

This week

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



Today: C Pointers & Arrays

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

Good Breadboard Tips

- Use black for ground, red for 5V / 3.3V
- Connect 3.3V to the red line power "rail"
- Connect GND to the blue line power rail
- Keep connections as flat to the board as possible
- Snipping down resistors for this assignment makes things much cleaner
- Look at pictures of good breadboard layouts in lab / the assignment

Why Learning Python as a First Language has its Downsides

- This question came up on Ed in a private question. What is going on here?

```
loop:
    mov r0, #0

    cmp r0, #0
    beq option1

    cmp r0, #1
    beq option2

option1:
    do something

option2:
    do something

b loop
```

Why Learning Python as a First Language has its Downsides

- This question came up on Ed in a private question. What is going on here?

```
loop:
  mov r0, #0    first

  cmp r0, #0    second
  beq option1   third

  cmp r0, #1
  beq option2

option1:
  do something fourth

option2:
  do something fifth

b loop
```

Not a function!
Indentation is
irrelevant in Assembly
and C!

Assembly code is
straight-line unless
there is a branch!

Why C?

Higher-level abstractions, structured programming

Named variables, constants

Arithmetic/logical operators

Control flow

Portable

Not tied to particular ISA or architecture

Low-level enough to get to machine when needed

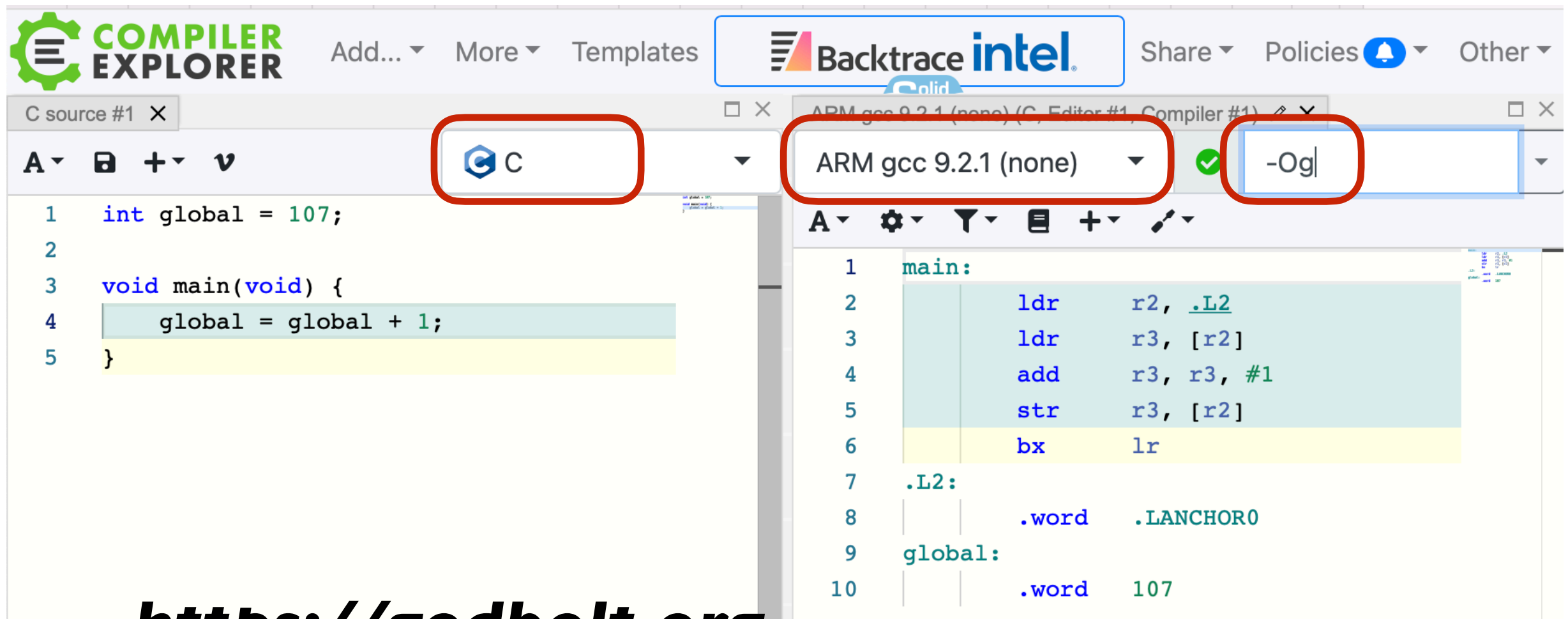
Bitwise operations

Direct access to memory

Embedded assembly, too!

Compiler Explorer

is a neat interactive tool to see translation from C to assembly.
Let's try it now!



The screenshot shows the Compiler Explorer web interface. The top navigation bar includes the Compiler Explorer logo, a 'Backtrace intel' badge, and links for 'Add...', 'More', 'Templates', 'Share', 'Policies', and 'Other'. The main interface is split into two panes. The left pane, titled 'C source #1', contains the following C code:

```
1 int global = 107;
2
3 void main(void) {
4     global = global + 1;
5 }
```

The right pane, titled 'ARM gcc 9.2.1 (none)', shows the generated assembly code:

```
1 main:
2     ldr    r2, .L2
3     ldr    r3, [r2]
4     add    r3, r3, #1
5     str    r3, [r2]
6     bx     lr
7 .L2:
8     .word  .LANCHOR0
9 global:
10    .word  107
```

Three red boxes highlight the configuration settings: the language dropdown set to 'C', the compiler dropdown set to 'ARM gcc 9.2.1 (none)', and the optimization level dropdown set to '-Og'.

