Module 2-D

Embedded C

Tim Rogers 2022

Reading

- Textbook, Chapter 10, “Mixing C and Assembly”, pages 215 – 236.
  - Talking about this in this lecture module.
- Textbook, Chapter 15, “General-purpose Timers”, pages 373 – 414.
  - Talking about advanced timer use in the next lecture module.
- Future reading:
  - Textbook, Chapter 21, Digital-to-Analog Conversion, pp. 507 – 526.
    - You should read this first.
  - FRM, Chapter 14, Digital-to-analog converter (DAC), pp. 269 – 281.
    - Scan. Learn basics like I/O registers, enabling, use.
  - Textbook, Chapter 20, Analog-to-Digital Conversion (ADC), pp. 481 – 506.
    - Read this later.
  - FRM, Chapter 13, Analog-to-Digital converter (ADC), pp. 229 – 268.
    - Scan this later. Learn basics like I/O registers, enabling, use.

Learning Outcome #2

“an ability to interface a microcontroller to various devices.”

How?

- ✅ A. General Purpose I/O
- ✅ B. Interrupts and Exceptions
- ✅ C. Basic Timers
- D. Embedded C
- E. Advanced Timers
- F. Debouncing and Multiplexing

Results of a C Compiler…

- Because it’s so simple to create bloated, inefficient code!
  - We have 32K of RAM and 256K of ROM.
    - More than we’ll ever need!

```c
int first(int x) {
    return x;
}
```

Compile

```asm
.global first
first:
        push {r7,lr}
        sub  sp, #4
        add  r7, sp, #0
        str  r0, [r7, #0]
        nop
        ldr  r2, [r7, #0]
        movs r0, r2
        mov  sp, r7
        add  sp, #4
        pop  {r7,pc}
```

C is good for managing complexity

- The code is no always not optimal or precise, you can generate more functionality more quickly.
  - Your grades for the class are often correlated to how well you understand.
    - Therefore, we're going to continue using assembly language in places.

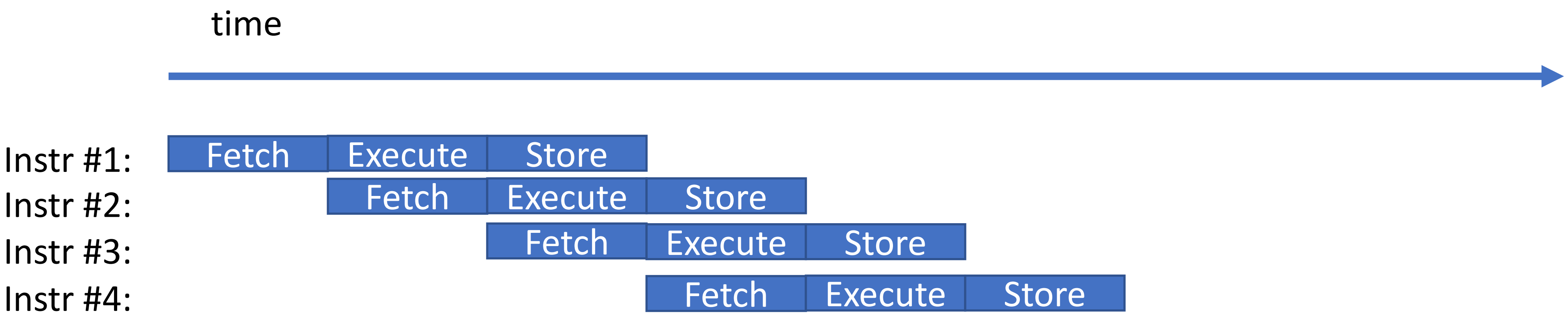
With assembly language, you know exactly what is happening.

```
.text
.global micro_wait
micro_wait:
    // Total delay = r0 * (1+10*(1+3)+1+1+1+1+3)+1
      //             = r0 * 48 cycles
      // At 48MHz, this is one usec per loop pass.
      // Maximum delay is 2^31 usec = 2147.5 sec.
      movs r1, #10    // 1 cycle
loop: subs r1, #1     // 1 cycle
      bne loop        // 3 cycles (Why?)
      nop             // 1 cycle
      nop             // 1 cycle
      nop             // 1 cycle
      subs r0, #1     // 1 cycle
      bne  micro_wait // 3 cycles (Why?)
      bx   lr         // 1 cycle
```

- Manual states NOPs aren't suitable for timing loops.
  - True for more advanced micros, not ours: always 1 cycle.

