This week

- Assignment 1 due Tuesday: you'll have proved your bare-metal mettle!
- Lab 2 prep
    - do pre-lab reading!
    - bring your tools

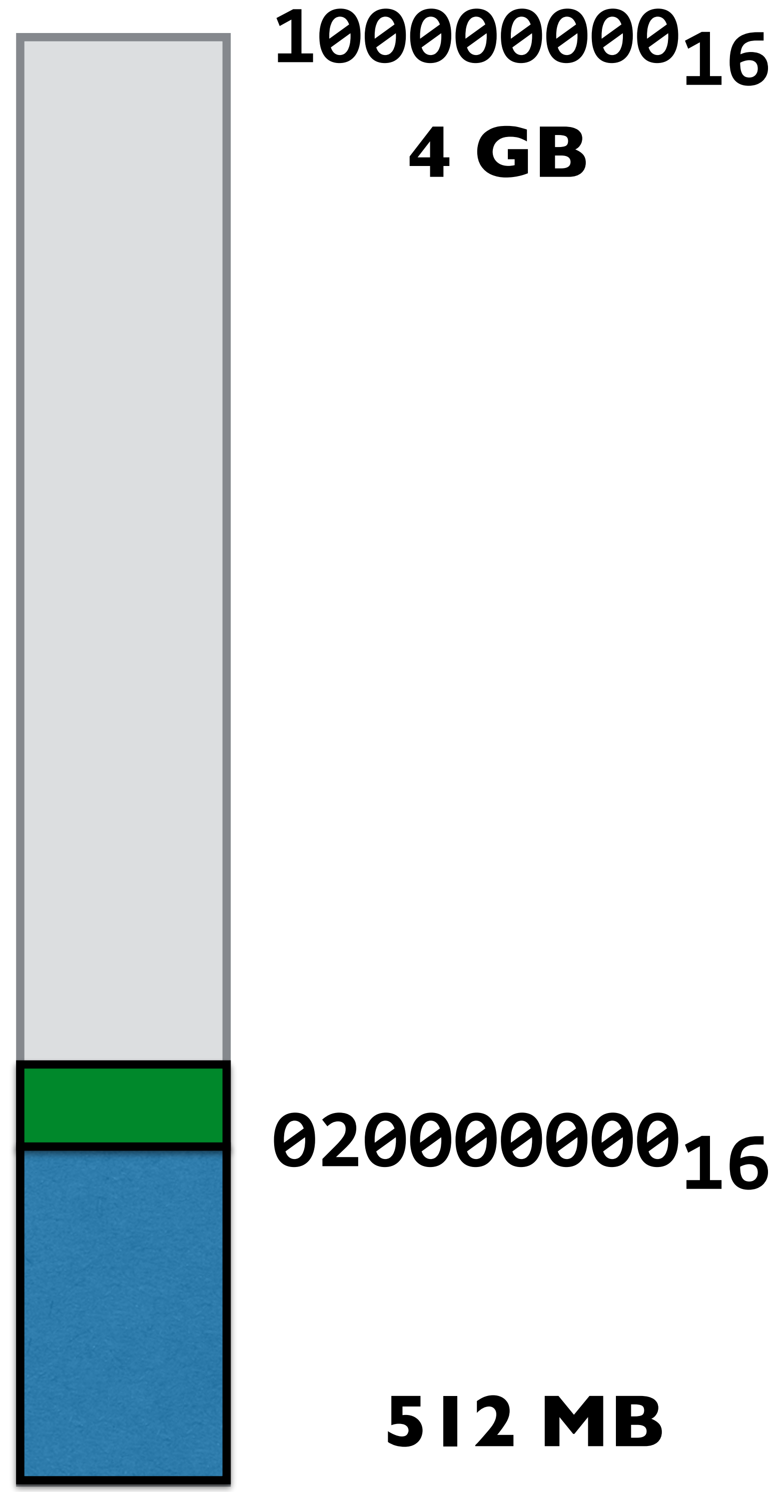
Goals for today

- Understand `str`/`ldr`
- Understand C pointers
- ARM addressing modes, translation to/from C
- Details: volatile qualifier, bare-metal build

Memory

Memory is a linear sequence of bytes

Addresses start at 0, go to 2^{32}-1 (32-bit architecture)



Accessing memory in assembly

`ldr` copies 4 bytes from memory address to register
`str` copies 4 bytes from register to memory address

The memory address could be:

- the location of a global or local variable or
- the location of program instructions or
- a memory-mapped peripheral or
- an unused/invalid location or ...

