CSE351: Memory and data

http://xkcd.com/138/

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
     c.getMPG();
```

Assembly language:

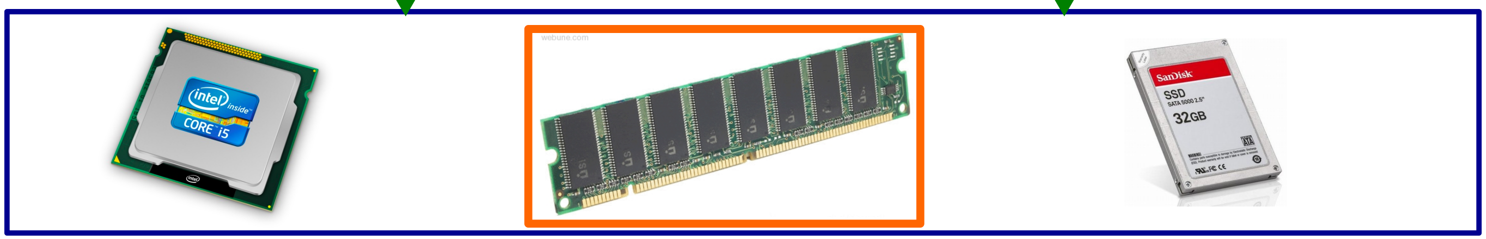
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

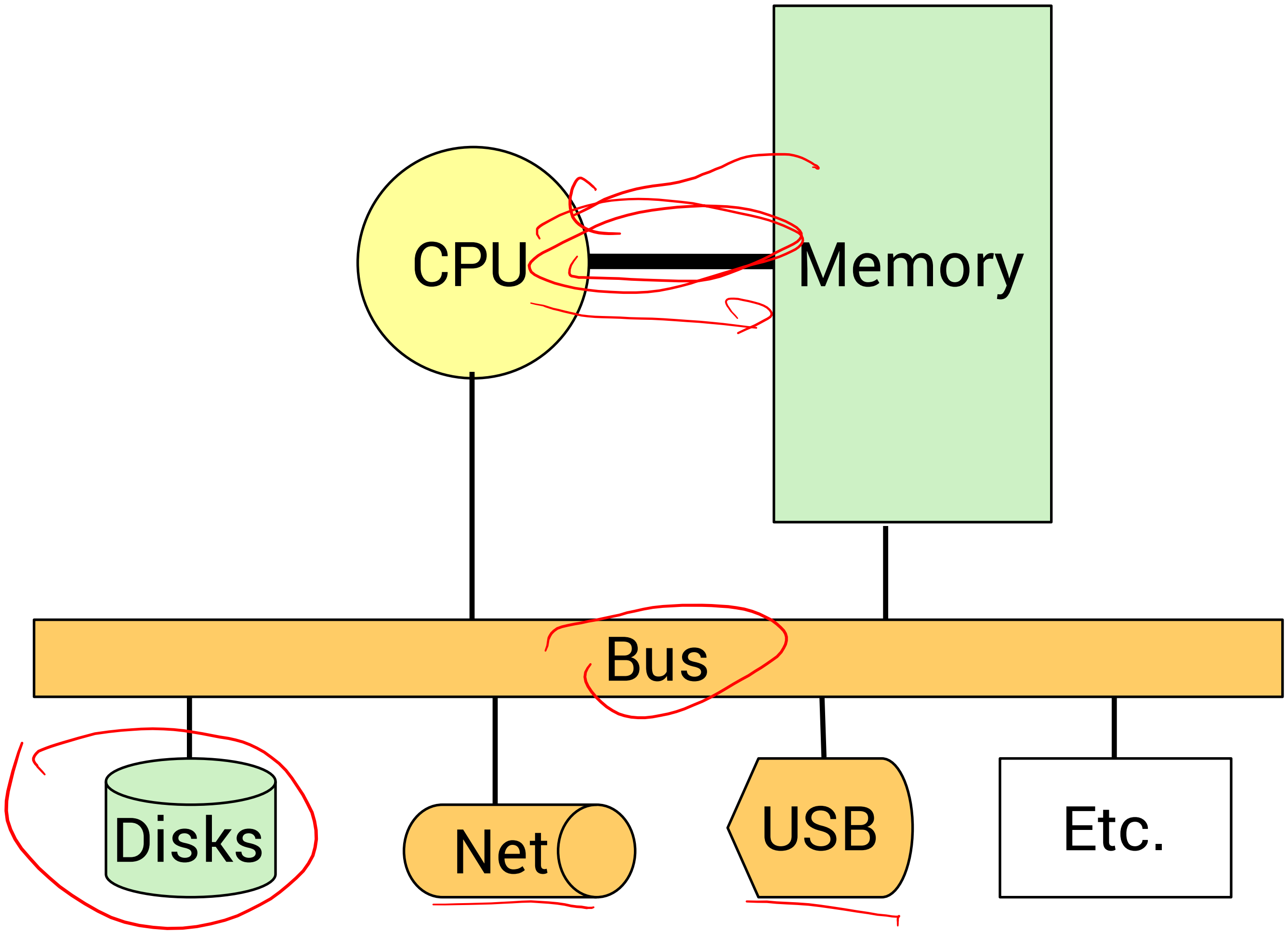
OS:

Computer system:

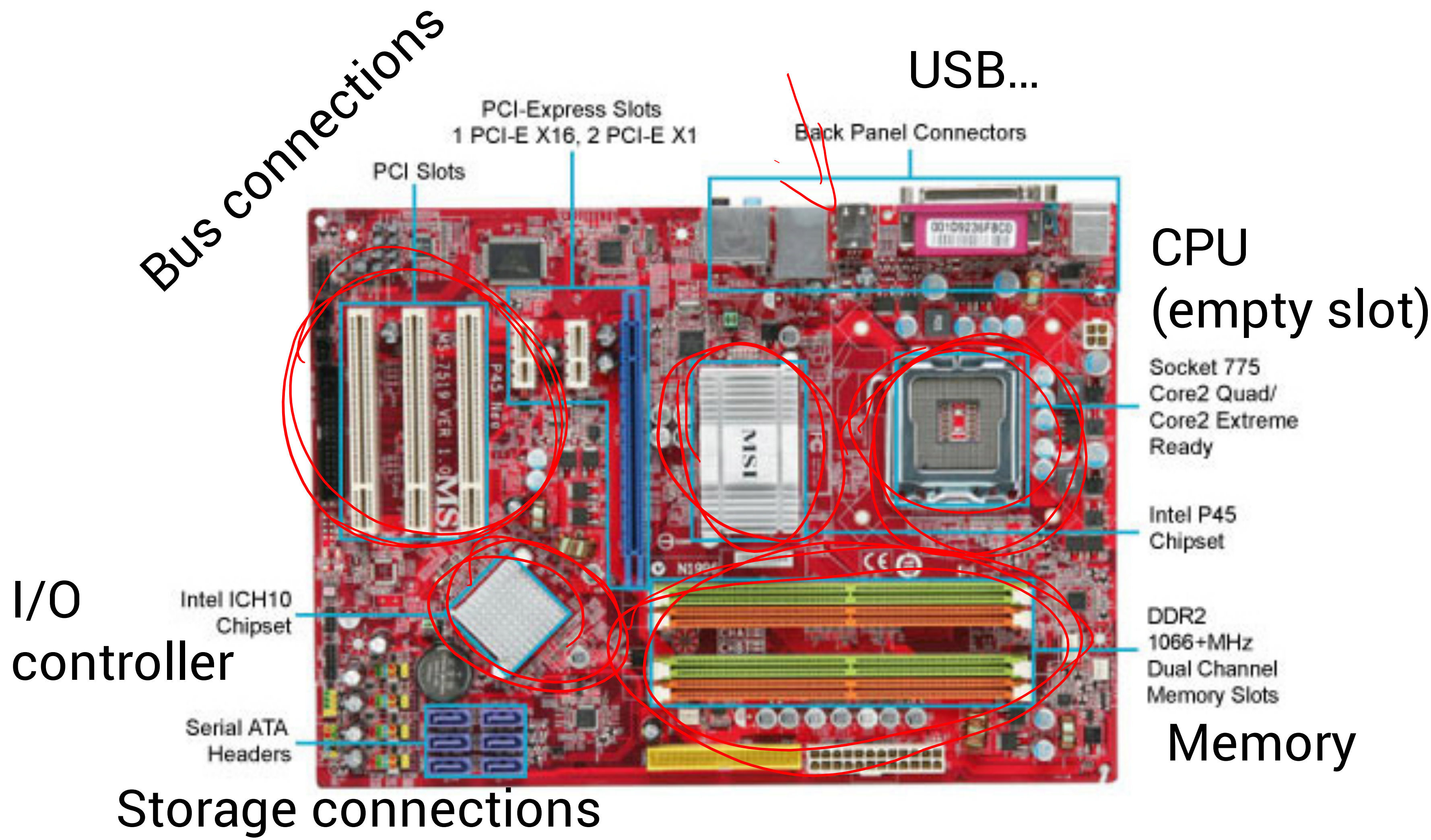