<https://godbolt.org>

Configure settings to follow along:

C

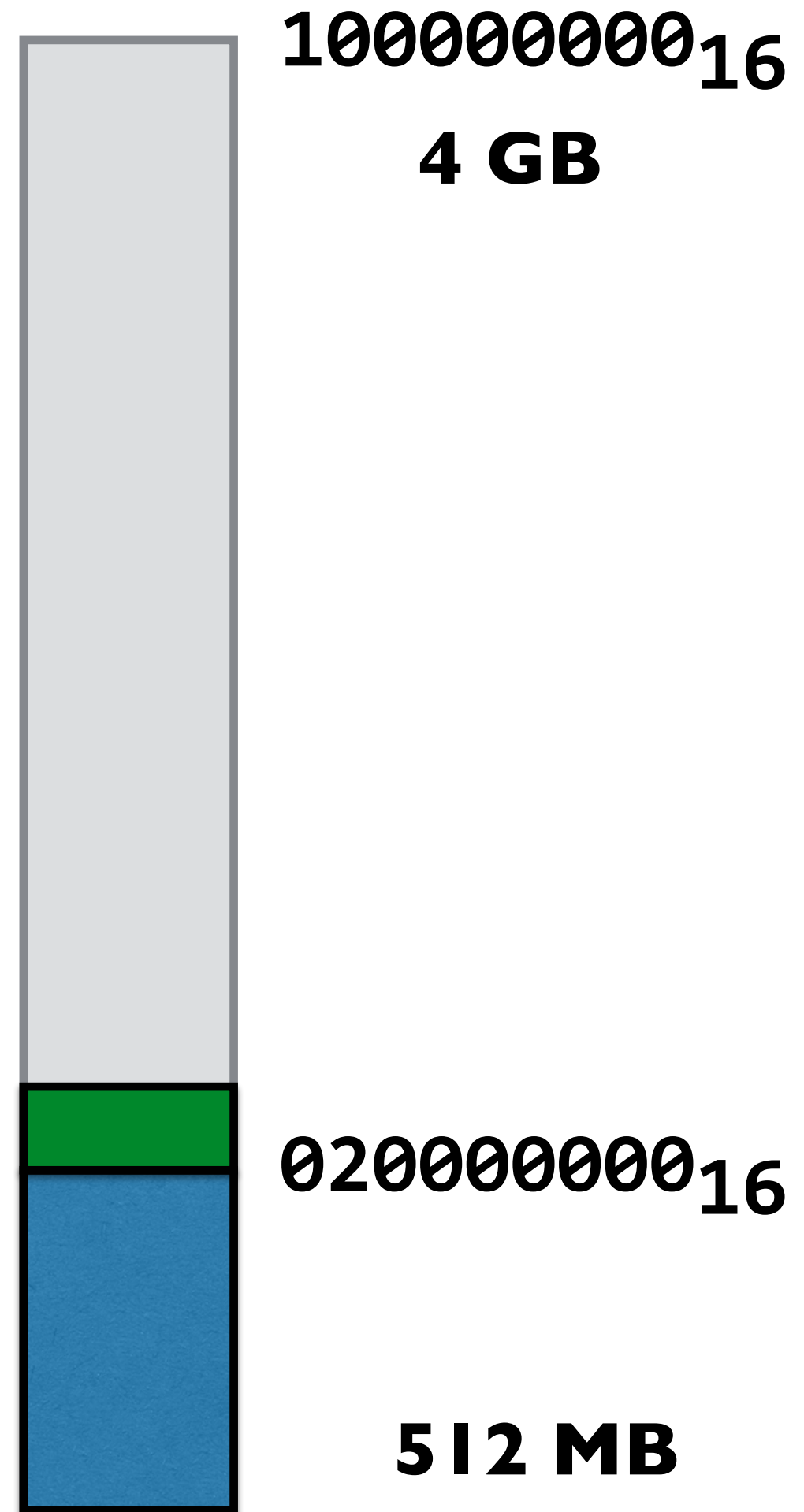
ARM gcc 9.2.1 (none)

-Og

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

[8010]	
	20
	20
	00
[800c]	20
	e5
	80
	10
[8008]	00
	e3
	a0
	19
[8004]	02
[8003]	e5
[8002]	9f
[8001]	00
[8000]	04

Same memory,
grouped into 4-byte words

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

Note little-endian byte ordering

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.

