Admin

Assign 1 due Tuesday 5pm
Show off your bare-metal mettle!

Pre-lab for lab2
Read gcc/make guides
Read about 7-segment display
Watch Ben E breadboard magic

Today: Hail the all-powerful C pointer

Addresses, pointers as abstractions for accessing memory
Memory layout for arrays and structs
Use of `volatile`

From C to Assembly

C language used to describe computation at high-level

- Portable abstractions (names, syntax, operators), consistent semantics
- Compiler emits asm for specific ISA/hardware
  - *major technical wizardry in back-end !*

Last lecture:

- C variable ⇒ registers
- C arithmetic/logical expression ⇒ ALU instructions
- C control flow ⇒ branch instructions

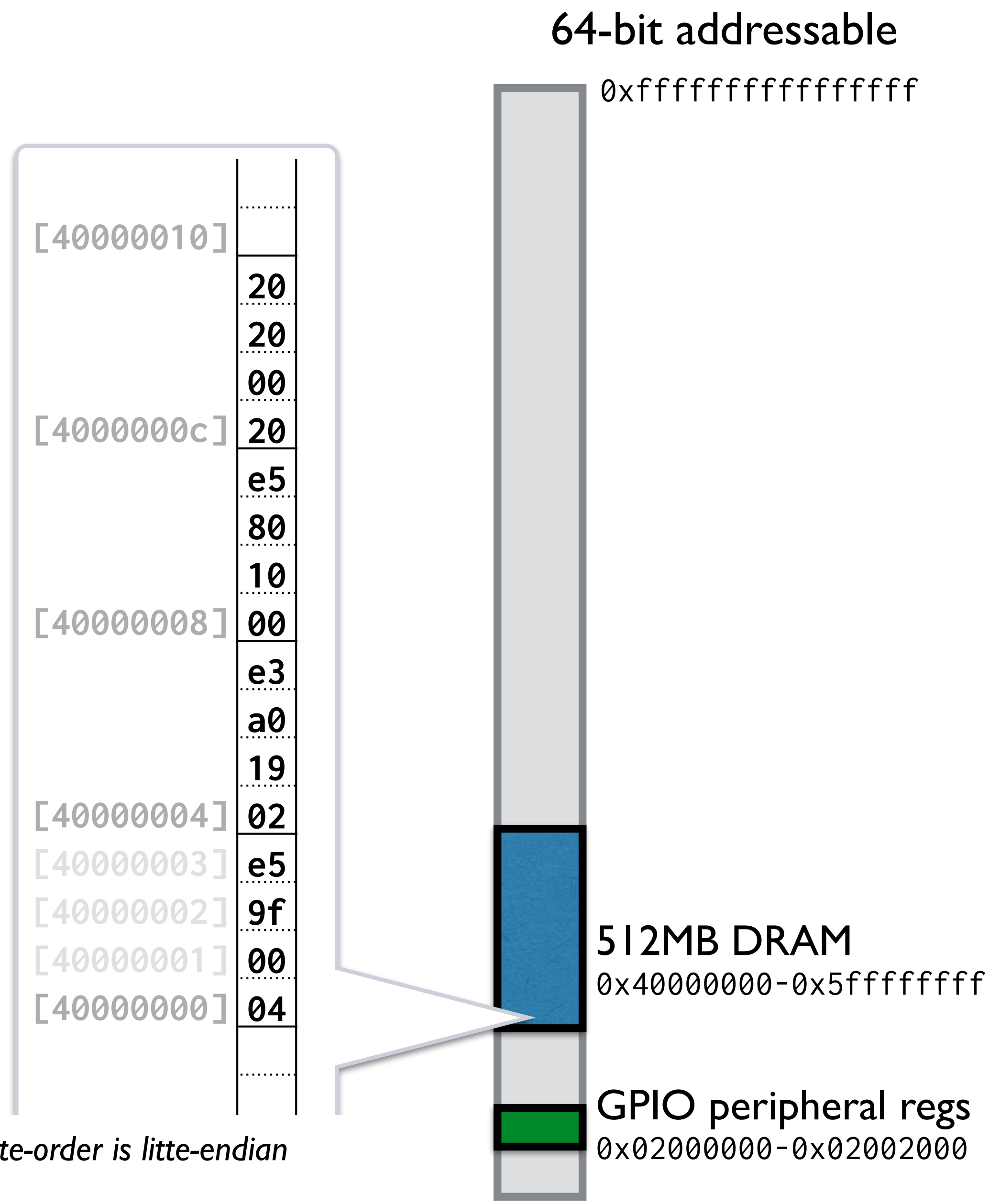
This lecture:

- C pointer ⇒ memory address
- Read/write memory ⇒ load/store instructions
- Array/struct data layout ⇒ address arithmetic

Memory

Linear sequence of bytes, indexed by address

Instructions:
`lw` (load) from memory to register
`sw` (store) from register to memory



Byte-order is litte-endian

Accessing memory in assembly

`lw` and `sw` copy 4 bytes from memory address to register (or vice versa)

The memory address could be:

- location reserved for a global or local variable *or*
- location containing program instruction *or*
- memory-mapped peripheral *or* ...

The 4 bytes of data being copied could represent:

- a RISC-V instruction *or*
- an integer *or*
- 4 characters *or*
- bit pattern that controls peripheral *or* ...

```
lui     a0,0x2000
addi    a1,zero,1

sw      a1,0x30(a0)

sw      a1,0x40(a0)
```

`lw` and `sw` access memory location by address
No notion of "boundaries", agnostic to data type
Up to asm programmer to use correct address and respect type

C **pointers** (+ type system!) improved abstraction for accessing memory

Pointer vocabulary

An *address* is a memory location. Address represented as `unsigned long (64-bit)`

A *pointer* is a variable that holds an address

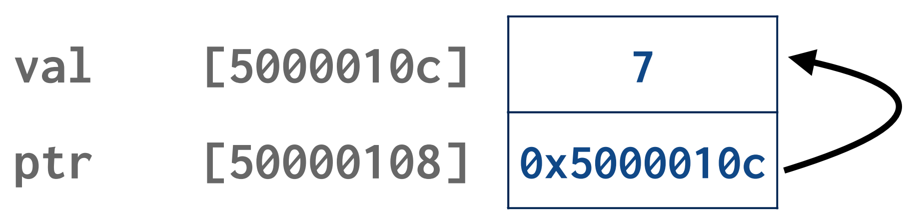
The "*pointee*" is the data stored at that address

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

C code

```
int val = 5;
int *ptr = &val;
*ptr = 7;
```

Memory



C pointer types

C enforces *type system:* every variable declares data type

- Reserves correct number of bytes to store
- Determines what operations are legal for that data

Operations must respect data type

- Can't multiply two **`int*`** pointers, can't deference an **`int`**

C pointer variables distinguished by type of pointee

- Dereferencing an **`int*`** pointer accesses **`int`**
- Dereferencing a **`char*`** pointer accesses **`char`**
- Co-mingling pointers of different type disallowed
- Generic **`void*`** pointer, raw address of indeterminate pointee type

```
    lui     a0,0x2000
    addi    a1,zero,1
    sw      a1,0x30(a0)

loop:
    xori    a1,a1,1
    sw      a1,0x40(a0)

    lui     a2,0x3f00
delay:
    addi    a2,a2,-1
    bne     a2,zero,delay

    j       loop
```

blink.s → c_blink.c

let’s do it!

What do C pointers buy us?