The 4 bytes of data being copied could be:

- an address or
- an 32-bit integer or
- 4 characters or
- an ARM instruction, or...

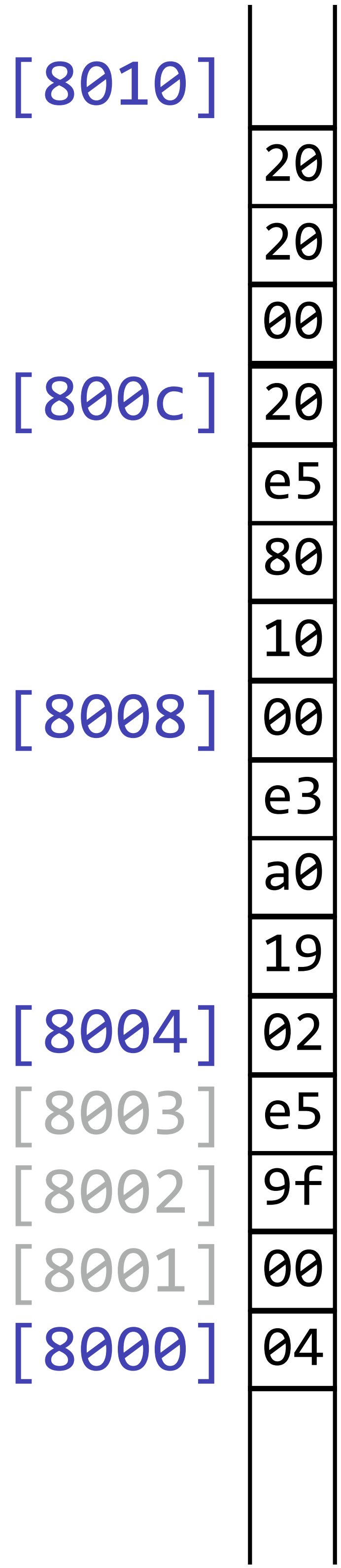
And *assembly code doesn't care*

```
FSEL2: .word 0x20200008
SET0:  .word 0x2020001C

ldr r0, FSEL2
mov r1, #1
str r1, [r0]

ldr r0, SET0
mov r1, #(1<<20)
str r1, [r0]
```

Memory as a linear sequence of indexed bytes



Same memory,
grouped into 4-byte words

[800c]	20200020
[8008]	e5801000
[8004]	e3a01902
[8000]	e59f0004

Note little-endian byte ordering

ARM load/store instructions

```
ldr r0, [r1]

str r0, [r1]
```

Store is a misfit among ARM instructions — operands are in order of src, dst (reverse of all other instructions)

ASM and memory

At the assembly level, a 4-byte word could represent

- an address,
- an int,
- 4 characters
- an ARM instruction

Assembly has no type system to guide or restrict us on what we do with those words.

Keeping track of what's what in assembly is *hard* and very bug-prone.