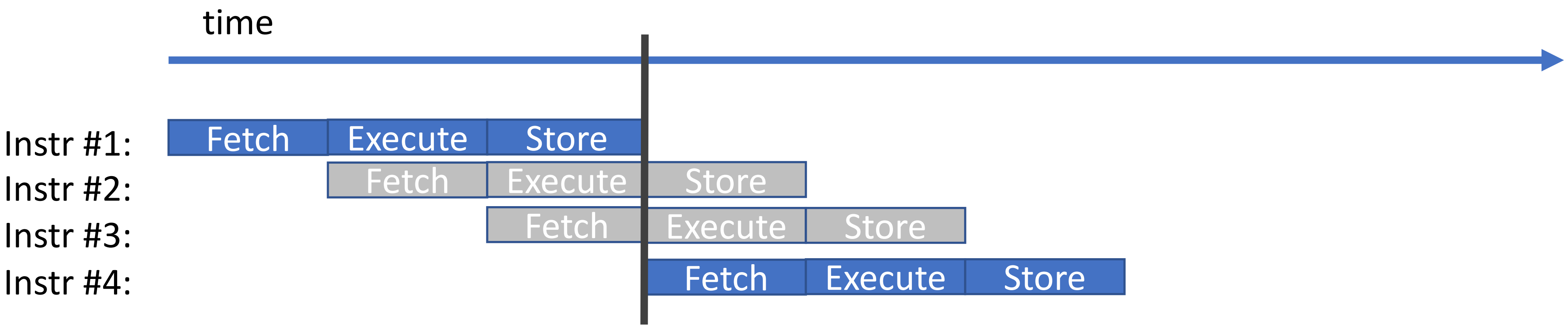
Why Do Branches Take 3 Cycles?

- I mentioned that the ARM Cortex-M0 had a three-stage pipeline.
  - Each instruction takes 3 cycles
  - Every instruction starts on the 2nd cycle of the previous one



Why Do Branches Take 3 Cycles?

- When an instruction is a branch, the instructions immediately following it may or may not be executed.
  - If the branch is taken, we need to throw away those instructions.
  - We can't fetch the right instructions until we update the PC!



C operators:

- Bitwise logical operators:

| OR

& AND

^ XOR

- Unary logical operator:

  ~ Bitwise NOT (different than negate)

- Shift operators:
  - << Left shift (like multiplication)
  - >> Right shift (like division)
    - An unsigned integer uses the LSR instruction.
    - A signed integer uses the ASR instruction.

Modifying bits of a word

- OR bits into a word (turn ON bits):

  x = x | 0x0a0c shorthand: x |= 0x0a0c

  Turns ON the bits with ‘1’s in 0000 1010 0000 1100
- AND bits into a word (mask OFF ‘0’ bits):

  x = x & 0x0a0c shorthand: x &= 0x0a0c

  Turns OFF all except bits with ‘1’s in 0000 1010 0000 1100
- AND inverse bits of a word (mask OFF ‘1’ bits):

  x = x & ~0x0a0c shorthand: x &= ~0x0a0c

  Turns OFF bits with ‘1’s in 0000 1010 0000 1100
- XOR bits of a word (toggle the ‘1’ bits)

  x = x ^ 0x0a0c shorthand: x ^= 0x0a0c

  Inverts the bits with ‘1’s in 0000 1010 0000 1100

Shifting values

- Shift a value left by 5 bits:

  x = x << 5 shorthand: x <<= 5

- Shift a value right by 8 bits:

  x = x >> 8 shorthand: x >>=8

- There is no rotate operator in C.
  - Improvise by combining shifts/ANDs/ORs.
  - rotate a 32-bit number right by 4:
    - **x = (x >> 4) & 0x0fffffff | (x << 28) & 0xf0000000**
- No way to directly set or check flags in C.