- **Memory & data**
- Integers & floats
- Machine code & C
- x86 assembly
- Procedures & stacks
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

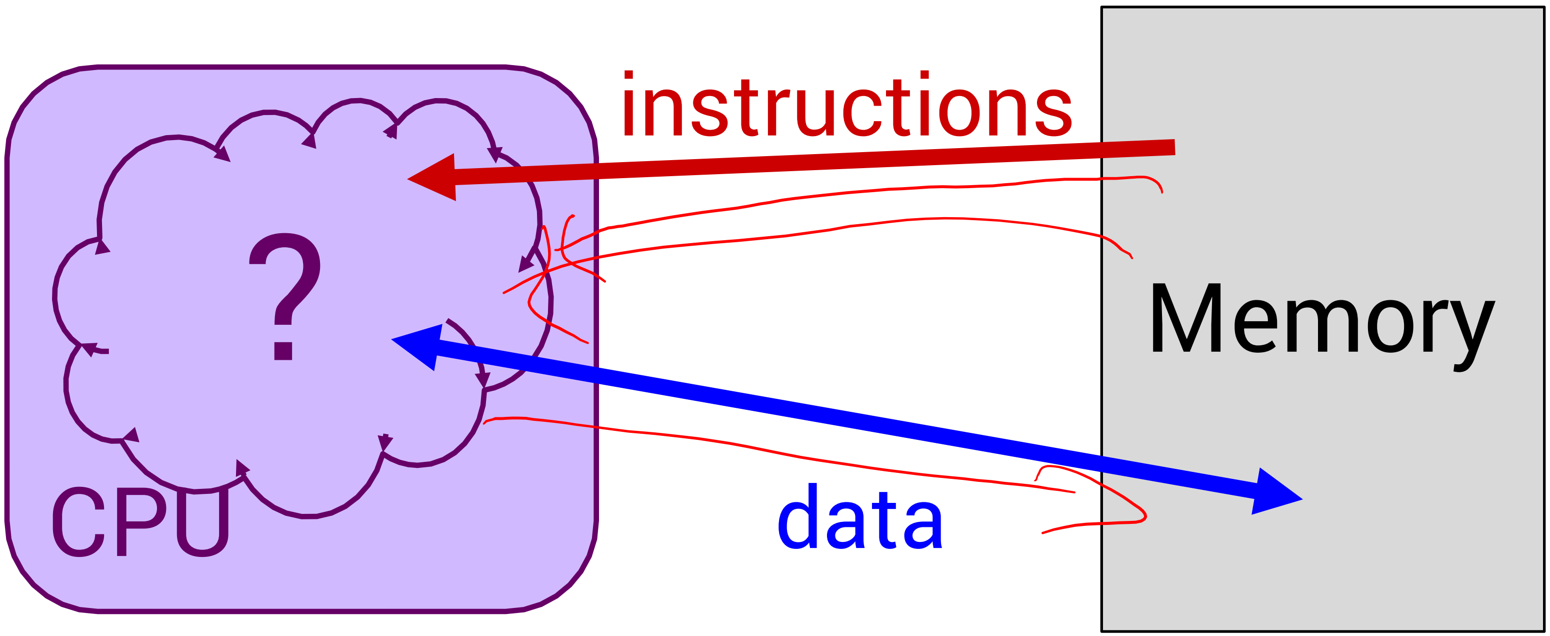
Hardware: Logical View



Hardware: Physical View

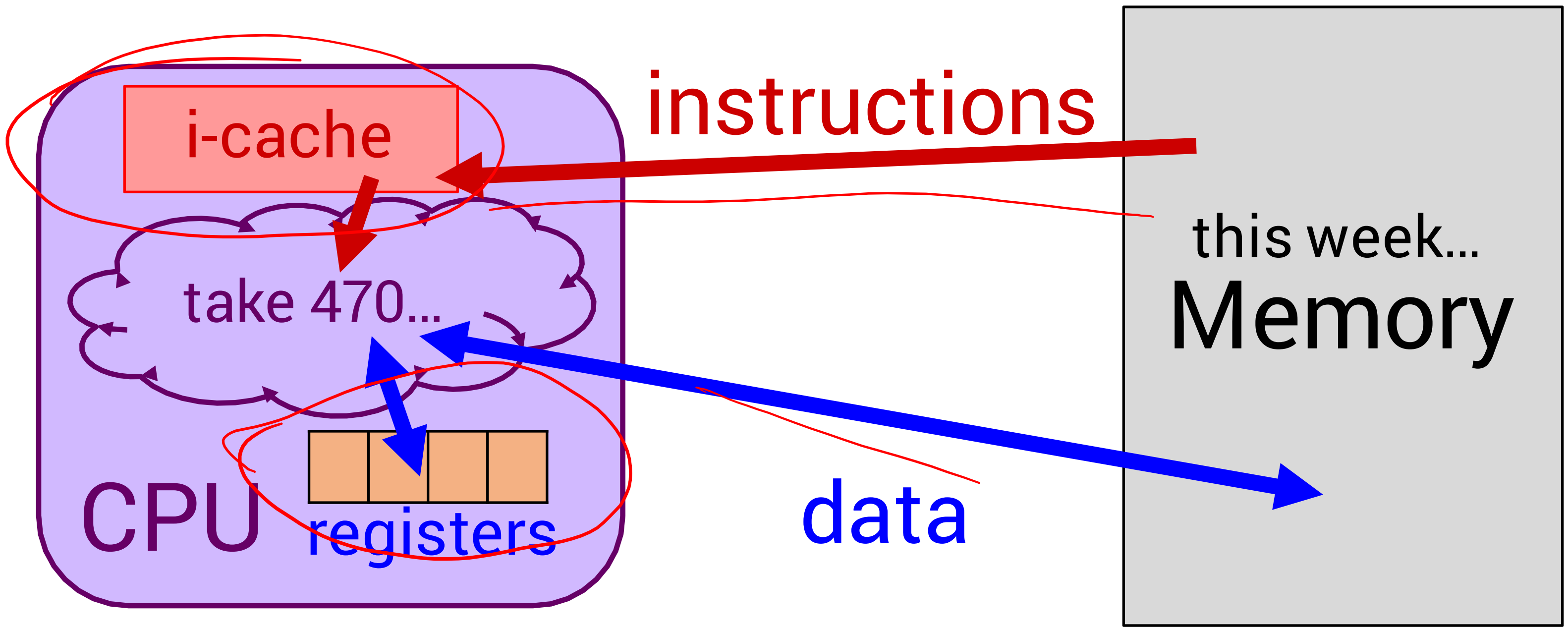


Hardware: 351 View (version 0)