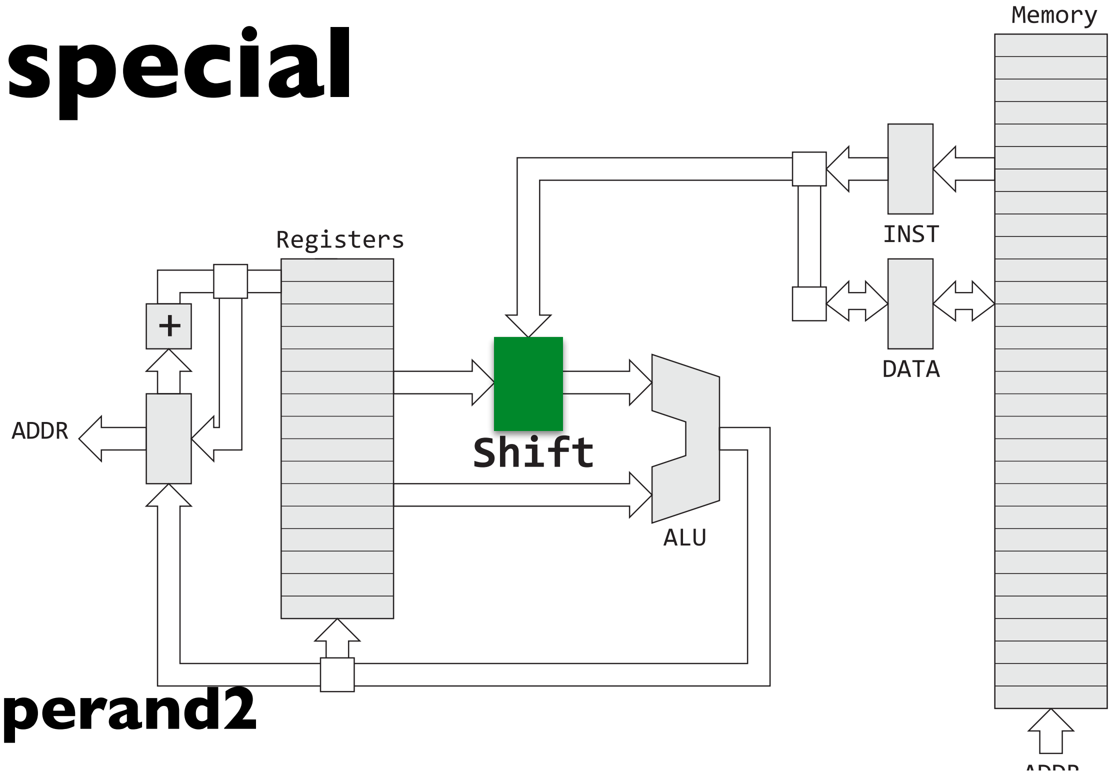
Funny program

`pc` is the register containing the address of the current instruction (processor updates it on each execution, changes it on branch instructions)

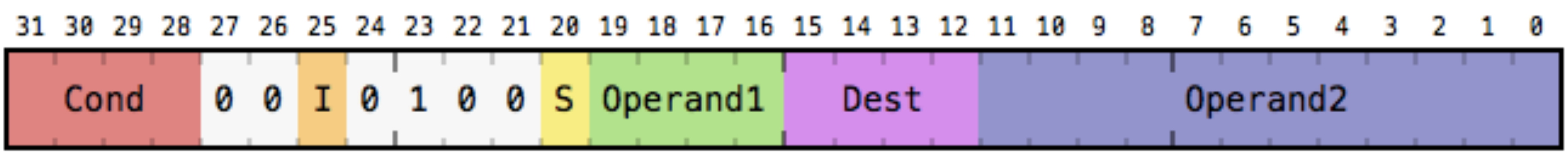
What does this program do?

```
ldr r1, [pc - 4]
add r1, r1, #1
str r1, [pc - 12]
```

Operand 2 is special

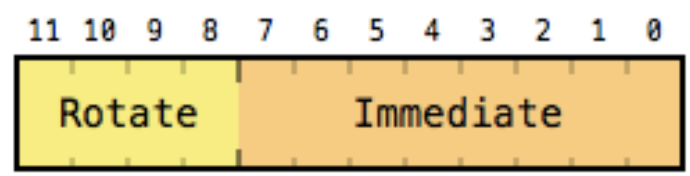


Dest = Operand1 op Operand2

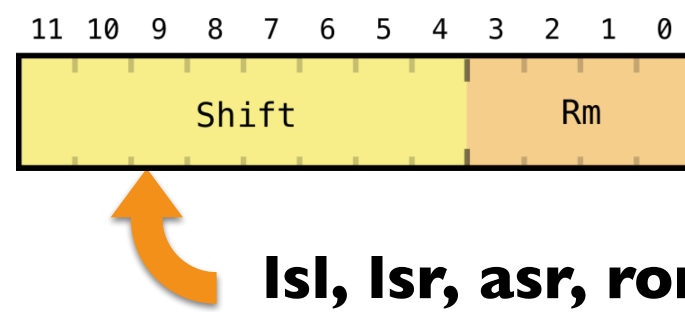


add r0, r1, #0x1f000
sub r0, r1, #6
rsb r0, r1, #6
add r0, r1, r2, lsl #3
mov r1, r2, ror #7

I=1



I=0



lsl, lsr, asr, ror

Funny program

`pc` is the register containing the address of the current instruction (processor updates it on each execution, changes it on branch instructions)

What does this program do?
Adds to the `add` instruction

```
ldr r1, [pc - 4]
add r1, r1, #1
str r1, [pc - 12]
```

```
      add r1, r1, #1
         e2 81 10 01
    +1 = e2 81 10 02
    +2 = e2 81 10 04
    +4 = e2 81 10 08
                 ...
 + 128 = e2 81 11 00
```

Funny program

`pc` is the register containing the address of the current instruction (processor updates it on each execution, changes it on branch instructions)

What does this program do?
Adds to the `add` instruction

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```

```
      add r1, r1, #1
         e2 81 10 01
    +1 = e2 81 10 02
    +2 = e2 81 10 04
    +4 = e2 81 10 08
                 ...
 + 128 = e2 81 11 00
```

Operating on addresses is extremely powerful!
We need some safety rails.