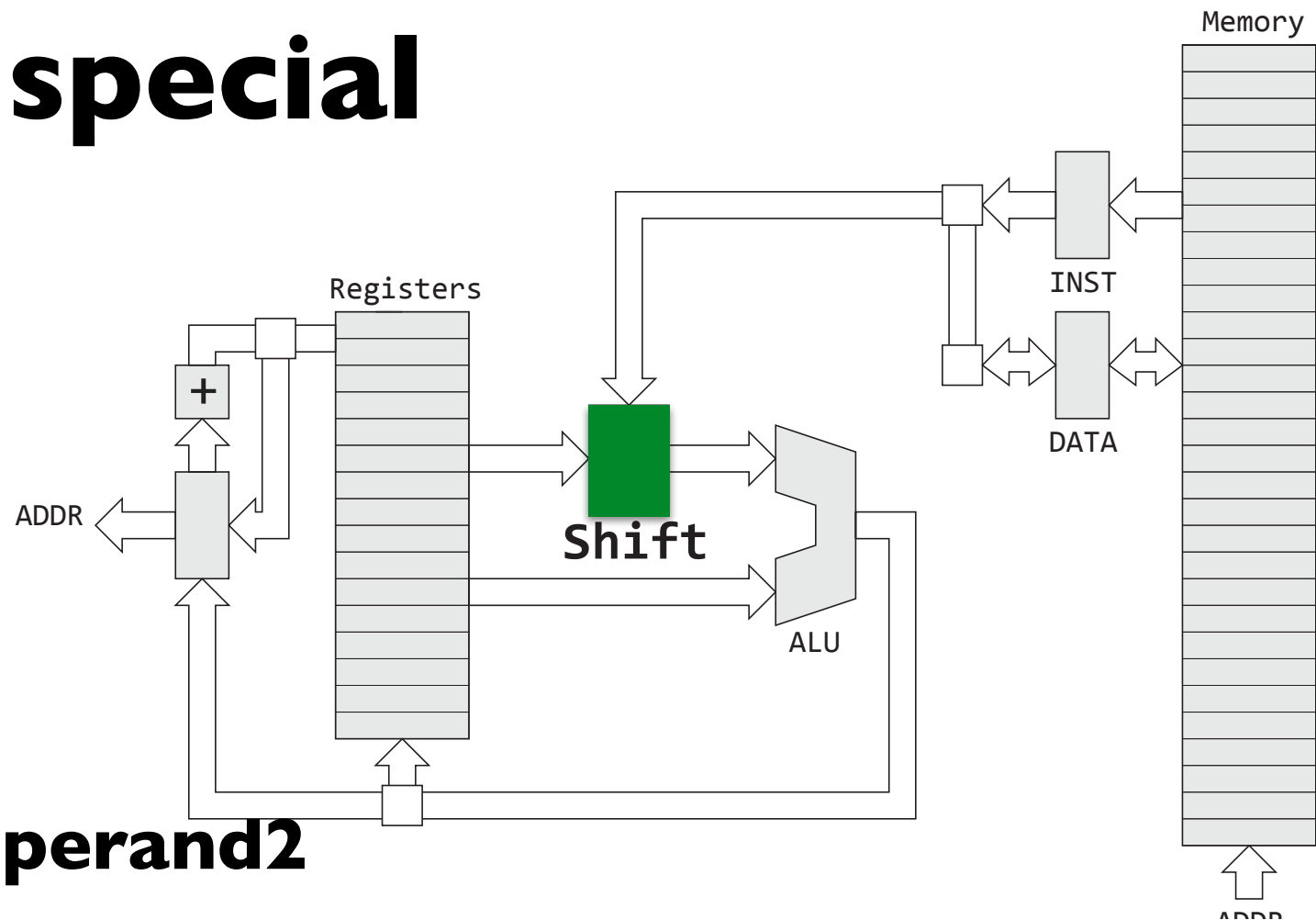
Funny program

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

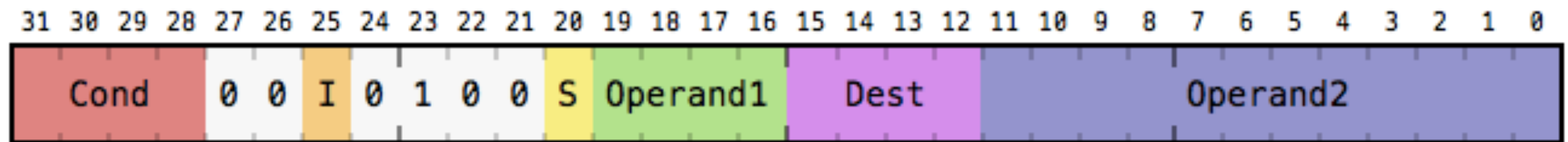
What does this program do?

```
loop:
[8000] ldr r1, [pc, #-4]
[8004] add r1, r1, #1
[8008] str r1, [pc, #-12]
[800c] b 0x8000
```

Operand 2 is special



Dest = Operand1 op Operand2



add r0, r1, #0xf000

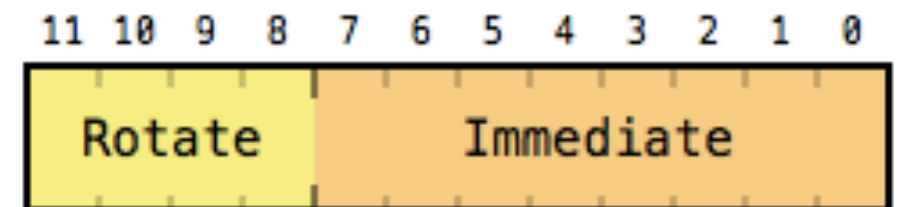
sub r0, r1, #6

rsb r0, r1, #6

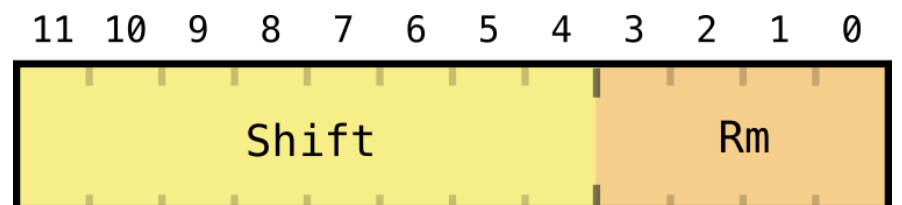
add r0, r1, r2, lsl #3

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

	<code>add r1, r1, #1</code>	
	<code>e2 81 10 01</code>	
	<code>+1 = e2 81 10 02</code>	
<code>ldr r1, [pc, #-4]</code>	<code>+2 = e2 81 10 04</code>	
<code>add r1, r1, #1</code>	<code>+4 = e2 81 10 08</code>	
	<code>...</code>	
<code>str r1, [pc, #-12]</code>	<code>+ 128 = e2 81 11 00</code>	

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*.

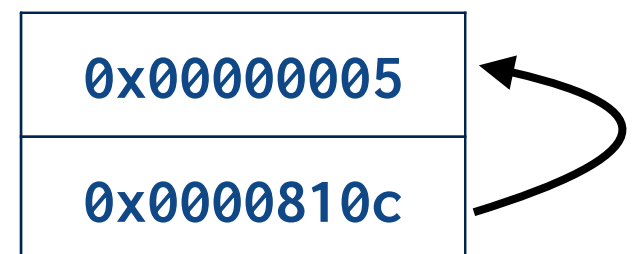
C code

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

Memory

val [810c]

ptr [8108]



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.