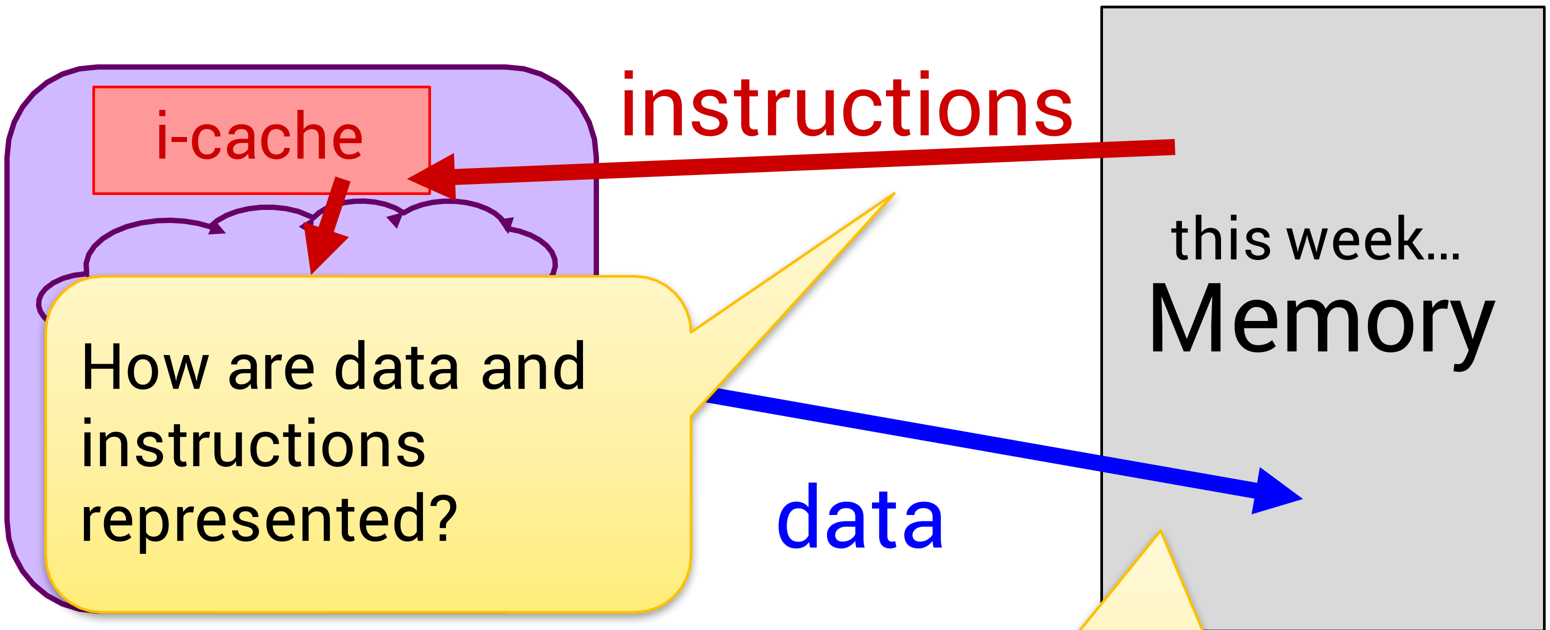
- **CPU executes instructions; memory stores data**
- **To execute an instruction, the CPU must:**
  - fetch an instruction;
  - fetch the data used by the instruction; and, finally,
  - execute the instruction on the data…
  - which may result in writing data back to memory.