C pointer vocabulary

An *address* is a memory location. Representation is unsigned 32-bit int.

A *pointer* is a variable that holds an address.

The "*pointee*" is the data stored at that address.

* is the *dereference* operator, & is *address-of*.

C code

```
int val = 5;
int *ptr = &val;
```

Memory

val	[810c]	0x00000005
ptr	[8108]	0x0000810c

What do C pointers buy us?

- Access specific memory by address, e.g. FSEL2
- Allow us to specify not only an address, but also what we expect to be stored at that address: the data type
  - int* vs char* vs key_event_t*
- Access data by its offset relative to other nearby data (array elements, struct fields)
  - Storing related data in related locations organizes use of memory
- Efficiently refer to shared data, avoid redundancy/duplication
- Build flexible, dynamic data structures at runtime

CULTURE FACT:

IN CODE, IT'S NOT CONSIDERED RUDE TO POINT.

C Pointer Operations

```c
int val = 5;
int* ptr = &val;
```

0x0000810c	0x05	0x00	0x00	0x00
0x00008110	0x0c	0x81	0x00	0x00

C Pointer Operations

```
int val = 5;
int* ptr = &val;
```

0x0000810c	0x05	0x00	0x00	0x00
0x00008110	0x0c	0x81	0x00	0x00

```
*ptr = 7;
```

0x0000810c	0x07	0x00	0x00	0x00
0x00008110	0x0c	0x81	0x00	0x00

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```c
*ptr = 7;
```

0x0000810c	0x07	0x00	0x00	0x00
0x00008110	0x0c	0x81	0x00	0x00

```c
int** dptr = &ptr;
```

0x0000810c	0x07	0x00	0x00	0x00
0x00008110	0x0c	0x81	0x00	0x00
0x00008114	0x10	0x81	0x00	0x00

C Pointer Operations

```
int val = 5;
int* ptr = &val;
```

0x0000810c	0x05	0x00	0x00	0x00
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```
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0x00008110	0x0c	0x81	0x00	0x00
0x00008114	0x10	0x81	0x00	0x00

```
*dptr = NULL;
```

0x0000810c	0x07	0x00	0x00	0x00
0x00008110	0x00	0x00	0x00	0x00
0x00008114	0x10	0x81	0x00	0x00

C Pointer Operations

```
char a = 'a';
char b = 'b';
char* ptr = &b;
```

0x61 0x62

0x0000810c	'a'	'b'	0x00	0x00
0x00008110	0x0d	0x81	0x00	0x00

C Pointer Operations

```
char a = ‘a’;
char b = ‘b’;
char* ptr = &b;

*ptr = ‘c’;
```

0x61 0x62

0x0000810c	‘a’	‘b’	0x00	0x00
0x00008110	0x0d	0x81	0x00	0x00

0x63

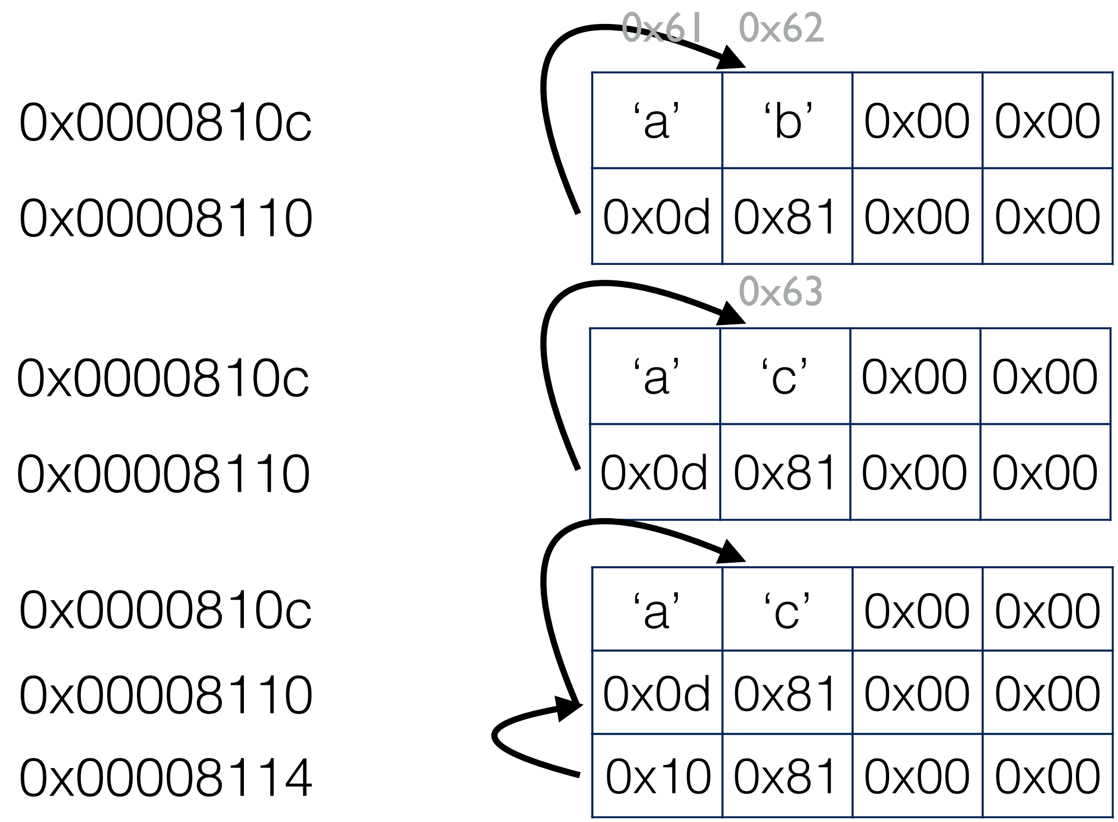
0x0000810c	‘a’	‘c’	0x00	0x00
0x00008110	0x0d	0x81	0x00	0x00

C Pointer Operations

