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

Modules

- **Meaningful decomposition of the system into parts**

Interfaces (`*.h` files) and implementations (`*.c`)

- **Provide natural and easy-to-use abstractions for the users of the module**
- **Hide unnecessary details of the implementation**

Modules tested independently with unit tests

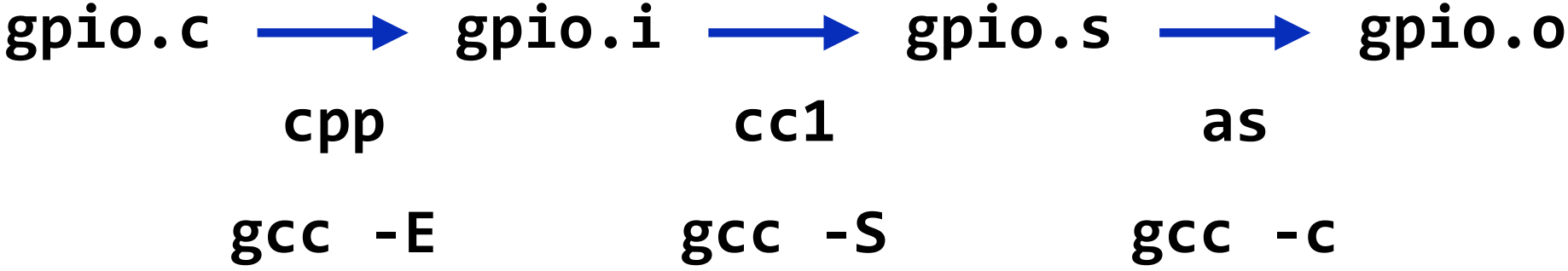
Obi-wan, what is a good design for my modules?

"The Build"

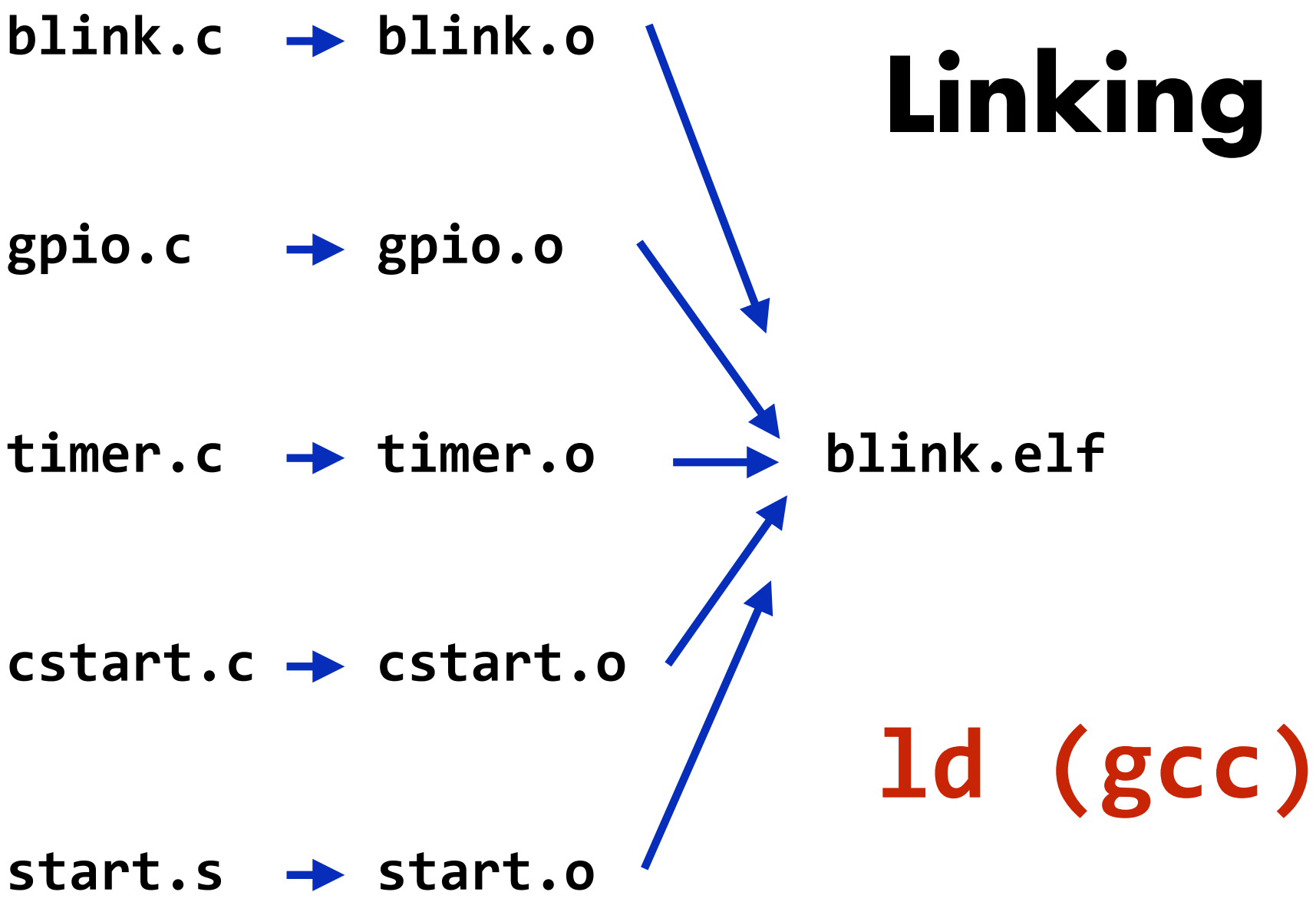
NASA Command Center during SpaceX Mission

cs107e Command Center: `Makefile`

gcc is all powerful



gcc –save-temps


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)

Common Errors

1. Symbol undefined
2. Symbol multiplied defined

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
```

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

```
$ 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
```

```
// _start must be global,
//   by default local.