- Access data at specific address, e.g. `PB_CFG0 0x2000030`
- Access data by its offset relative to other nearby data (array elements, struct fields)
  - Related data grouped together, organizes memory
- Guide/constrain memory access to respect data type
  - (Better, but pointers still fundamentally unsafe...)
- 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 arrays

Array is simply sequence of elements stored in contiguous memory
No sophisticated array "object", no track length, no bounds checking

Declare array by specifying element type and count of elements
Compiler reserves memory of correct size starting at base address
Access to elements by index is relative to base

```
char letters[4];
int nums[5];

letters[0] = 'a';
letters[3] = 'c';

nums[2] = 0x107e;
```

[50000118]	61	?	?	63
[50000114]	?			
[50000110]	?			
[5000010c]	0000107e			
[50000108]	?			
[50000104]	?			

Address arithmetic

Memory addresses can be manipulated arithmetically!

Arithmetic used to access data at neighboring location

```
unsigned int *base, *neighbor;

base = (unsigned int *)0x20000030;  // PB_CFG0
neighbor = base + 1;                // 0x20000034, PB_CFG1
```

IMPORTANT ⚠️ ⚠️ ⚠️

C pointer add/subtract always **scaled** by `sizeof(pointee)`

e.g. operates in pointee-sized units

Array indexing is just pretty syntax for pointer arithmetic

```
array[index]   <=>   *(array + index)
```

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
```

C-strings

No string "abstraction", just sequence of chars in memory, e.g. char array
char* points to first character
Must be terminated by null char (zero byte)

Trace the following code. Draw a memory diagram!

```
char *s = "Leland";
char *t;
char buf[9];

t = s;
s[0] = 'R';
*t = 'Z';
s = buf + 4;    // where does s point?
s[1] = t[3];    // what value changes?
```

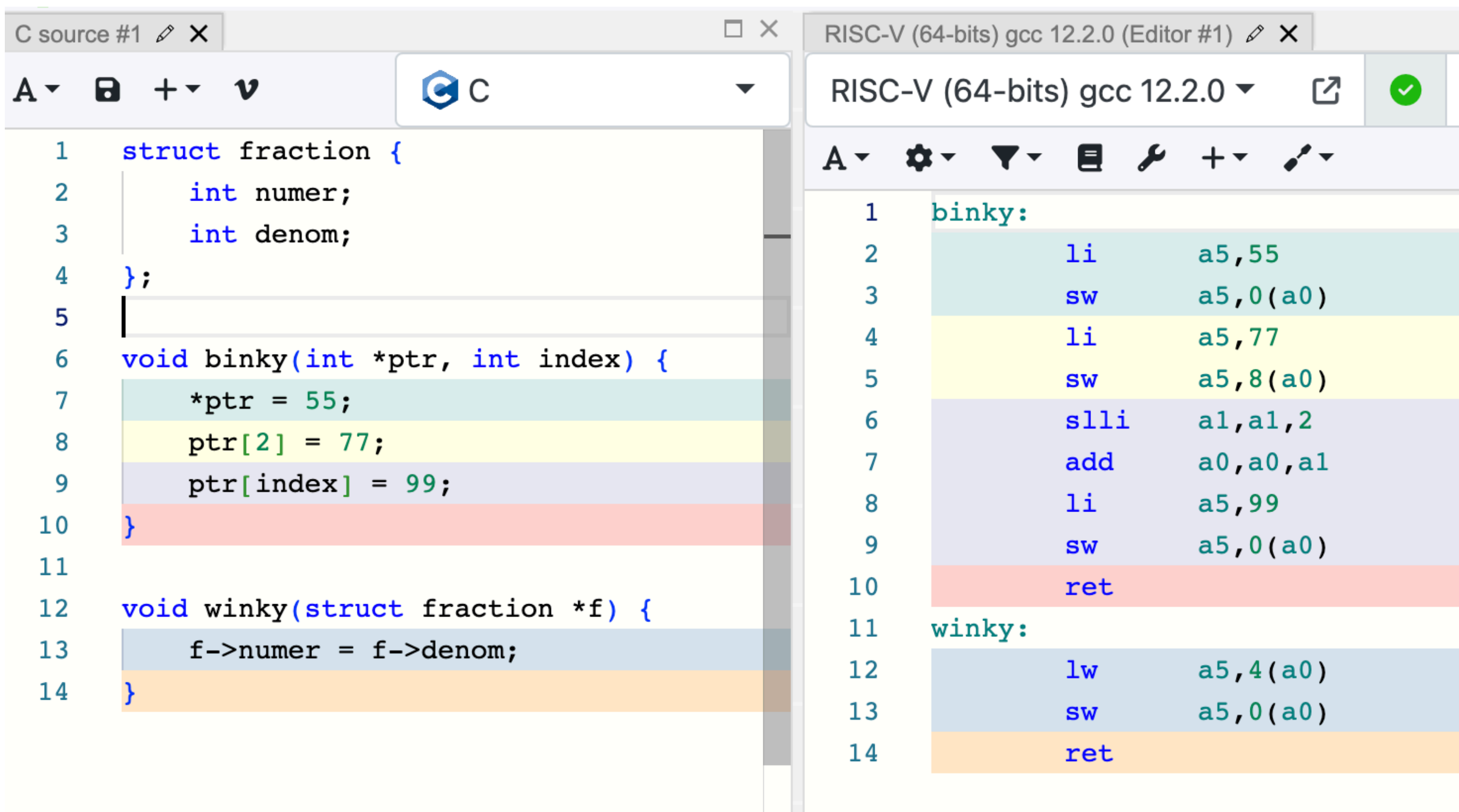
RISC-V addressing mode