```
char a = 'a';
char b = 'b';
char* ptr = &b;
```

```
*ptr = 'c';
```

```
char** dptr = &ptr;
```



C Pointer Operations

```
char a = 'a';
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char* ptr = &b;
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	0x61	0x62		
0x0000810c	‘a’	‘b’	0x00	0x00
0x00008110	0x0d	0x81	0x00	0x00

```
*ptr = 'c';
```

		0x63		
0x0000810c	‘a’	‘c’	0x00	0x00
0x00008110	0x0c	0x81	0x00	0x00

```
char** dptr = &ptr;
```

0x0000810c	‘a’	‘c’	0x00	0x00
0x00008110	0x0d	0x81	0x00	0x00
0x00008114	0x10	0x81	0x00	0x00

```
*dptr = NULL;
```

0x0000810c	‘a’	‘c’	0x00	0x00
0x00008110	0x00	0x00	0x00	0x00
0x00008114	0x10	0x81	0x00	0x00

Pointer Quiz: & *

```
int m, n, *p, *q;

p = &n;
*p = n;        // 1. same as prev line?

q = p;
*q = *p;       // 2. same as prev line?

p = &m, q = &n;
*p = *q;
m = n;         // 3. same as prev line?
```

C pointer types

C has a *type system:* tracks the type of each variable.

Operations have to respect the data type.

- Can't multiply int*'s, can't deference an int

Distinguishes pointer variables by type of pointee

- Dereferencing an int* is an int
- Dereferencing a char* is a char

C arrays

An array allocates multiple instances of a type contiguously in memory

```
char ab[2];
ab[0] = 'a';
ab[1] = 'b';
```

		0x61	0x62		
0x0000810c		'a'	'b'		

```
int ab[2];
ab[0] = 'a';
ab[1] = 9;
```

		0x61			
0x0000810c		'a'	0x00	0x00	0x00
0x00008110		0x09	0x00	0x00	0x00

Arrays and Pointers

You can assign an array to a pointer

```
int ab[2] = {5, 7};
int* ptr = ab; // ptr = &(ab[0]);
```

Incrementing pointers advances address by size of type

```
ptr = ptr + 1; // now points to ab[1]
```

What does the assembly look like?
What if ab is a char[2] and ptr is a char*?

Pointer Arithmetic

Incrementing pointers advances address by size of type.

```
struct point {
  int x; // 32 bits, 4 bytes
  int y; // 32 bits, 4 bytes
};
struct point points[100];
struct point* ptr = points;
ptr = ptr + 1; // now points to points[1]
```

Suppose points is at address 0x100. What is the value of ptr after the last line of code?