Hardware: 351 View (version 1)



- The CPU holds instructions temporarily in the instruction cache
- The CPU holds data temporarily in a fixed number of registers
- Instruction and operand fetching is HW-controlled
- Data movement is programmer-controlled (in assembly language)
- We'll learn about the instructions the CPU executes – take cse/ee470 to find out how it actually executes them

Hardware: 351 View (version 1)



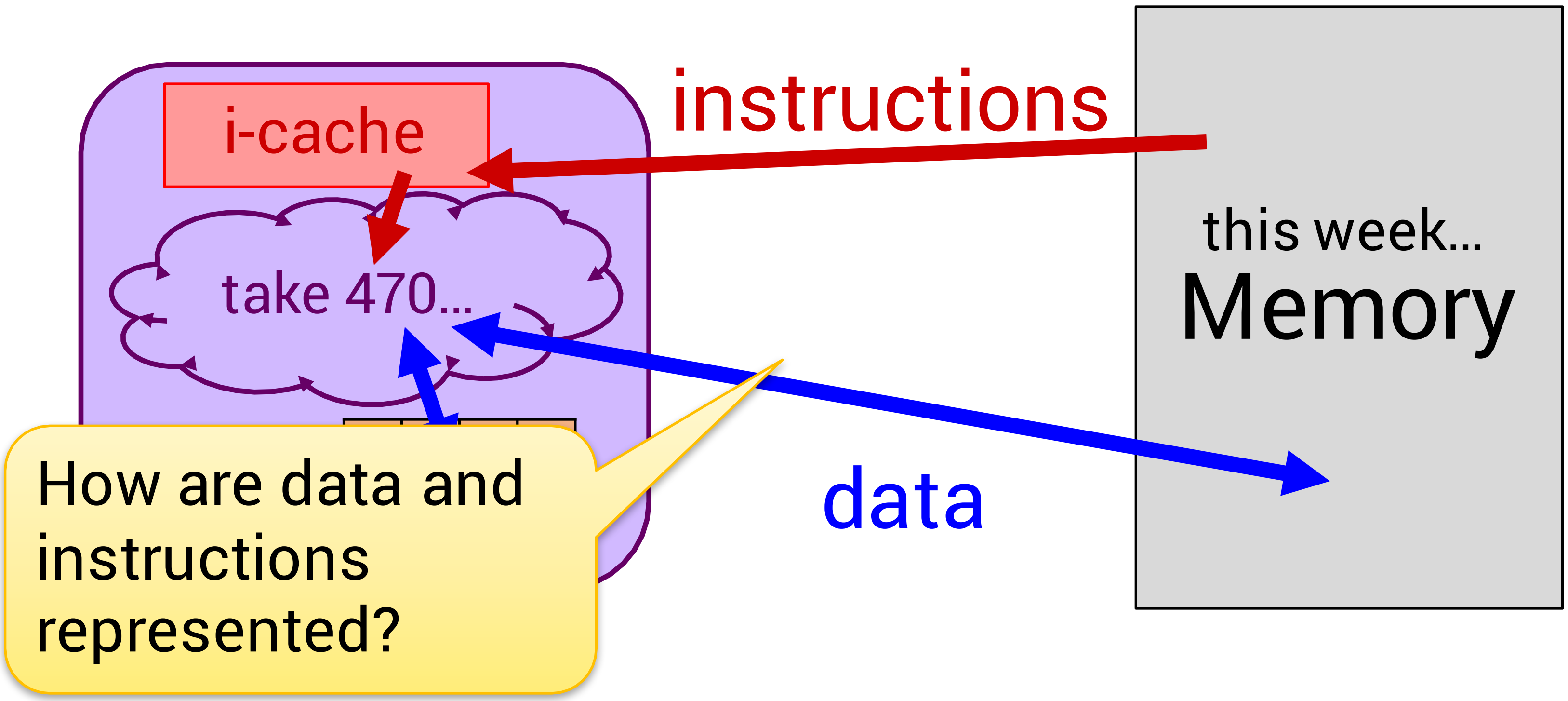
How are data and instructions represented?

How does a program find its data in memory?

- The CPU holds instructions tempora e.
- The CPU holds data temporarily in a .
- Instruction fetching is HW-controlle
- Data movement is programmer-controlled.

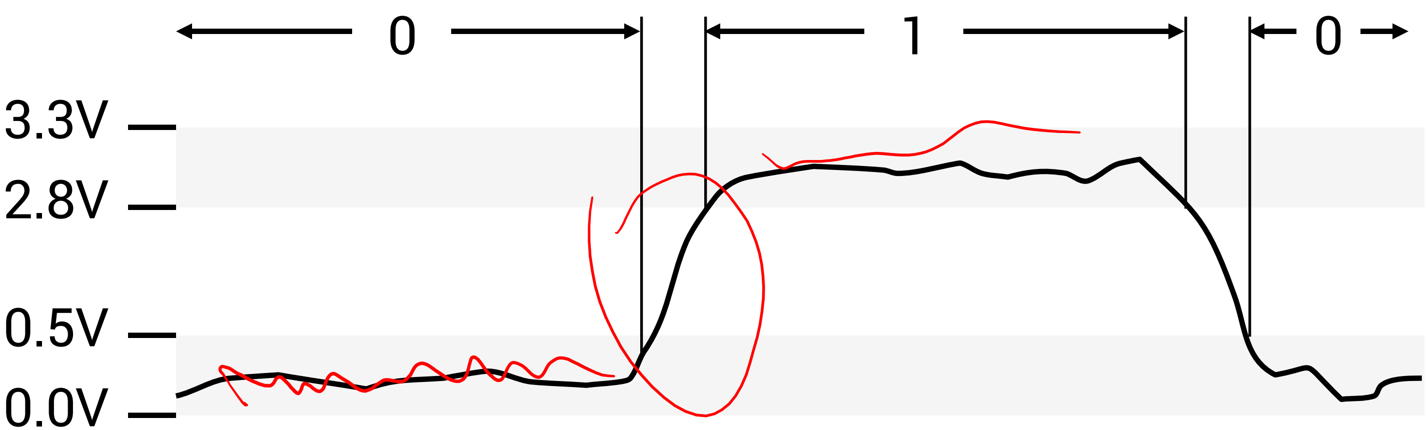
Memory, Data, and Addressing

- **Representing information as bits and bytes**
- **Organizing and addressing data in memory**
- **Manipulating data in memory using C**
- **Boolean algebra and bit-level manipulations**


instructions
i-cache
take 470…
this week…
Memory
data
How are data and instructions represented?

Binary Representations

- **Base 2 number representation**
  - A base 2 digit (0 or 1) is called a *bit*.