Combining operators

- Turn on the nth bit of the ODR:

  ODR |= 1<<n

- Turn off the nth bit of the ODR:

  ODR &= ~(1<<n)

- Note that either side of the << can be a constant or a variable.
- Warning: These look a lot easier than assembly but remember that they are ***not atomic***.
  - If an interrupt occurs in the middle of the bloated code to implement the statement, strange things could happen.
  - Use of BRR/BSRR are just as effective in C as they are in assembly language, and they are still **atomic**.

Pointers

- If you did not take an advanced C class, you might not have studied pointers.
- That's OK. You've been using addresses. It's the same thing (but with types):
  - int x, *p; ….
  - x = *p   is similar to: ldr r0,[r1]
  - x = p[3]   is similar to: ldr r0,[r1,#12]
  - p += 1   is similar to: adds r1, #4

Type casts

- In an embedded system, we usually know where everything is in memory.
- To create a pointer to the RCC_AHBENR register, we might say:

```
int *rcc_ahbenr = (int *) 0x40021014;
```

  - Here, the **type cast** says, "Trust me that this is really a pointer to an integer."

Structures

- In C, we can define hierarchical types to organize information that goes together.
  - The grouping is called a **struct**.
  - Each element within a struct is called a **field**.
  - We access fields with a dot (**.**) operator.
  - For a pointer to a struct, we access a field with an arrow (**->**) operator.

Complex struct example

```
struct Student {
    char name[128];
    unsigned int age;
    int km_north_of_equator;
    int hours_of_sleep;
};

void Adjust_Schedule(void) {
    struct Student s = {
        "Typical ECE 362 student",
        20,
        4495,
        8,
    };

    for(month=1; month<=5; month+=1) {
        s.hours_of_sleep -= 1;
    }
}
```

struct declaration

Space allocated for one struct “s”

“.” just represents an offset into the struct

A useful struct for ECE 362

```c
struct GPIOx_type {
    unsigned int MODER;            // offset 0x0
    unsigned int OTYPER;         // offset 0x4
    unsigned int OSPEEDR;        // offset 0x8
    unsigned int PUPDR;           // offset 0xc
    unsigned int IDR;            // offset 0x10
    unsigned int ODR;               // offset 0x14
    unsigned int BSRR;           // offset 0x18
    unsigned int LCKR;            // offset 0x1c
    unsigned int AFR[2];         // offset 0x20
    unsigned int BRR;            // offset 0x28
};

struct GPIOx_type *GPIOA = (struct GPIOx_type *) 0x48000000;
struct GPIOx_type *GPIOB = (struct GPIOx_type *) 0x48000400;
struct GPIOx_type *GPIOC = (struct GPIOx_type *) 0x48000800;
```

Assuming the previous definitions

```
// Read bit from PA0.  Write bit to PC8.
//

for(;;)
    (*GPIOC).ODR = (*GPIOC).ODR & ~0x00000100 |
                   ((*GPIOA).IDR & 0x00000001) << 8;
```

Using arrows instead

```
for(;;)
  GPIOC->ODR =    GPIOC->ODR & ~0x00000100 |
               (  GPIOA->IDR & 0x00000001) << 8;
```

```
ldr  r0, =GPIOA      // Load, into RO, base address of GPIOA
    ldr  r1, =GPIOC      // Load, into R1, base address of GPIOC
again:
    ldr  r2, [r0, #IDR] // Load, into R2, value of GPIOA_IDR
    movs r3, #1
    ands r2, r3      // Look at only bit zero.
    lsls r2, #8      // Translate bit 0 to bit 8
    ldr  r4, [r1, #ODR] // Load value of ODR
    ldr  r3, =0xfffffeff    // Load mask
    ands r4, r3      // AND off bit with mask
    orrs r4, r2      // OR in the new value
    str  r4, [r1, #ODR] // Store value to GPIOC_ODR
    b    again
```

STM32 Standard Firmware

- C structure definitions for control registers is provided with the standard firmware.
  - Advantage: You don’t have to look up the addresses and offsets for things.
  - The C code on the previous slide actually compiles and does what it looks like it does.
  - More about this in a few slides when we talk about CMSIS.