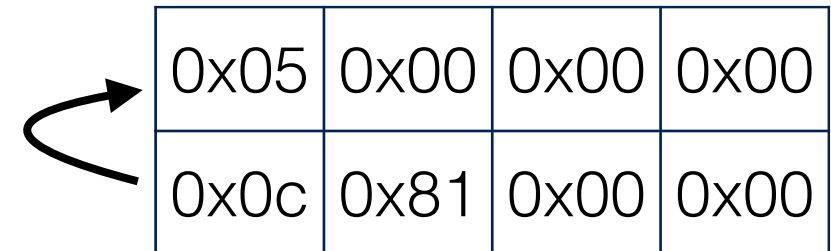


C Pointer Operations

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

0x0000810c

0x00008110



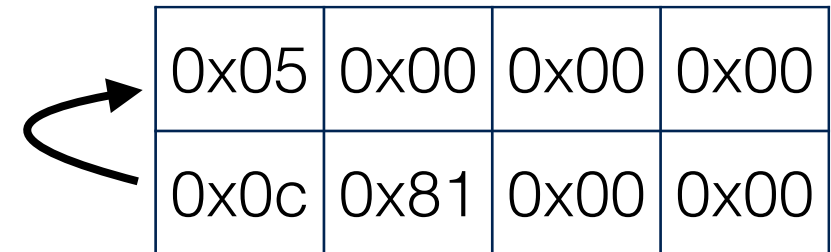
0x05	0x00	0x00	0x00
0x0c	0x81	0x00	0x00

C Pointer Operations

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

0x00000810c

0x000008110

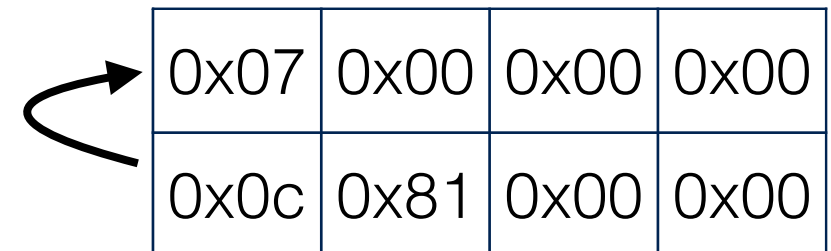


0x05	0x00	0x00	0x00
0x0c	0x81	0x00	0x00

```
*ptr = 7;
```

0x00000810c

0x000008110



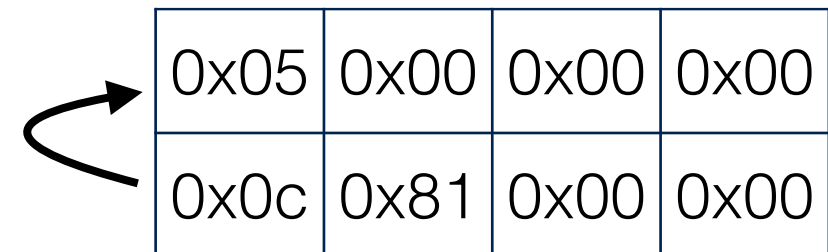
0x07	0x00	0x00	0x00
0x0c	0x81	0x00	0x00

C Pointer Operations

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

0x0000810c

0x00008110

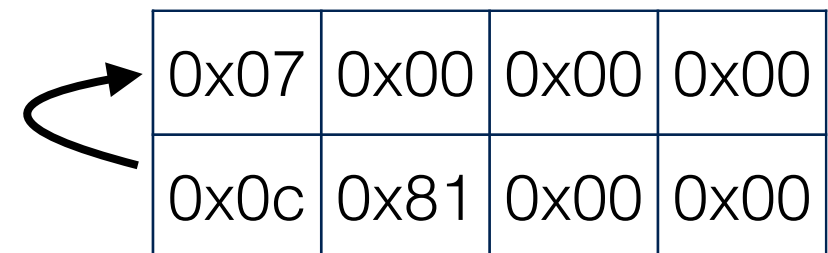


0x05	0x00	0x00	0x00
0x0c	0x81	0x00	0x00

```
*ptr = 7;
```

0x0000810c

0x00008110



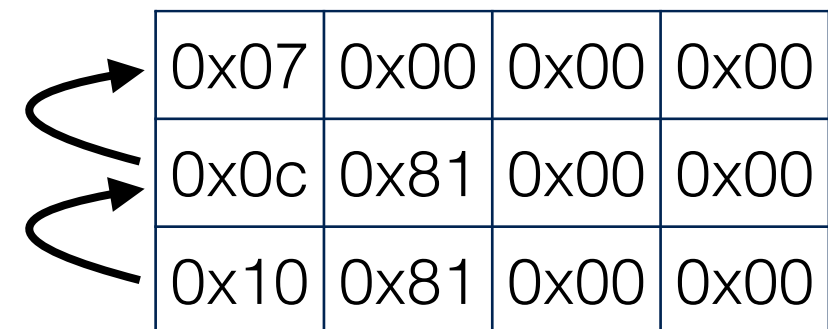
0x07	0x00	0x00	0x00
0x0c	0x81	0x00	0x00

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

0x0000810c

0x00008110

0x00008114



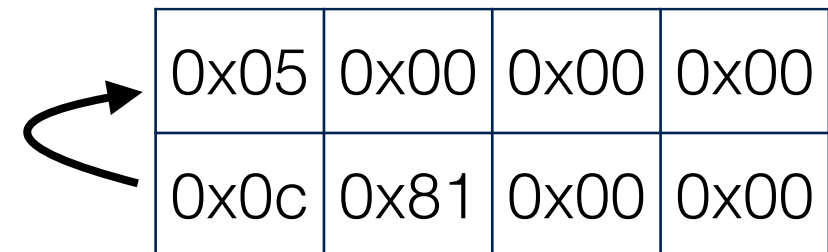
0x07	0x00	0x00	0x00
0x0c	0x81	0x00	0x00
0x10	0x81	0x00	0x00