  - Represent 351_{10} as 0000000101011111_2 or 101011111_2
- **Electronic implementation**
  - Easy to store with bi-stable elements
  - Reliably transmitted on noisy and inaccurate wires



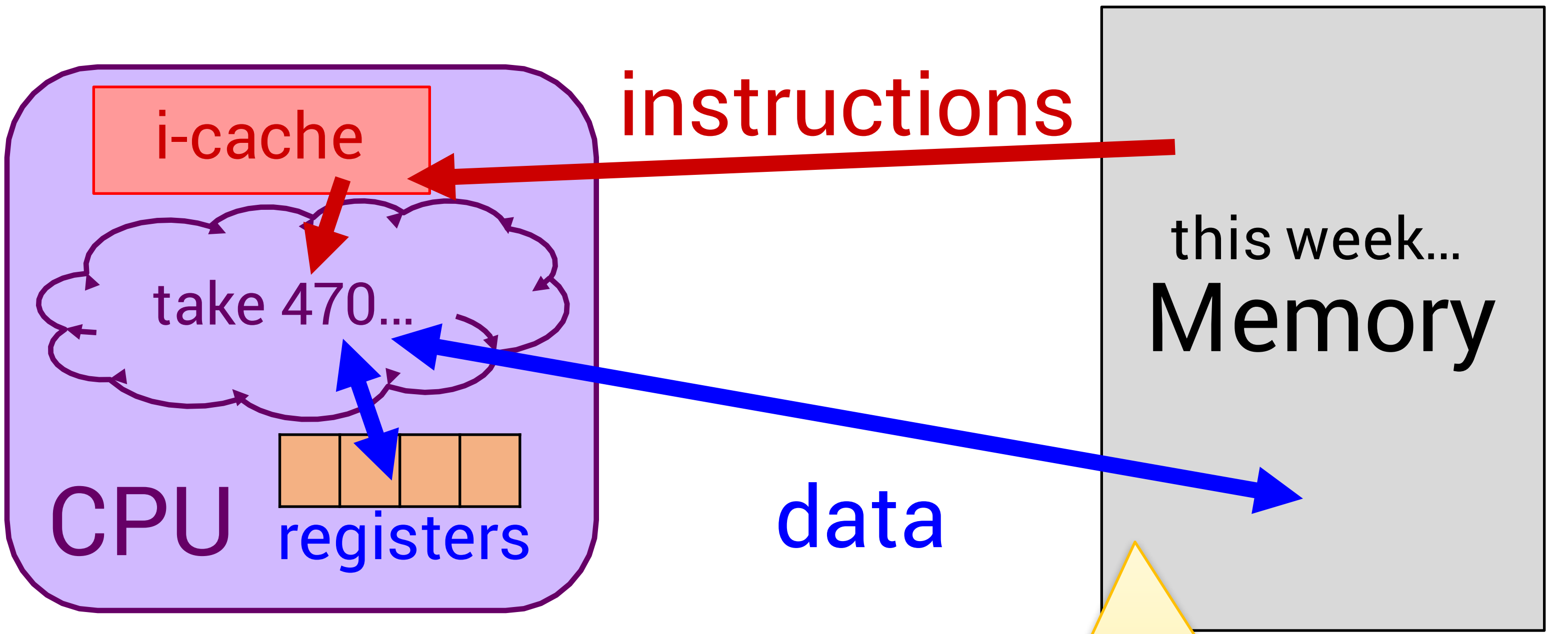
Describing Byte Values

- **Binary** 00000000_2 -- 11111111_2
  - Byte = 8 bits (binary digits)

0	0	1	0	1	1	0	1	
$0*2^7$	$0*2^6$	$1*2^5$	$0*2^4$	$1*2^3$	$1*2^2$	$0*2^1$	$1*2^0$	
		32		8	4		1	45_{10}

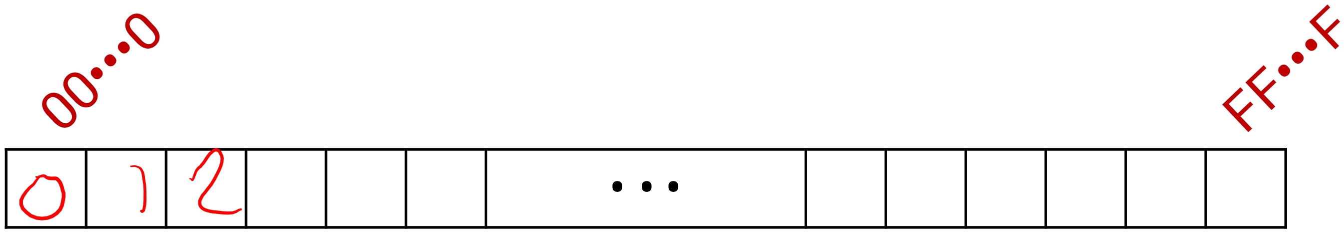
- **Decimal** 0_{10} -- 255_{10}
- **Hexadecimal** 00_{16} -- FF_{16}
  - Byte = 2 hexadecimal (or "hex" or base 16) digits
  - Base 16 number representation
  - Use characters '0' to '9' and 'A' to 'F'
  - Write $FA1D37B_{16}$ in the C language
    - as `0xFA1D37B` or `0xfa1d37b`
- More on specific data types later…

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111



How does a program find its data in memory?

Byte-Oriented Memory Organization



- **Conceptually, memory is a single, large array of bytes, each with a unique *address* (index)**
- **The value of each byte in memory can be read and written**
- **Programs refer to bytes in memory by their *addresses***
  - Domain of possible addresses = *address space*
- **But not all values (*e.g.,* 351) fit in a single byte…**
  - Store addresses to "remember" where other data is in memory
  - How much memory can we address with 1-byte (8-bit) addresses?
- **Many operations actually use multi-byte values**

Machine Words

8192

1024×8

0

- **Word size = address size = register size**