Storage class of variables

- Variables in C can be given a storage class which defines how the compiler can access them.
  - One of these classes is ***const***.
  - Const says that a variable must not be mutated after its initial assignment.
  - Compiler is free to put such a "variable" in the text segment where it cannot be modified.

Example of const

```c
int var = 15;
const int one = 1;  // The value of "one" cannot be changed.

// Since "one" is a global const variable,
// it is placed in the text segment.

int main(void) {
    int x;
    for(x=0; x<20; x += one)
        var += one;

    one = 2;    // not allowed.  Fault handler!
    return 0;
}
```

Other examples of const

```
// Most commonly, "const" is used to describe pointers
// whose memory region a program is not allowed to modify.

const int *GPIOA_IDR = (const int *) 0x48000010;


...

int x = *GPIOA_IDR;                  // fine
*GPIOA_IDR = 5;                      // compiler error
* ((int *) GPIOA_IDR) = 5;          // do it anyway

// const is a reminder that something should not be modified.
// You can still get around it.
```

What about this code?

```
int count = 0;

int myfunc(void) {
    int begin = count;
    while (count == begin)
        ;
    return count;
}
```

Compiler thinks count never changes

So it never checks it!

Bad if something outside this thread changes count

A Normal C example

```c
#include <stdio.h>
#include <signal.h>

int count = 0;

void handler(int sig) {
  count += 1;
  printf("\nChanged to %d\n", count);
}

int main(void) {
    signal(SIGINT, handler);    // Set up a <ctrl>-C handler.

    int begin = count;           // Copy value of count.
    while (count == begin)       // Check to see if count changed.
        ;
    printf("Count changed.\n");
    return count;
}
```

Compiled without optimizations: <ctl>-c will exit the program

Compiled with –O3. Will never exit!

How can we tell the compiler?

- Sometimes, we want to tell the compiler that a variable might change in ways that it cannot possibly know.
- We give it a storage class of ***volatile***.
- Add volatile to any type like this:

    volatile int count = 0;

- Tells the C compiler to always check it rather than holding its value in a register as an optimization.

Mixed storage classes

- Can something be both const and volatile?
  - Yes.
  - This is a read-only variable that changes in ways that the compiler cannot understand.
    - e.g.:

```
const volatile int *gpioa_idr = (const volatile int *)0x48000010;
```

Assembly to blink PC8

```
.equ RCC, 0x40021000
.equ AHBENR, 0x14
.equ IOPCEN, 0x80000
.equ GPIOC, 0x48000800
.equ MODER, 0x0
.equ ODR, 0x14
.equ BSRR, 0x18
.equ BRR, 0x28
.equ PIN8_MASK,     0x00030000
.equ PIN8_OUTPUT,   0x00010000

.global main
main:
    // OR IOPCEN bit into RCC AHBENR
    ldr   r0, =IOPCEN
    ldr   r1, =RCC
    ldr   r2, [r1,#AHBENR]
    orrs r2, r0
    str   r2, [r1,#AHBENR]
```

```
// Enable pin 8 as an output
    ldr   r0, =PIN8_MASK
    ldr   r1, =GPIOC
    ldr   r2, [r1,#MODER]
    bics r2, r0
    ldr   r0, =PIN8_OUTPUT
    orrs r2, r0
    str   r2, [r1,#MODER]
forever:
    ldr   r0, =0x100
    str   r0, [r1,#BSRR] // pin 8 on
    ldr   r0, =1000000
    bl    micro_wait
    ldr   r0, =0x100
    str   r0, [r1,#BRR]  // pin 8 off
    ldr   r0, =1000000
    bl    micro_wait
    b     forever
```