C Pointer Operations

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

0x0000810c

0x00008110

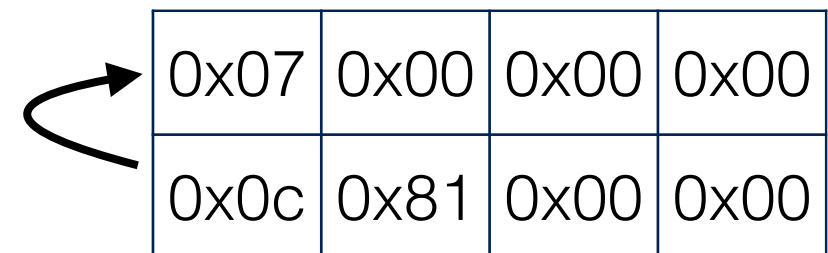


0x05	0x00	0x00	0x00
0x0c	0x81	0x00	0x00

```
*ptr = 7;
```

0x0000810c

0x00008110



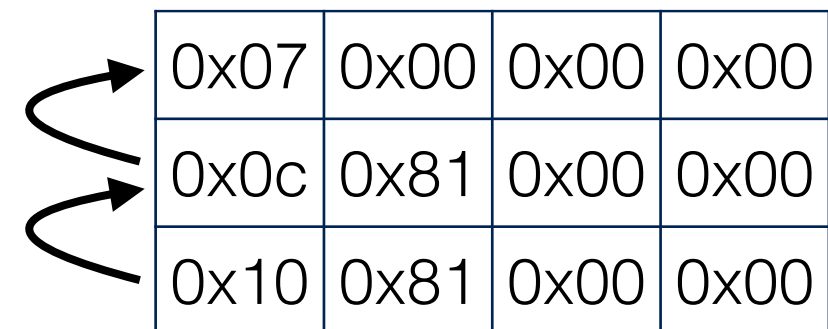
0x07	0x00	0x00	0x00
0x0c	0x81	0x00	0x00

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

0x0000810c

0x00008110

0x00008114



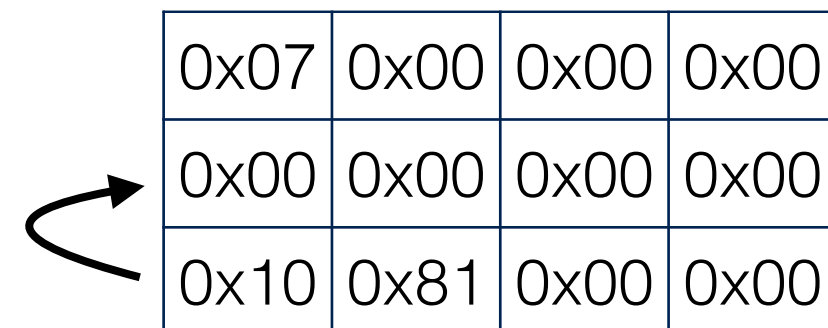
0x07	0x00	0x00	0x00
0x0c	0x81	0x00	0x00
0x10	0x81	0x00	0x00

```
*dptr = NULL;
```

0x0000810c

0x00008110

0x00008114



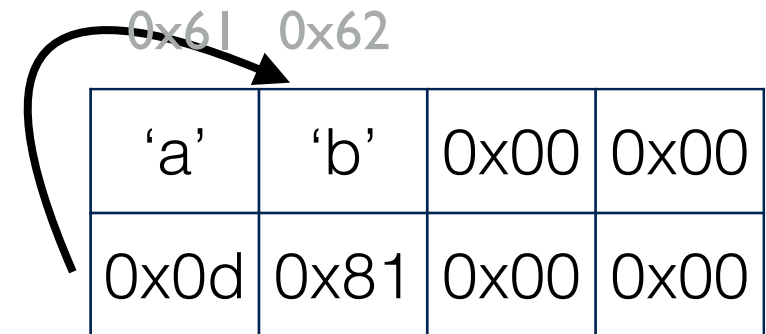
0x07	0x00	0x00	0x00
0x00	0x00	0x00	0x00
0x10	0x81	0x00	0x00