- **Word size bounds the size of the *address space* and memory**
  - word size = *w* bits => 2^w addresses
  - Until recently, most machines used **32-bit (4-byte) words**
    - Potential address space: $\mathbf{2^{32}}$ addresses
      2^{32} bytes $\approx$ **4 x $\mathbf{10^9}$ bytes** = 4 billion bytes = **4GB**
    - Became too small for memory-intensive applications
  - Current x86 systems use **64-bit (8-byte) words**
    - Potential address space:
      $\mathbf{2^{64}}$ addresses
      2^{64} bytes $\approx$ **1.8 x $\mathbf{10^{19}}$ bytes**
      = 18 billion billion bytes
      = **18 EB** (exabytes)

```
1 kB = 2^10
1 MB = 2^20
1 GB = 2^30
1 TB = 2^40
1 PB = 2^50
1 EB = 2^60
```

Prefixes for multiples of bits (b) or bytes (B)

Decimal		Binary		
Value	SI	Value	IEC	JEDEC
1000	k kilo	1024	Ki kibi	K kilo
1000^2	M mega	1024^2	Mi mebi	M mega
1000^3	G giga	1024^3	Gi gibi	G giga
1000^4	T tera	1024^4	Ti tebi	–
1000^5	P peta	1024^5	Pi pebi	–
1000^6	E exa	1024^6	Ei exbi	–
1000^7	Z zetta	1024^7	Zi zebi	–
1000^8	Y yotta	1024^8	Yi yobi	–

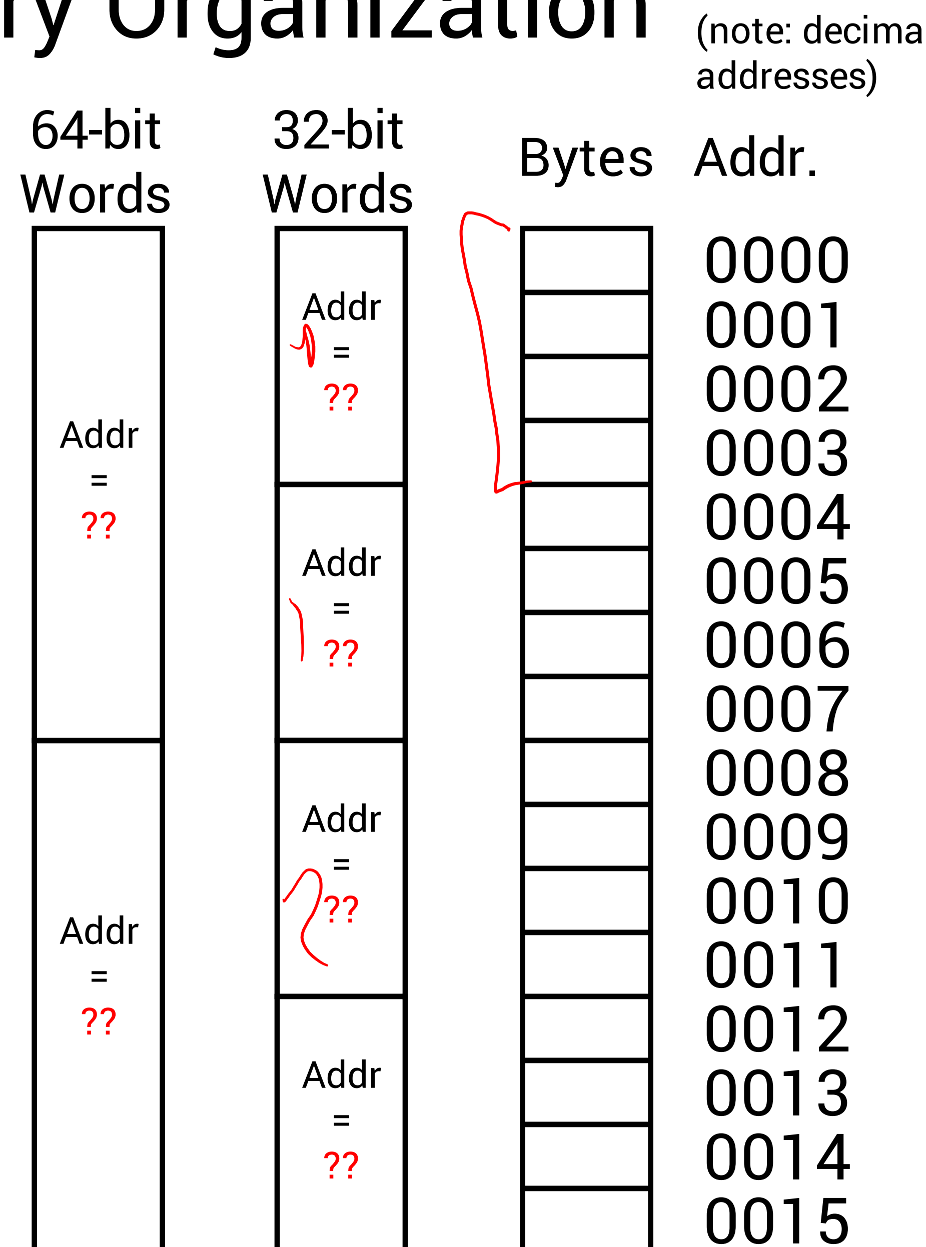
V • T • E

https://en.wikipedia.org/wiki/Binary_prefix

(Facebook's cold storage archive: ~1 EB)

Word-Oriented Memory Organization

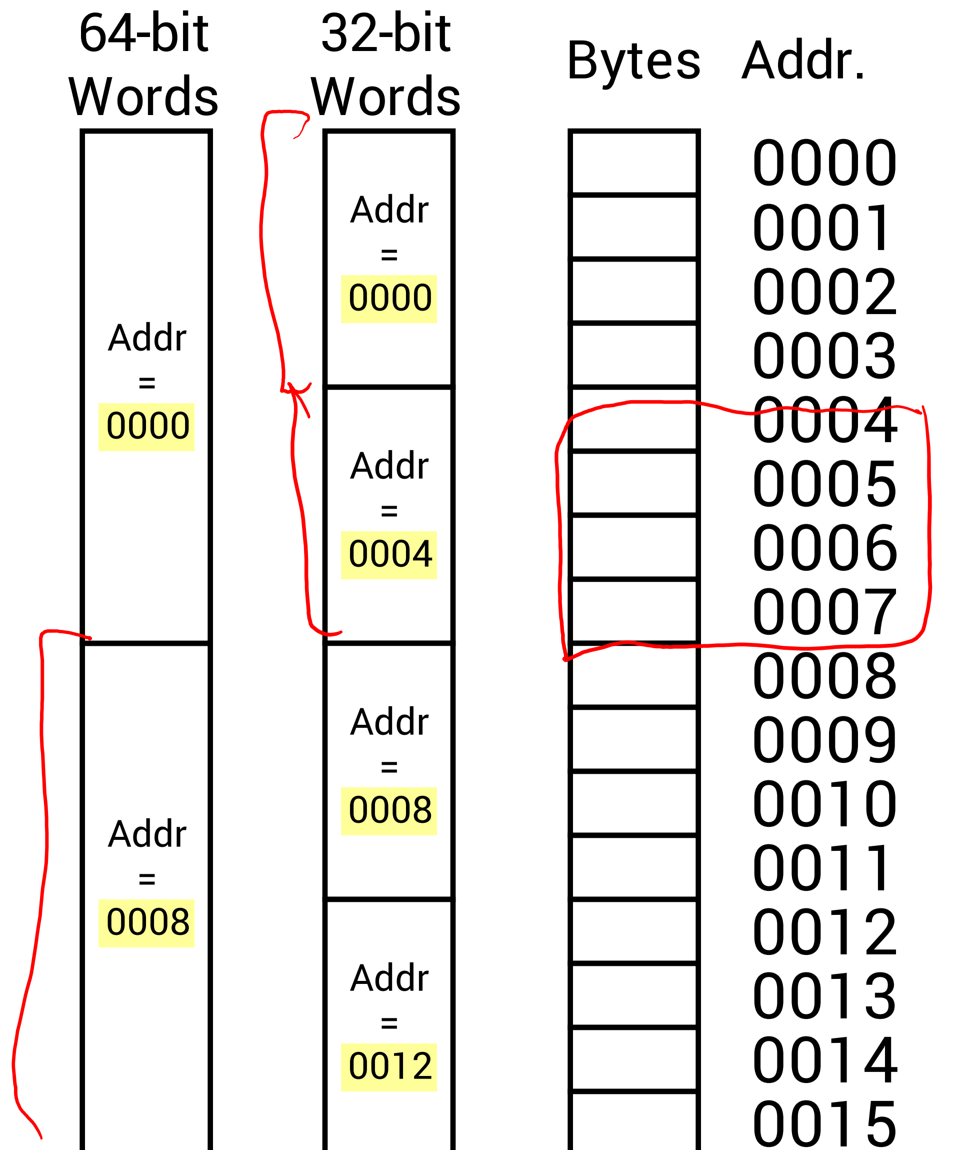
- **Addresses specify locations of bytes in memory**
  - Address of word = address of first byte in word
  - Addresses of successive words differ by word size (in bytes): *e.g.*, 4 (32-bit) or 8 (64-bit)
  - Address of word 0, 1, .. 10?