C to blink PC8

```c
#include "stm32f0xx.h"

void micro_wait(int);

int main(void)
{
    RCC->AHBENR  |=  RCC_AHBENR_GPIOCEN;
    GPIOC->MODER &= ~GPIO_MODER_MODER8;
    GPIOC->MODER |=  GPIO_MODER_MODER8_0;

    for(;;) {
        GPIOC->BSRR = GPIO_ODR_8;
        micro_wait(1000000);
        GPIOC->BRR = GPIO_ODR_8;
        micro_wait(1000000);
    }
}
```

CMSIS

- Cortex Microcontroller Software Interface Standard
  - Definitions for registers and values with which to modify them
  - Usable with C structure mechanisms (->)
  - Need to build a project with Standard Peripheral firmware
  - Definitions are from provided header files.
- Open a project and look at the file:

  CMSIS/device/stm32f0xx.h

C code to copy pa0 to pc8

```c
#include "stm32f0xx.h"

int main(void)
{
    RCC->AHBENR  |=  RCC_AHBENR_GPIOAEN|RCC_AHBENR_GPIOCEN;
    GPIOC->MODER &= ~GPIO_MODER_MODER8;
    GPIOC->MODER |=  GPIO_MODER_MODER8_0;
    GPIOA->PUPDR &= ~GPIO_PUPDR_PUPDR0;
    GPIOA->PUPDR |=  GPIO_PUPDR_PUPDR0_1;

    for(;;) {
        int status = (GPIOA->IDR & 1);
        GPIOC->BSRR = ((1<<8)<<16) | (status << 8);

        // I could have said, instead:
        // GPIOC->BSRR = (0x0100<<16) | ((GPIOA->IDR & 1) << 8);
    }
}
```

Putting assembly language inside a C function

- Called "inline assembly language."
- Different with every compiler.
- We’re using GCC, and it works like this:
  - The asm() statement encapsulates assembly language (with labels, if you like) in a string.
  - Colon-separated definitions allow you to supply input and output arguments to the instructions, and a list of registers that are modified (clobbered) as side-effects.
  - The statement does not produce a value.
    - i.e. you can’t say x=asm("…");

Inline assembly syntax

```
asm("   instruction
        instruction
     label:
        instruction
        instruction"
    : <output operand list>
    : <input operand list>
    : <clobber list>);
```

Inline assembly example

```
int main(void) {
    int count = 0;
    for(;;) {
        count += 1;
        asm("nop");
        count += 1;
    }
}

// I’ll bet you think this is too trivial.
// There is a subtle problem.
// The compiler might reorder the asm()
// statement if it thinks it’s a good idea.
```

Inline assembly example

```c
int main(void) {
    int count = 0;
    for(;;) {
        count += 1;
        asm volatile("nop");
        count += 1;
    }
}

// volatile tells the compiler that it is
// important to leave the asm statement
// exactly where we put it.
```

Inline assembly example

```
void mywait(int x) {
    asm volatile("        mov r0, %0\n"
                 "again:\n"
                 "        nop\n"
                 "        nop\n"
                 "        nop\n"
                 "        nop\n"
                 "      sub r0, #1\n"
                 "        bne again\n"
                 :  : "r"(x) : "r0", "cc");
}

int main(void) {
    for(;;) {
        mywait(1000000);
    }
}
```

sub r0, #1 ?

- Why isn't that subs r0,#1 ?
- Because inline assembly does not use unified syntax. Things are a little bit strange.

Inline assembly example

```c
// Remember that C has no rotate operator.

int main(void) {
	int x = 1;
	for(;;) {
		asm volatile("ror %0,%1\n" : "+l"(x) : "l"(1) : "cc");
	}
}
```

Inline assembly constraints

- The "r" and the "l" and the "+l" are operand constraints.
  - They are different for every architecture, and you will have to look them up every time you use them.
    - Even if you are an expert with GCC.
  - Look up “GCC inline assembly contraints” for the complete story on this.

Register constraints

- You can force a variable to use a register with the register keyword:

  register int x = 5;

- You can force a variable to use a specific register (in GCC) like this:

  register int x asm("r6");