C Pointer Operations

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

0x0000810c

0x00008110



C Pointer Operations

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

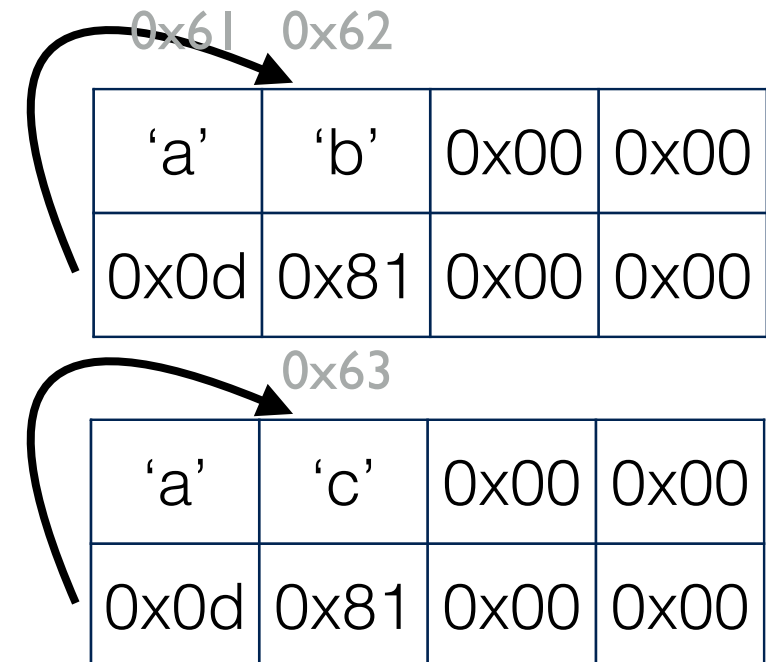
```
*ptr = 'c';
```

0x0000810c

0x00008110

0x0000810c

0x00008110



C Pointer Operations

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

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

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

0x0000810c

0x00008110

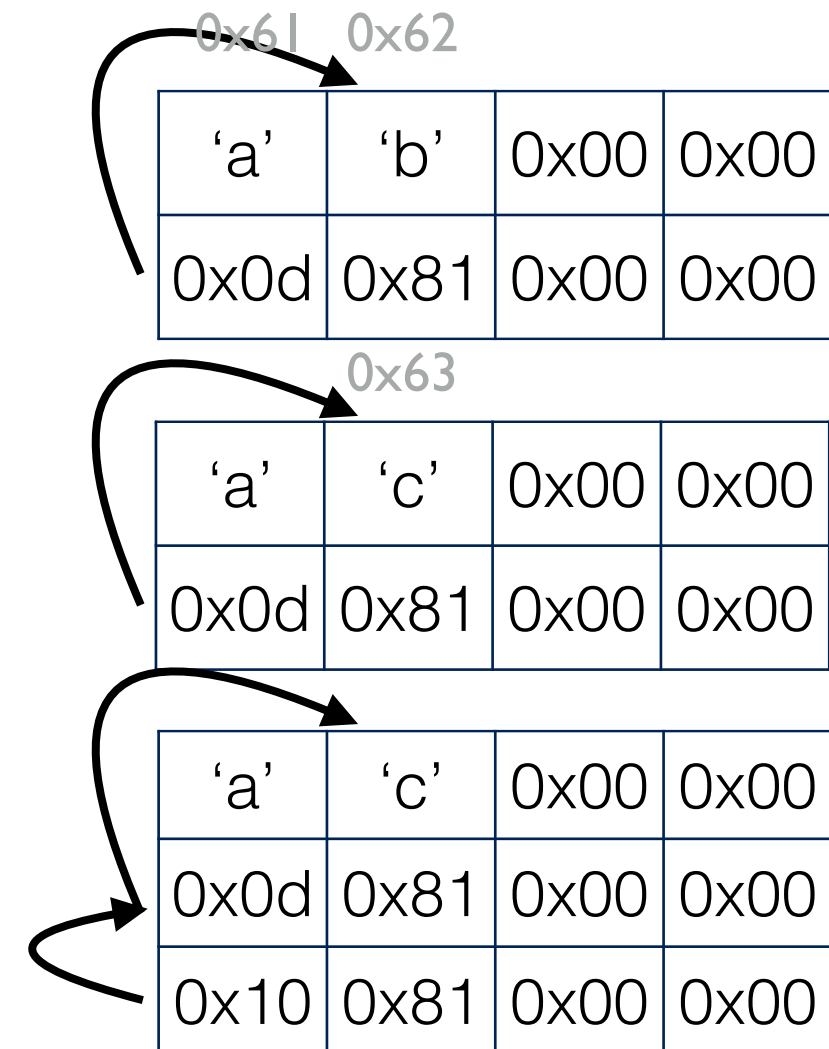
0x0000810c

0x00008110

0x0000810c

0x00008110

0x00008114



C Pointer Operations

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

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

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

```
*dptr = NULL;
```

0x0000810c

0x00008110

0x0000810c

0x00008110

0x0000810c

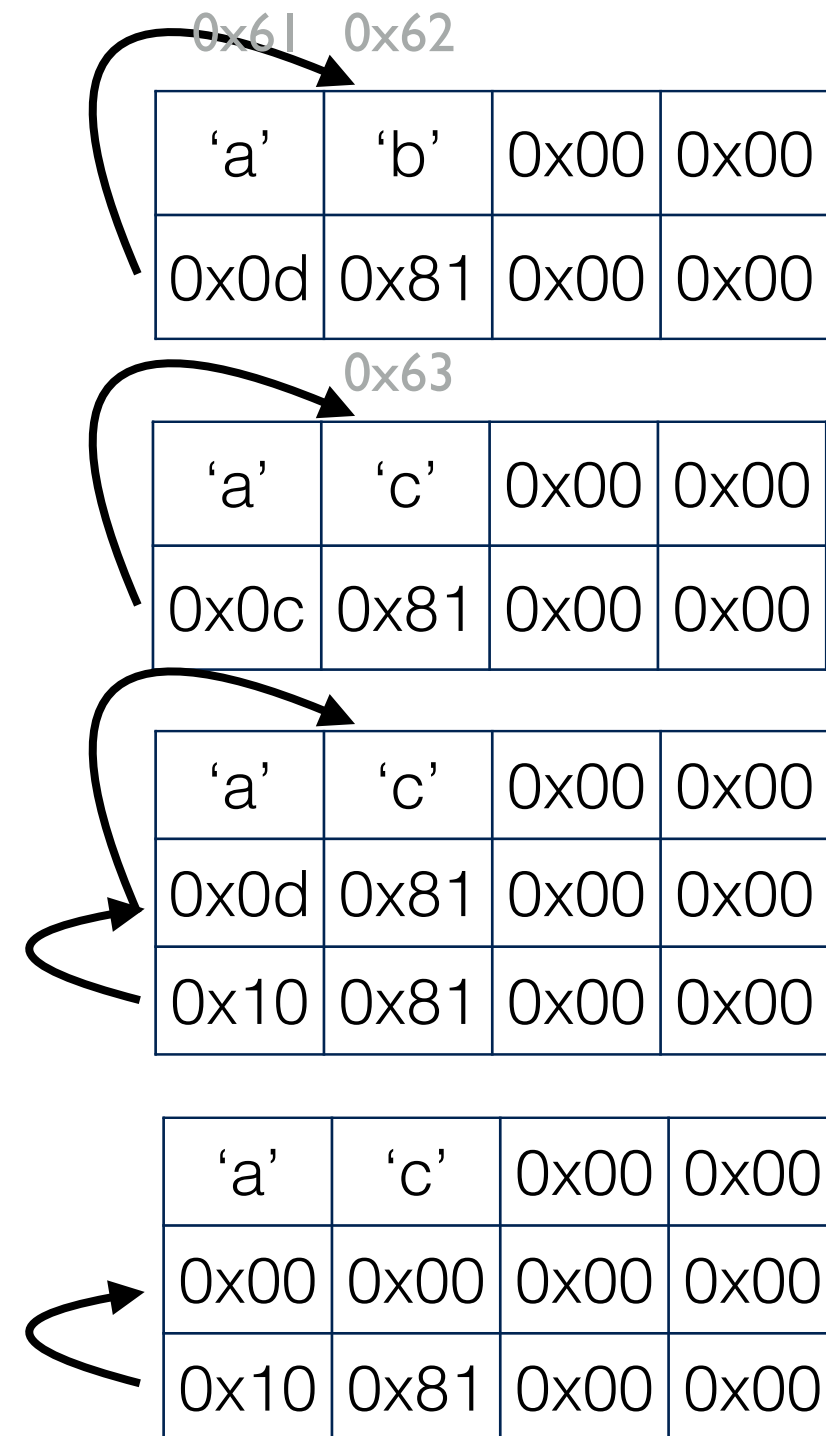
0x00008110

0x00008114

0x0000810c

0x00008110

0x00008114



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';
```

0x0000810c

	'a'	'b'	
0x61	0x62		

