

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
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

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.
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

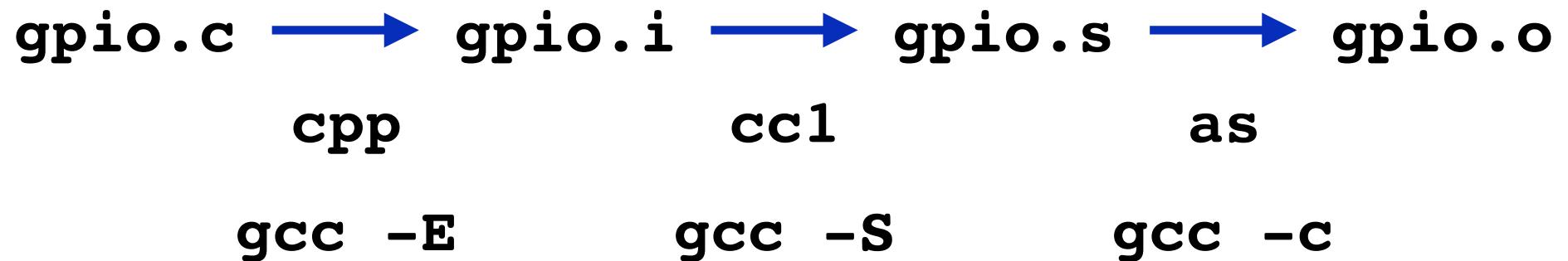
Some modules call other modules: you need module A to be able to invoke a function in module B

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

"The Build"



gcc is all powerful



gcc --save-temp

Linking

main.c → main.o

clock.c → clock.o

gpio.c → gpio.o

timer.c → timer.o

cstart.c → cstart.o

start.s → start.o

main.elf

ld (gcc)

Common Errors

1. Symbol undefined
2. Symbol multiply defined

Symbols

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.

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.

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?

Can you think of a way to force linking if you change OBJECTS in a Makefile?

What happens if you link with
`ld ... -lpi gpio.o`?

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

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

memmap

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

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

_start must be located
at #0x8000!!

Magic constant that's part of Raspberry Pi boot sequence.

```
% arm-none-eabi-nm -n main.elf
00008000 T _start
00008008 t hang
0000800c T main
00008020 T timer_init
00008024 T timer_get_time
0000802c T delay_us
00008038 T delay
0000806c T gpio_init
00008070 T gpio_set_function
00008074 T gpio_get_function
00008078 T gpio_write
0000807c T gpio_read
00008080 T clock_init
00008084 T clock_run
00008088 T __cstart
000080d8 T __bss_end__
000080d8 T __bss_start__
```

```
# size reports the size of the text
% arm-none-eabi-size main.elf
      text    data     bss   dec hex filename
      216        0       0   216   d8 main.elf

% arm-none-eabi-size *.o
      text    data     bss   dec hex filename
        8        0       0     8     8  clock.o
      80        0       0    80    50  cstart.o
      20        0       0    20    14  gpio.o
      20        0       0    20    14  main.o
      12        0       0    12      c start.o
      76        0       0   76    4c  timer.o

# Note that the sum of the sizes of the .o's
# is equal to the size of the main.exe
```

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 main.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!
```

data/

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

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

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

```
% arm-none-eabi-nm -S tricky.o
00000004 00000004 C i
00000000 00000004 b j
00000000 00000004 D k
00000004 00000004 d l
00000000 00000004 R m
                      U p
00000000 00000048 T tricky
```

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

```
# The static const variable n
# has been 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

Data Symbols

Types

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

Sections

Instructions go in `.text`

Data goes in `.data`

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

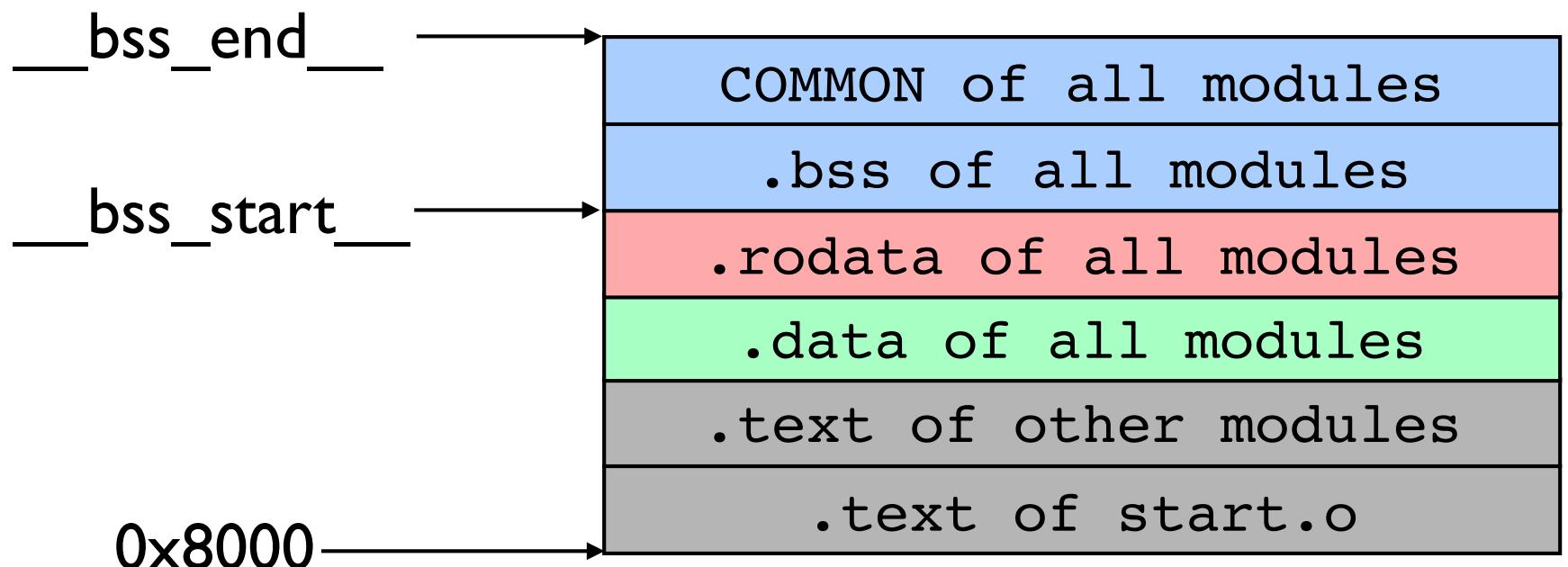
Uninitialized data goes in `.bss`

+ other information about the program

- symbols, relocation, debugging, ...

```
.text : {  
    start.o (.text)  
    *(.text*)  
} > ram  
.data : { *(.data*) } > ram  
.rodata : { *(.rodata*) } > ram  
_bss_start_ = .;  
.bss : {  
    *(.bss*)  
    *(COMMON)  
} > ram  
. = ALIGN(8);  
_bss_end_ = .;
```

```
MEMORY {
    ram : ORIGIN = 0x8000,
          LENGTH = 0x8000000
}
.text : {
    start.o (.text)
    *(.text*)
} > ram
.data : { *(.data*) } > ram
.rodata : { *(.rodata*) } > ram
__bss_start__ = .;
.bss : {
    *(.bss*)
    *(COMMON)
} > ram
.= ALIGN(8);
__bss_end__ = ..;
```



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