```
lw   a0, imm(a1)            // constant displacement
```

NO: variable displacement, scaled index, pre/post index

Could be useful for accessing C data types, how does RISC-V do it?

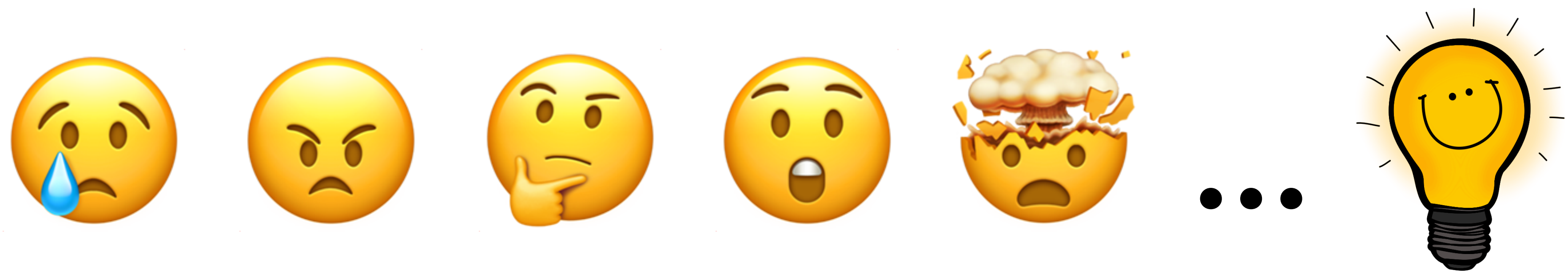
Use CompilerExplorer to find out more!



`c_button.c`

The little button that wouldn’t

A cautionary tale



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

```
    lui     a0,0x2000
    addi    a1,zero,0x1
    sw      a1,0x30(a0)
    sw      zero,0x60(a0)

loop:
    lw      a2,0x70(a0)
    and     a2,a2,a1
    beq     a2,zero,off

on:
    sw      a1,0x40(a0)
    j       loop

off:
    sw      zero,0x40(a0)
    j       loop
```

```
void main(void) {
  *PB_CFG0 = 1; // config PB0 output
  *PC_CFG0 = 0; // config PC0 input