Pointers and arrays

```
int n, arr[4], *p;

p = arr;
p = &arr[0];       // same as prev line
arr = p;           // ILLEGAL, why?

*p = 3;
p[0] = 3;          // same as prev line

n = *(arr + 1);
n = arr[1];        // same as prev line
```

Address arithmetic

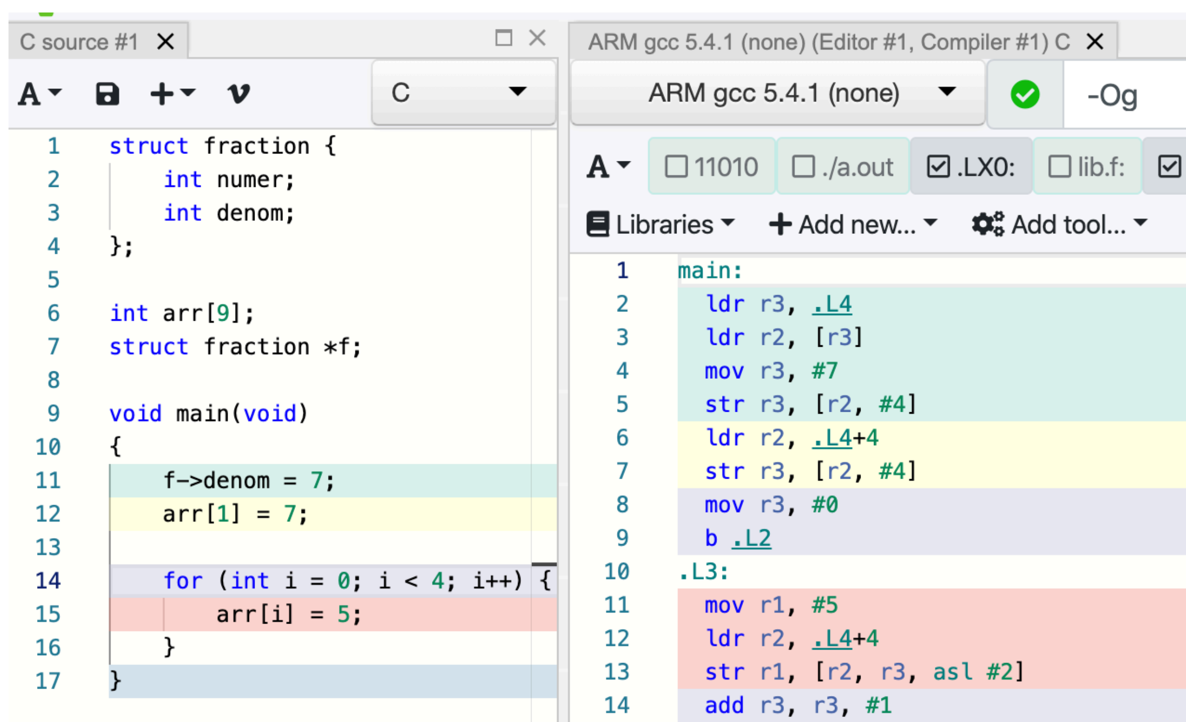
Fancy ARM addressing modes

```
ldr r0, [r1, #4]              // constant displacement
ldr r0, [r1, r2]              // variable displacement
ldr r0, [r1, r2, asl #3]      // scaled index displacement
```

(Even fancier variants add pre/post update to move pointer along)

Q: How do these relate to accessing data structures in C?

Try CompilerExplorer to find out!



C-strings

```
char *s = "Stanford";
char arr[] = "University";
char oldschool[] = {'L','e','l','a','n','d'};
char buf[100];
char *ptr;

// which assignments are valid?
1  ptr = s;
2  ptr = arr;
3  ptr = buf;
4  arr = ptr;
5  buf = oldschool;
```

\0
64
63
61
6c
65
4c

??\06463
616c654c

What does a typecast <u>actually do</u>?

Aside: why is this even allowed?

- Casting between different types of pointers — perhaps plausible
- Casting between pointers and int — sketchy
- Casting between pointers and float — bizarre

```
int *p; double *q; char *s;

ch  = *(char *)p;
val = *(int *)s;
val = *(int *)q;
```

Power of Types and Pointers

```
struct gpio {
  unsigned int fsel[6];
  unsigned int reservedA;
  unsigned int set[2];
  unsigned int reservedB;
  unsigned int clr[2];
  unsigned int reservedC;
  unsigned int lev[2];
};
```