// _start must be the first code
//   to execute

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

```
// memmap
MEMORY
{
    ram : ORIGIN = 0x8000,
          LENGTH = 0x8000000
}
.text : {
    start.o (.text)
    *(.text*)
} > ram

// Why must start.o go first?
```

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

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

Libraries

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

```
// 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
```

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.

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
00000000 R n
00000000 T tricky

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

# External variables are upper-case, static lower-case

# Zeroed global variables (j, l) in bss

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

# NB The static const variable m optimized out
```

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`

Sections in Memory

Instructions go in `.text`

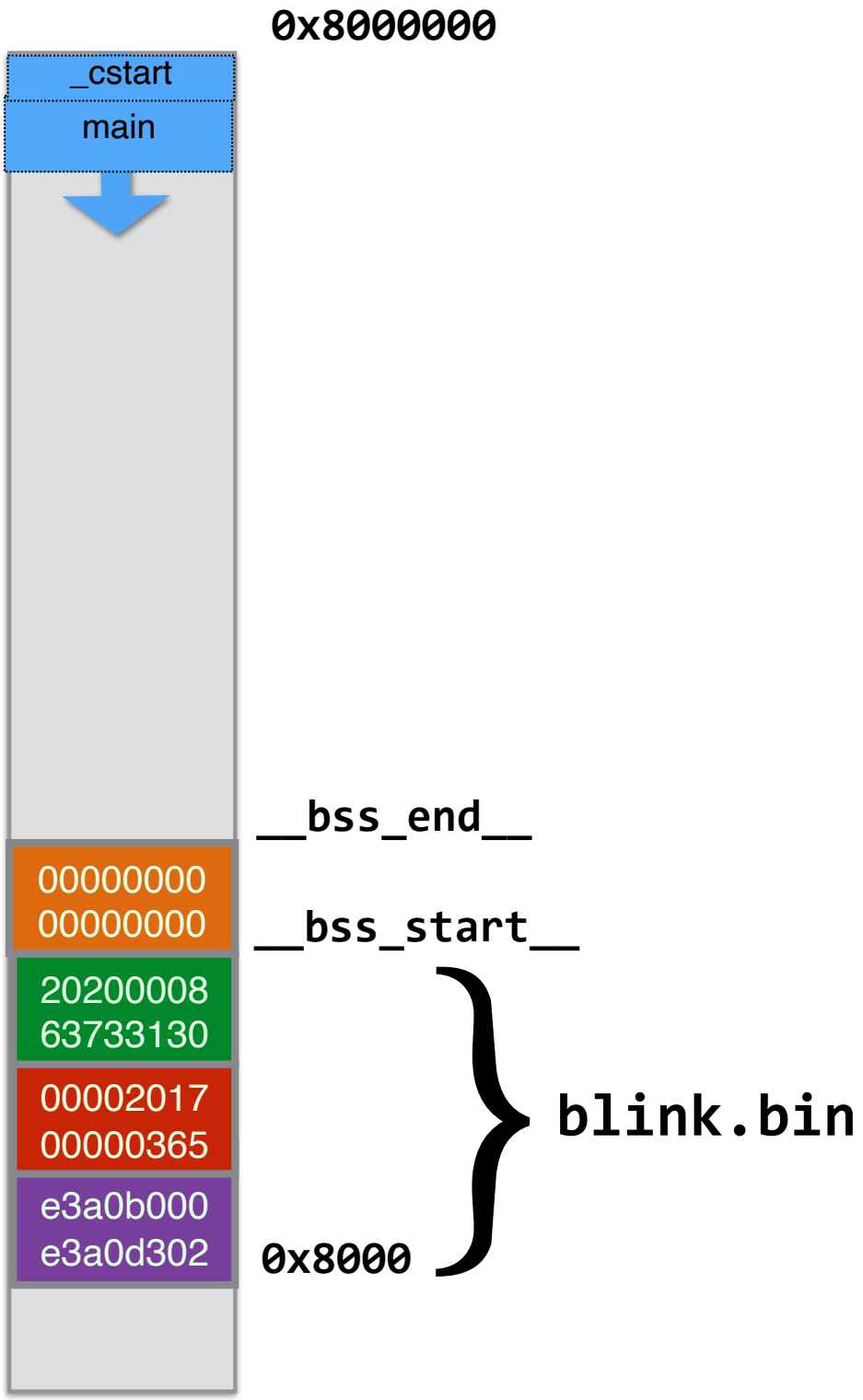
Data goes in `.data`

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

Zeroed data goes in `.bss`

```
SECTIONS
{
  .text 0x8000 :  { 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

```
$ 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__
```

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

Triggering a Rebuild

When to Rebuild?

Suppose you change `gpio.c`, what needs to be recompiled?

Suppose you change `gpio.h`, what needs to be recompiled?

Could you need to recompile if you changed the `Makefile`?

When to Rebuild?

Change to implementation (gpio.c)?

- **Must recompile implementation (gpio.o)**

Change to interface (gpio.h)?

- **Should (must) recompile clients of the interface (main.c)**
- **Add recipe that main.o depends on gpio.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**

depend/

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

Grading

See http://cs107e.github.io/assignments/

A:

- **7 basic fully functional + 3 extensions + bonus**
- **ok style/tests**
- **outstanding final project**

B:

- **7 basic mostly functional + 1 extension or bonus**
- **ok style/tests**
- **good final project**

We will file bug reports on your code and give you two weeks to fix them and earn 1/2 the deducted points back

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:   eaffffe     b   800c <hang>

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

// Note: the address of _cstart is #80d8
// Now _start knows where _cstart is!
```