   while (1) {
      if ((*PC_DATA & 1) != 0) {
         *PB_DATA = 1;
      } else {
         *PB_DATA = 0;
      }
   }
}
```

Peripheral registers

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

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

Peripheral registers access device state, and changing/reading the state may have more complex effects than a regular load/store of an ordinary memory address.

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

`volatile`

The compiler analyzes code to determine exactly where each variable is read/written. Generated assembly could be a literal translation of same steps or streamlined into equivalent sequence that has same effect. Neat!

But… if memory location can be read/written externally (by another process, by peripheral), optimizations may be invalid

Qualifying a variable as **`volatile`** restricts compiler— cannot remove, coalesce, cache, or reorder accesses to this variable. The generated assembly must faithfully perform each access of the variable exactly 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...!)

Pointers and structs

9.7.4 **Register List**

Ref: D1-H User Manual p.1093

Module Name	Base Address
GPIO	0x02000000

Register Name	Offset	Description
PB_CFG0	0x0030	PB Configure Register 0
PB_CFG1	0x0034	PB Configure Register 1
PB_DAT	0x0040	PB Data Register
PB_DRV0	0x0044	PB Multi_Driving Register 0
PB_DRV1	0x0048	PB Multi_Driving Register 1
PB_PULL0	0x0054	PB Pull Register 0

```
struct gpio {
   unsigned int cfg[4];
   unsigned int data;
   unsigned int drv[4];
   unsigned int pull[2];
};
```

```
volatile struct gpio *pb = (struct gpio *)0x2000030;

pb->cfg[0] = ...
```

The utility of pointers

Accessing data by location is ubiquitous and powerful

You learned in CS106B 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 using relative location

What do we gain by using C pointers over raw `lw/sw`?

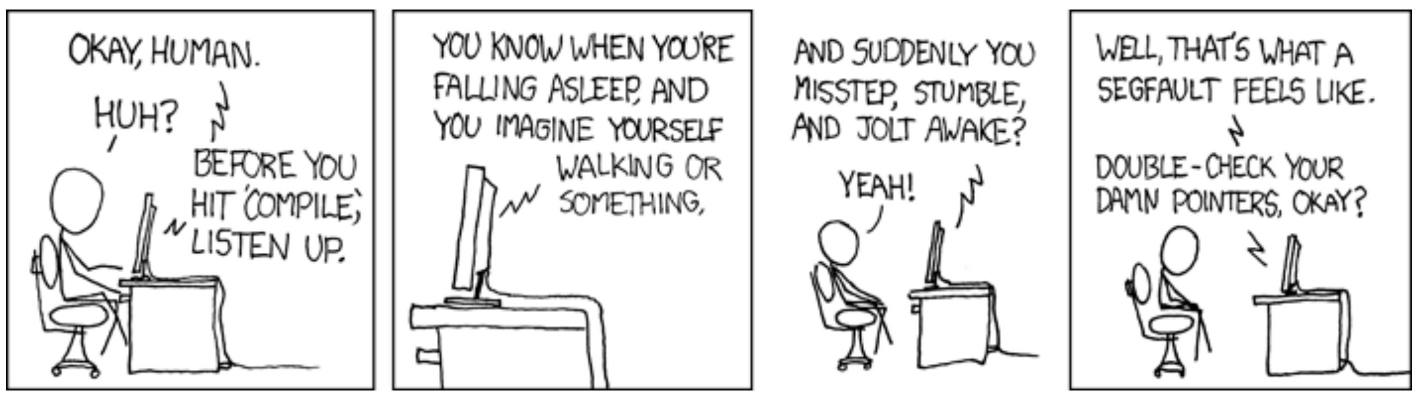
- Type system adds readability, some safety
- Pointee and level of indirection now explicit in the type
- Organize related data into contiguous locations, access using offset arithmetic

Segmentation fault

Pointers are ubiquitous in C, safety is low. Be vigilant!

Q. For what reasons might a pointer be invalid?

Q. What is consequence of accessing invalid address
...in a hosted environment?
...in a bare-metal environment?



"The fault, dear Brutus, is not in our stars,
But in ourselves, that we are underlings."
[Julius Caesar (I, ii, 140-141)]