Address	Field Name	Description	Size	Read/ Write
0x 7E20 0000	GPFSEL0	GPIO Function Select 0	32	R/W
0x 7E20 0000	GPFSEL0	GPIO Function Select 0	32	R/W
0x 7E20 0004	GPFSEL1	GPIO Function Select 1	32	R/W
0x 7E20 0008	GPFSEL2	GPIO Function Select 2	32	R/W
0x 7E20 000C	GPFSEL3	GPIO Function Select 3	32	R/W
0x 7E20 0010	GPFSEL4	GPIO Function Select 4	32	R/W
0x 7E20 0014	GPFSEL5	GPIO Function Select 5	32	R/W
0x 7E20 0018	-	Reserved	-	-
0x 7E20 001C	GPSET0	GPIO Pin Output Set 0	32	W
0x 7E20 0020	GPSET1	GPIO Pin Output Set 1	32	W
0x 7E20 0024	-	Reserved	-	-
0x 7E20 0028	GPCLR0	GPIO Pin Output Clear 0	32	W
0x 7E20 002C	GPCLR1	GPIO Pin Output Clear 1	32	W
0x 7E20 0030	-	Reserved	-	-
0x 7E20 0034	GPLEV0	GPIO Pin Level 0	32	R
0x 7E20 0038	GPLEV1	GPIO Pin Level 1	32	R

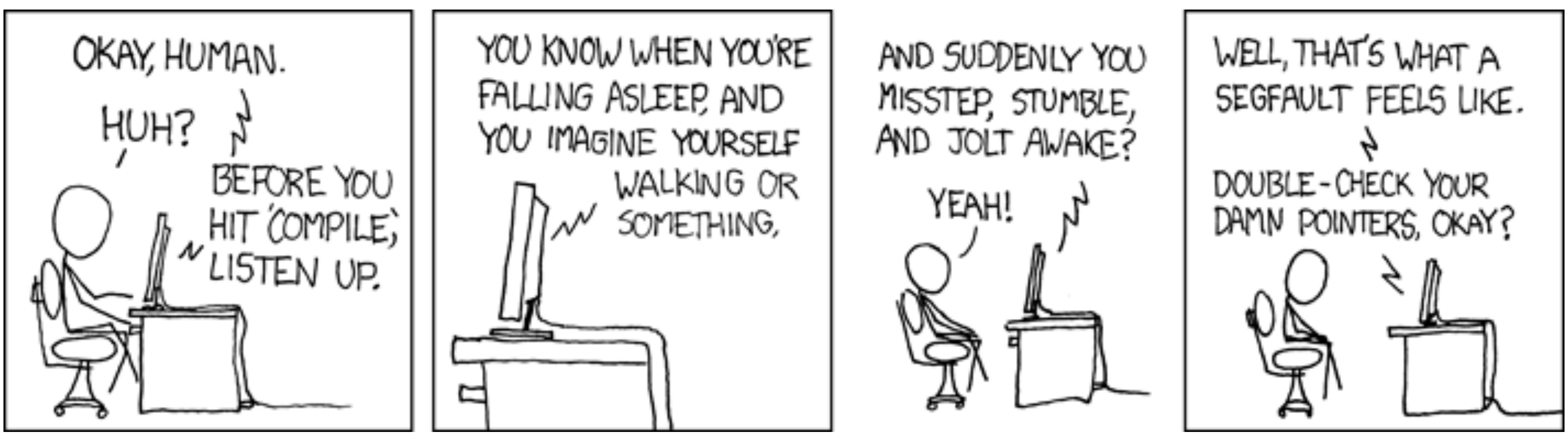
```
volatile struct gpio *gpio = (struct gpio *)0x20200000;
gpio->fsel[0] = ...
```

Pointers: the fault in our *s

Pointers are ubiquitous in C, and inherently dangerous. Be vigilant!

Q. For what reasons might a pointer be invalid?

Q. What is consequence of using an invalid pointer?



C vs. Assembly

```
.equ DELAY, 0x3F0000
ldr r0, FSEL2
mov r1, #1
str r1, [r0]
mov r1, #(1<<20)
loop:
  ldr r0, SET0
  str r1, [r0]
  mov r2, #DELAY
  wait1:
    subs r2, #1
    bne wait1
  ldr r0, CLR0
  str r1, [r0]
  mov r2, #DELAY
  wait2:
    subs r2, #1
    bne wait2
  b loop

FSEL2: .word 0x20200008
SET0: .word 0x2020001C
CLR0: .word 0x20200028
```

C?

Let's do it!

The utility of pointers

Accessing data by location is ubiquitous and powerful

You learned in previous course how pointers are useful

- Sharing data instead of redundancy/copying
- Construct linked structures (lists, trees, graphs)
- Dynamic/runtime allocation

Now you see how it works under the hood

- Memory-mapped peripherals located at fixed address
- Access to struct fields and array elements by relative location

What do we gain by using C pointers over raw `ldr`/`str`?

