`
your library: `blink-libpi`

Libraries

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.

```
// An library is an unix archive file

// An archive is a set of .o files

% arm-none-eabi-ar cry libpi.a \
    gpio.o \
    timer.o \
    cstart.o \
    start.o
% arm-none-eabi-nm libpi.a
```

data/

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

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

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

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

# Const variables (n) are marked as read-only

# Zeroed global variables (j, l) in bss

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

# NB The static variables m and o optimized out
```

Guide to Symbols

T/t - text

D/d - read-write data

R/r - read-only data

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

C - global uninitialized - common (instead of B)

lower-case letter means `static` (local)

Sections in Memory

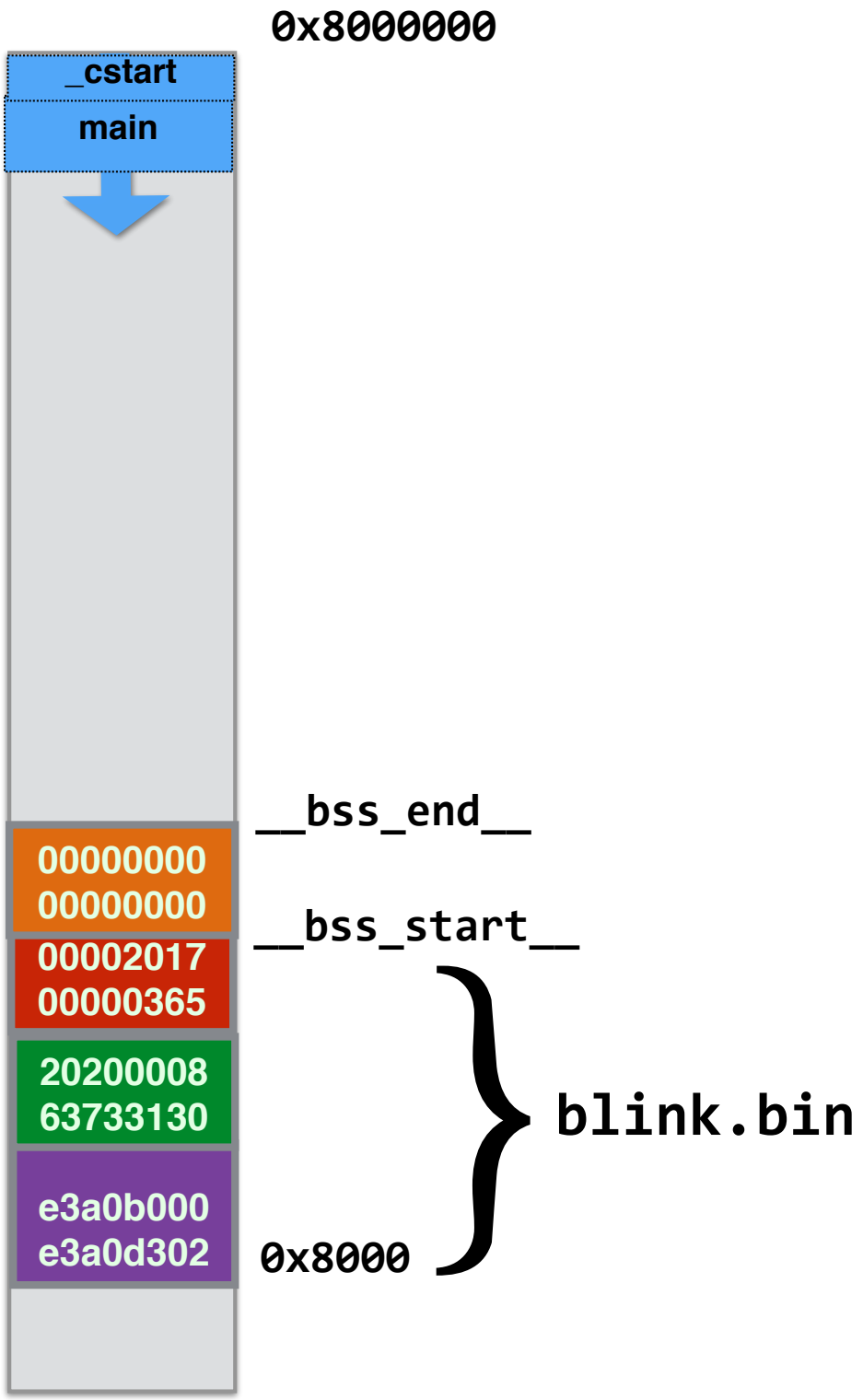
Instructions go in `.text`

Data goes in `.data`

Read-only data (`const`**) goes in** `.rodata`

Zeroed data goes in `.bss`

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



(zeroed data) **.bss**

(initialized data) **.data**

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

.text

```
$ arm-none-eabi-nm -S -n main.elf
00008000 T _start
0000800c t hang
00008010 00000048 T main
00008058 000000d0 T tricky
00008128 0000009c T _cstart
000081c4 00000004 R n
000081c8 00000004 r o
000081cc 00000004 D k
000081d0 00000004 d m
000081d4 D __bss_start__
000081d4 00000004 b j
000081d8 00000004 B l
000081dc 00000004 B i
000081e0 B __bss_end__
```

Triggering a Rebuild

When to Rebuild?

Change to implementation `clock.c`?

- **Must recompile implementation `clock.c` to make `clock.o`**

Change to implementation `gpio.c`?

- **Must recompile implementation `gpio.c` to make `gpio.o`**

Change to interface `gpio.h`?

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

Change to Makefile

- **Adding a file to MODULES may require rebuilding `main.elf`**
- **BEWARE: This is a hidden dependency not tracked by `make`**
- **Modify recipe for `main.elf` to depend on `Makefile`**

Builds

Automate the build! Manually typing in commands is 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**

Relocation

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

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

00000000 <_start>:
   0:   e3a0d302    mov sp, #134217728  ;
0x8000000
   4:   e3a0b000    mov fp, #0
   8:   ebfffffe    bl  0 <_cstart>

0000000c <hang>:
   c:   eafffffe    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 blink.elf.list

00008000 <_start>:
    8000:   e3a0d302    mov sp, #134217728  ;
0x8000000
    8004:   e3a0b000    mov fp, #0
    8008:   eb000032    bl  80d8 <_cstart>

0000800c <hang>:
    800c:   eafffffe    b   800c <hang>

000080d8 <_cstart>:
    80d8:   e92d4008    push    {r3, lr}

// Note: _cstart has been placed after hang
// Now the address of _cstart is #80d8
// Now _start knows where _cstart is!
```