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

0x0000810c

0x00008110

	'a'		
0x61	0x00	0x00	0x00
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

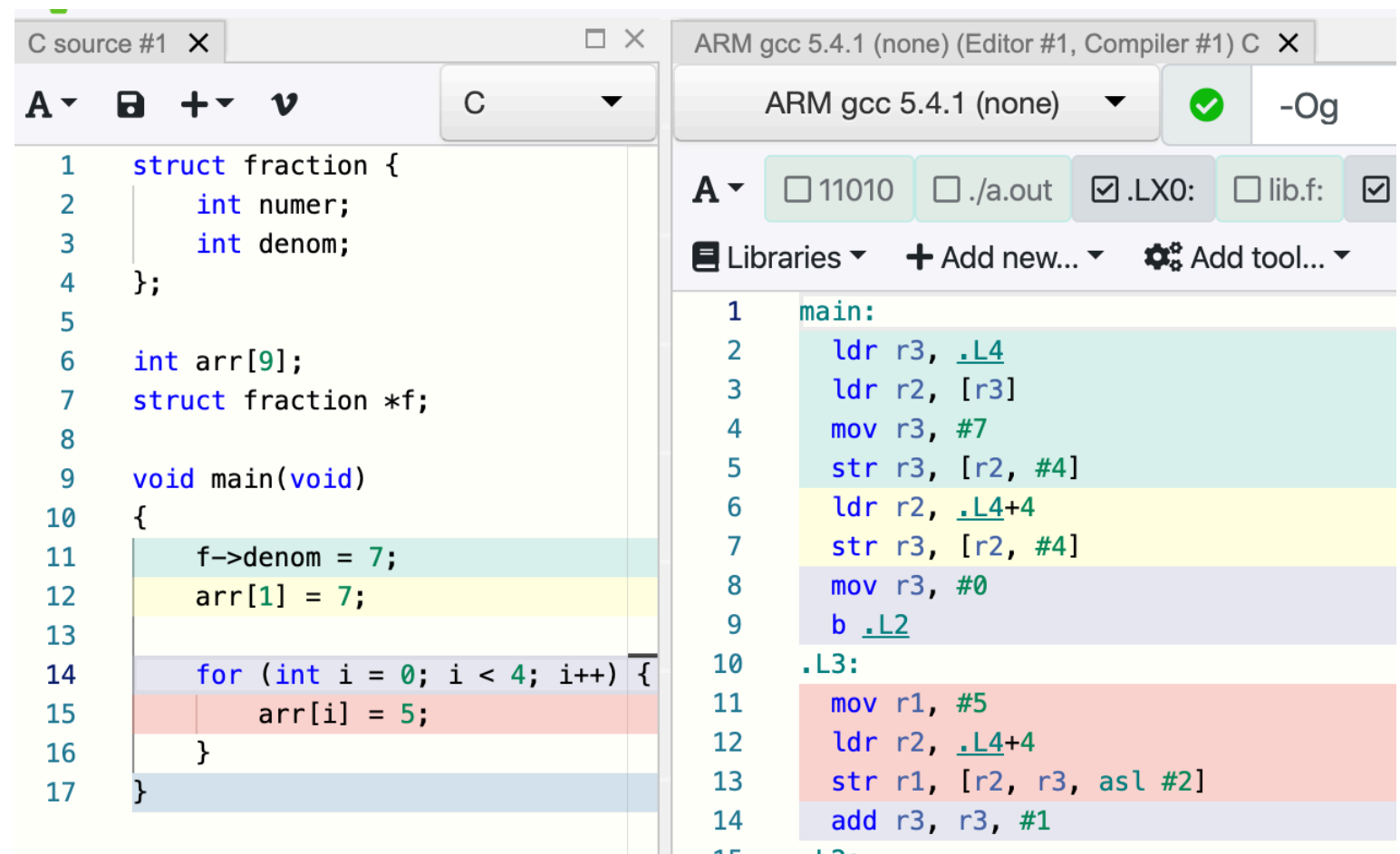
Fancy ARM addressing modes

```
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!



The screenshot shows the Compiler Explorer interface. On the left, the 'C source #1' tab displays the following C code:

```
1 struct fraction {
2     int numer;
3     int denom;
4 };
5
6 int arr[9];
7 struct fraction *f;
8
9 void main(void)
10 {
11     f->denom = 7;
12     arr[1] = 7;
13
14     for (int i = 0; i < 4; i++) {
15         arr[i] = 5;
16     }
17 }
```

On the right, the 'ARM gcc 5.4.1 (none) (Editor #1, Compiler #1) C' tab shows the generated assembly code:

```
1 main:
2     ldr r3, .L4
3     ldr r2, [r3]
4     mov r3, #7
5     str r3, [r2, #4]
6     ldr r2, .L4+4
7     str r3, [r2, #4]
8     mov r3, #0
9     b .L2
10 .L3:
11     mov r1, #5
12     ldr r2, .L4+4
13     str r1, [r2, r3, asl #2]
14     add r3, r3, #1
15 .L2:
```

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** actually do?