Word-Oriented Memory Organization

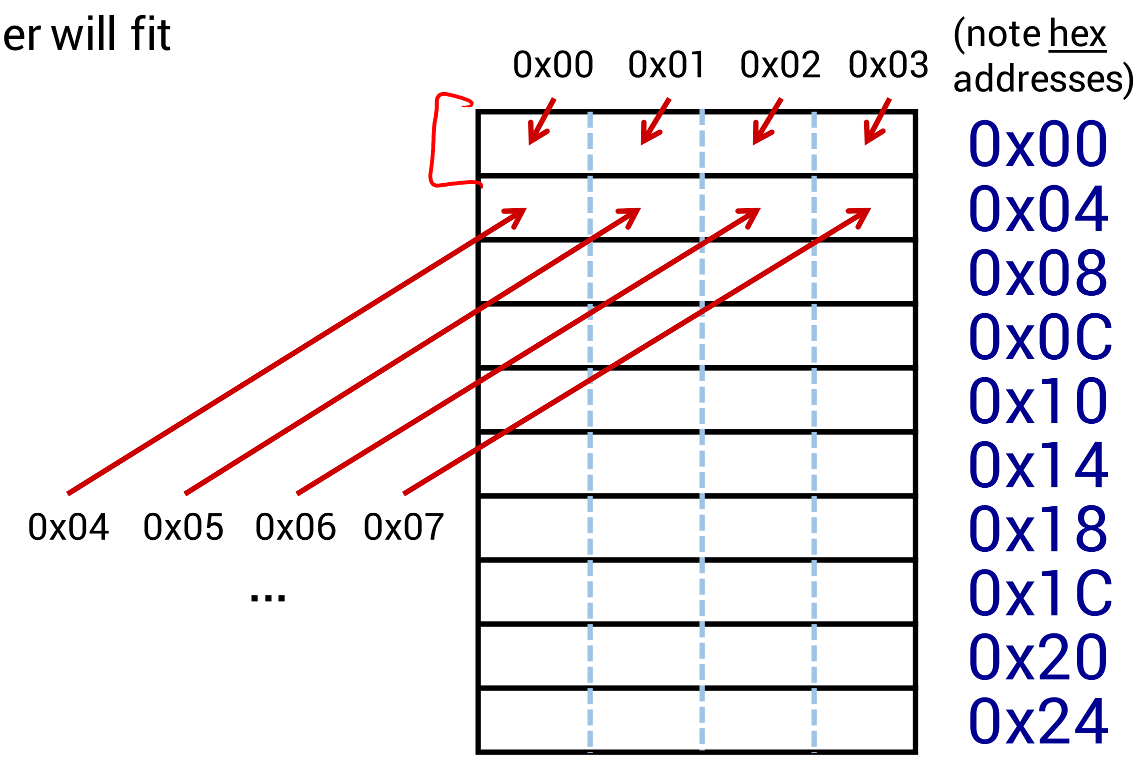
(note: decimal addresses)

- **Addresses still specify locations of *bytes* in memory**
  - Address of word
    = address of first byte in word
  - Addresses of successive words differ by word size (in bytes): *e.g.*, 4 (32-bit) or 8 (64-bit)
  - Address of word 0, 1, .. 10?
  - ***Alignment***



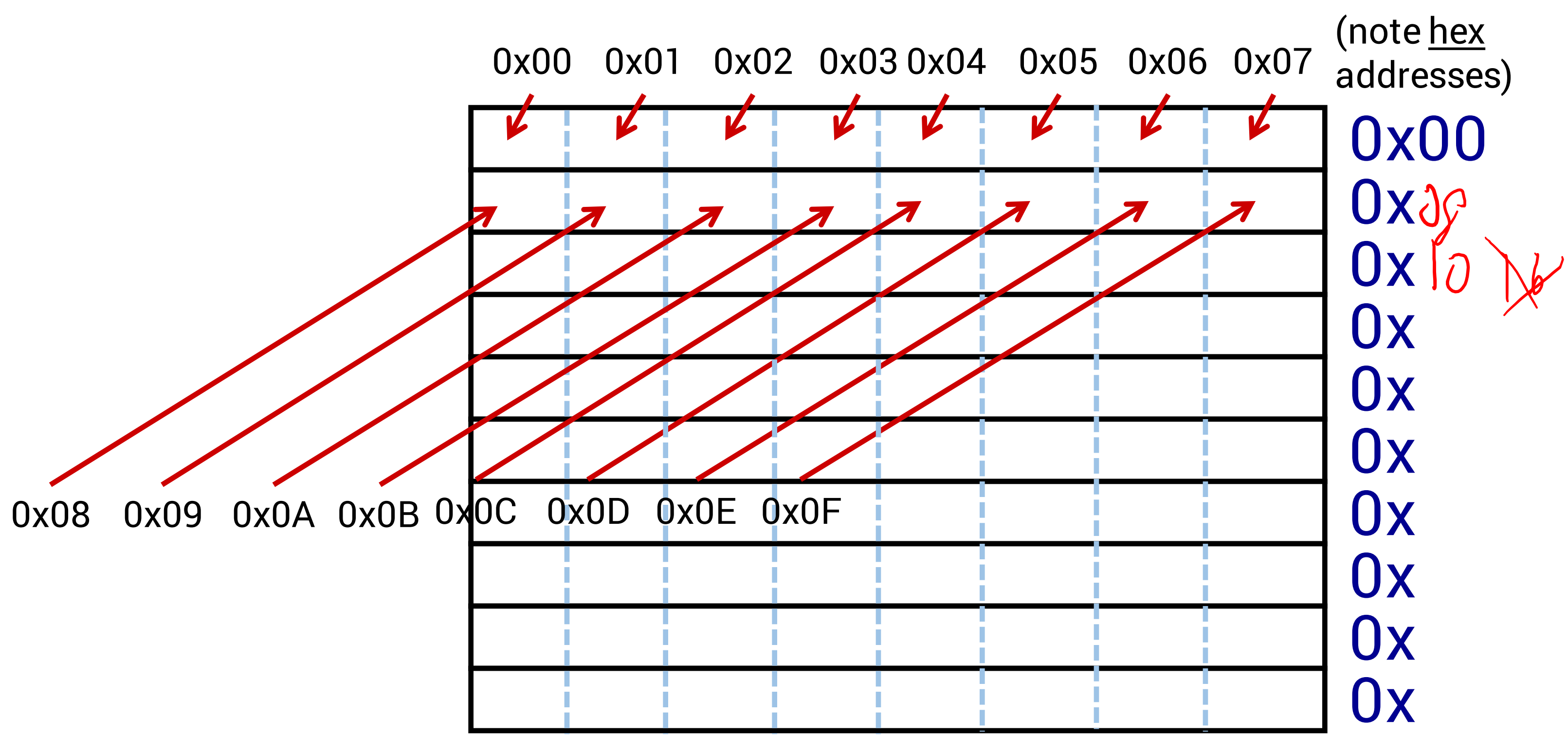
A Picture of Memory (32-bit view)

- **A "32-bit (4-byte) word-aligned" view of memory:**
  - In this type of picture, each row is composed of 4 bytes
  - Each cell is a byte
  - A 32-bit pointer will fit on one row



A Picture of Memory (64-bit view)

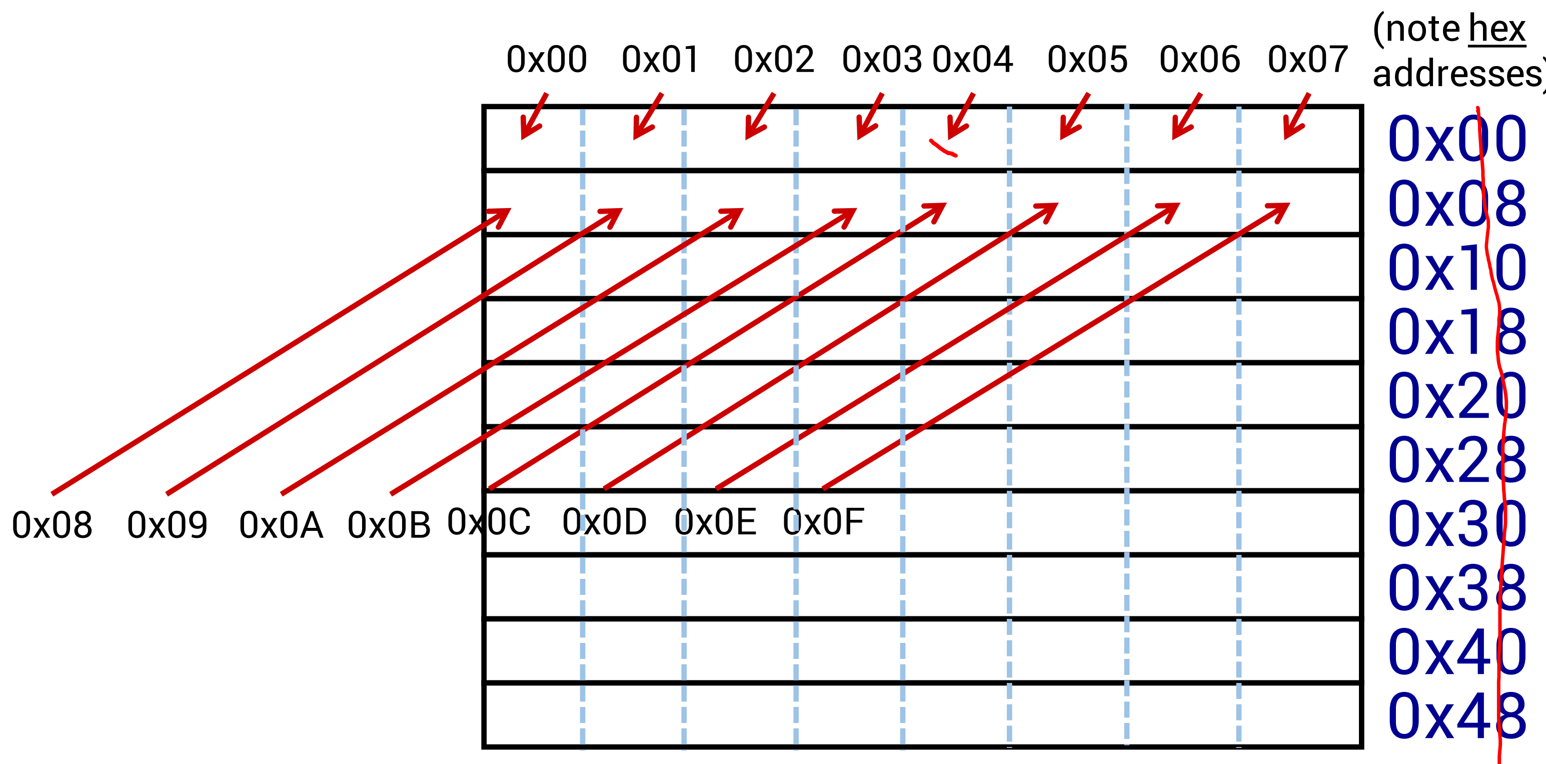
- **A "64-bit (8-byte) word-aligned" view of memory:**