- Type system adds readability, some safety
- Pointee and level of indirection now explicit in the type
- Organize related data into contiguous locations, access using offset arithmetic

Know your tools

Assembler (as)

- Transform assembly code (text) into object code (binary machine instructions)
- Mechanical translation, few surprises

Compiler (gcc)

- Transform C code (text) into object code
- (likely staged C-> asm -> object)
- Complex translation, high artistry

When coding directly in assembly, you get what you see.

For C source, you may need to look at what compiler has generated to be sure of what you're getting.

What transformations are *legal* ?
What transformations are *desirable* ?

When Your C Compiler Is Too Smart For Its Own Good

(or, why every systems programmer should be able to read assembly)

```
int i, j;

i = 1;
i = 2;
j = i;

// can be optimized to

i = 2;
j = i;

// is this ever not equivalent/ok?
```

button.c

The little button that wouldn’t

Peripheral registers

These registers are mapped into the address space of the processor (memory-mapped IO).

These registers may behave **differently** than ordinary memory.

For example: Writing a 1 bit into SET register sets output to 1; writing a 0 bit into SET register has no effect. Writing a 1 bit into CLR sets the output to 0; writing a 0 bit into CLR has no effect. To read the current value, access the LEV (level) register. So writing to SET can change the value of LEV, a different memory address!

*Q: What can happen when compiler makes assumptions reasonable for ordinary memory that **don't hold** for these oddball registers?*

Compile-time vs. runtime

Compile-time: compiler is running on your laptop

- reads your C code, parse/check semantically valid
- analyzes code to understand structure/intent
- generates assembly instructions, creates program binary

Runtime: program binary is running on Pi

- all that remains is generated assembly instructions
- fetch/decode/execute cycle

The work optimizer does at CT is intended to streamline number of instructions to be executed at RT

`volatile`

Ordinarily, the compiler uses its knowledge of reads/writes to optimize while keeping the same externally visible behavior.

However, for a variable that can be read/written externally in a way the C compiler can't know (by another process, by hardware), these optimizations may not be valid.

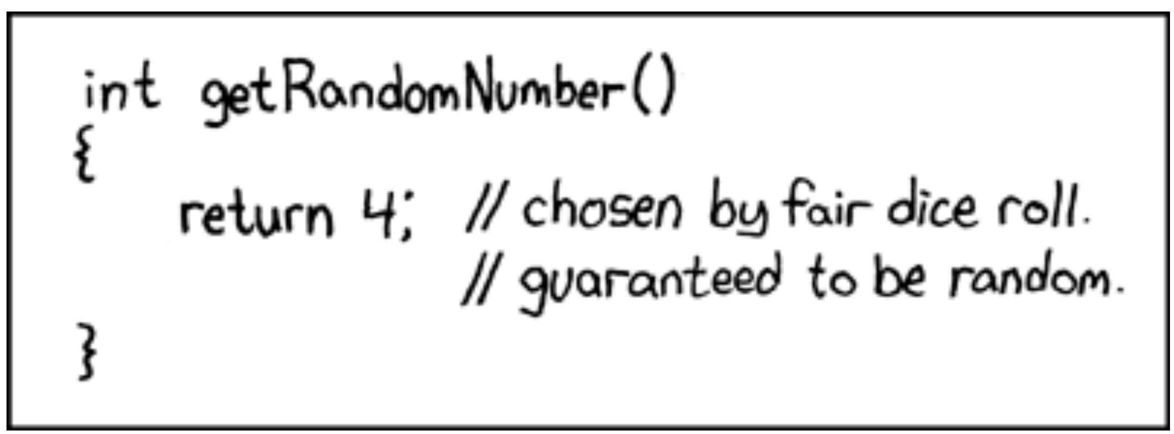
The **volatile** qualifier informs the compiler that it cannot remove, coalesce, cache, or reorder references to a variable. The generated assembly must faithfully execute each access to the variable as given in the C code.

(If ever in doubt about what the compiler has done, use tools to review generated assembly and see for yourself...!)

What is ‘bare metal’?

The default build process for C assumes a *hosted* environment. It provides standard libraries, all the stuff that happens before `main`.

To build bare-metal, our makefile disables these defaults; we must supply our own versions when needed.



Makefile settings

Compile freestanding

```
CFLAGS =-ffreestanding
```

Link without standard libs and start files

```
LDFLAGS = -nostdlib
```

Link with gcc to support division (violates

```
LDLIBS = -lgcc
```

Must supply own replacement for libs/start

That's where the fun is…!