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	GPFSSEL0	GPIO Function Select 0	32	R/W
0x 7E20 0000	GPFSSEL0	GPIO Function Select 0	32	R/W
0x 7E20 0004	GPFSSEL1	GPIO Function Select 1	32	R/W
0x 7E20 0008	GPFSSEL2	GPIO Function Select 2	32	R/W
0x 7E20 000C	GPFSSEL3	GPIO Function Select 3	32	R/W
0x 7E20 0010	GPFSSEL4	GPIO Function Select 4	32	R/W
0x 7E20 0014	GPFSSEL5	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

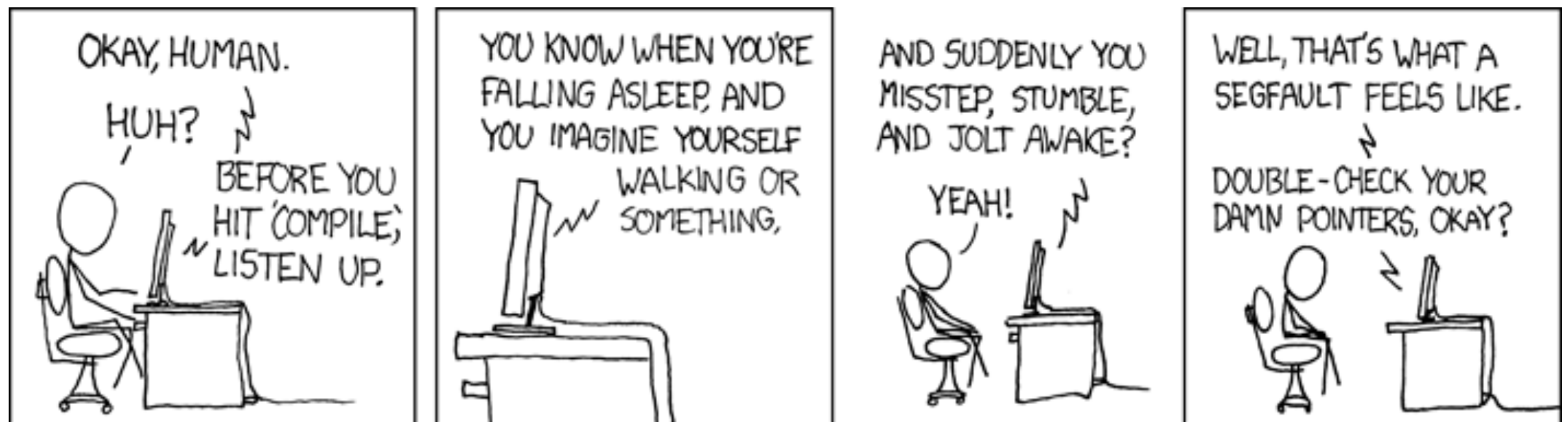
```
volatile struct gpio *gpio = (struct gpio *)0x20200000;  
gpio->fsel[0] = ...
```

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?



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;
```

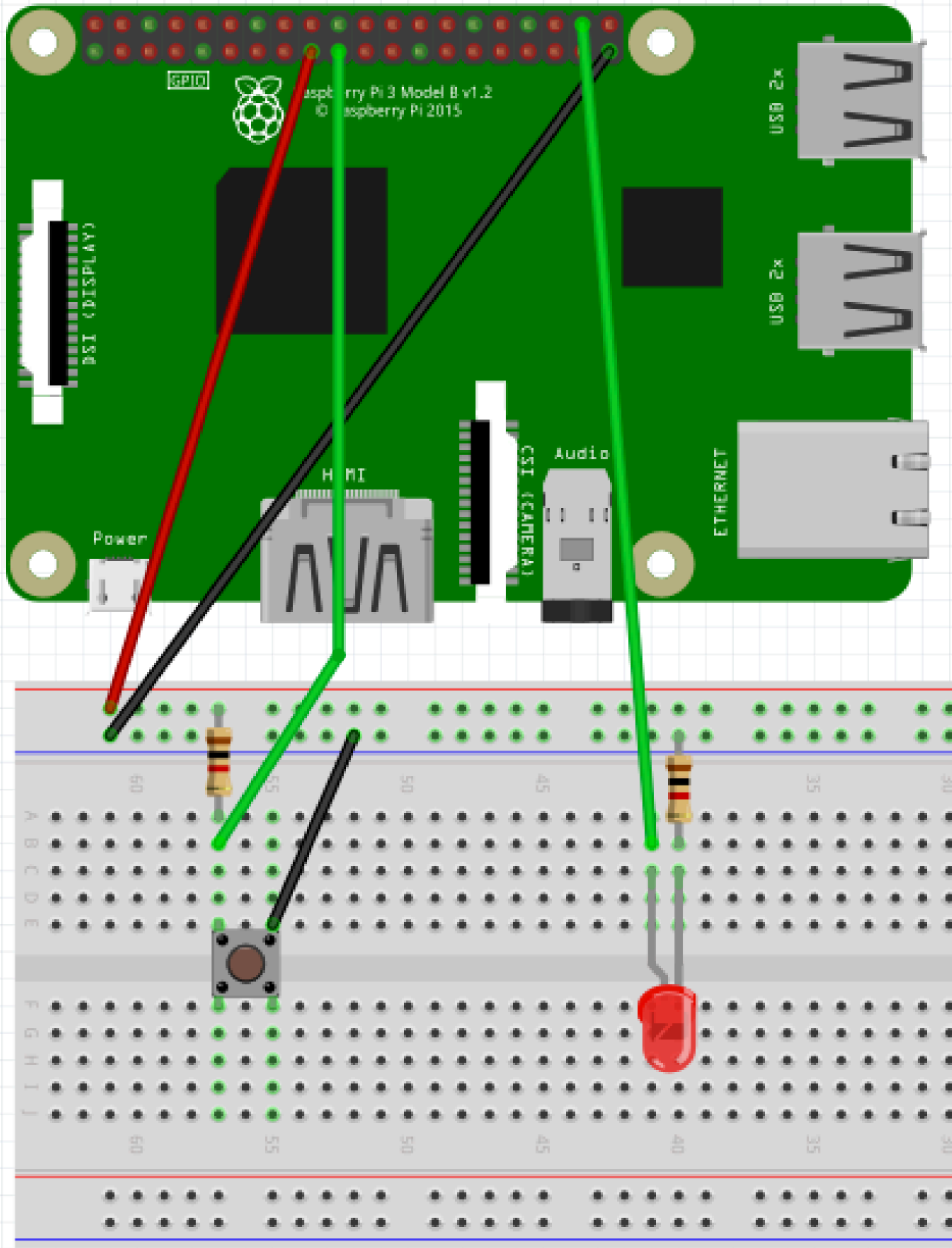
```
j = i;
```

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

button.c

The little button that wouldn't

button.c: The little button that wouldn't



Want cool diagrams like this?
Check out fritzing.org

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?*

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...!)