  - In this type of picture, each row is composed of 8 bytes
  - Each cell is a byte
  - A 64-bit pointer will fit on one row



A Picture of Memory (64-bit view)

- **A "64-bit (8-byte) word-aligned" view of memory:**
  - In this type of picture, each row is composed of 8 bytes
  - Each cell is a byte
  - A 64-bit pointer will fit on one row

1000



Addresses and Pointers

32-bit example
(pointers are 32-bits wide)

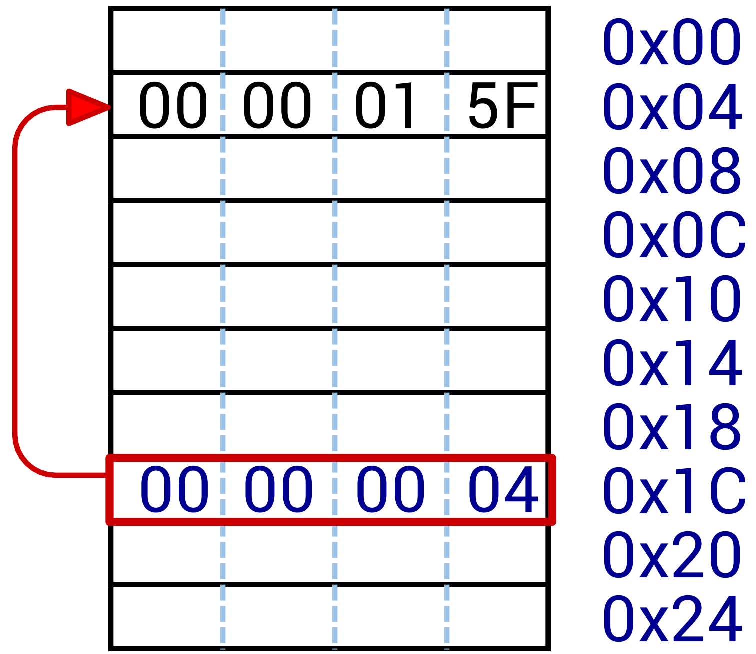
- **An *address* is a location in memory**
- **A *pointer* is a data object that holds an address**
- **The value 351 is stored at address 0x04**
  - $351_{10} = 15F_{16}$ = 0x00 00 01 5F

				0x00
00	00	01	5F	0x04
				0x08
				0x0C
				0x10
				0x14
				0x18
				0x1C
				0x20
				0x24

Addresses and Pointers

32-bit example
(pointers are 32-bits wide)

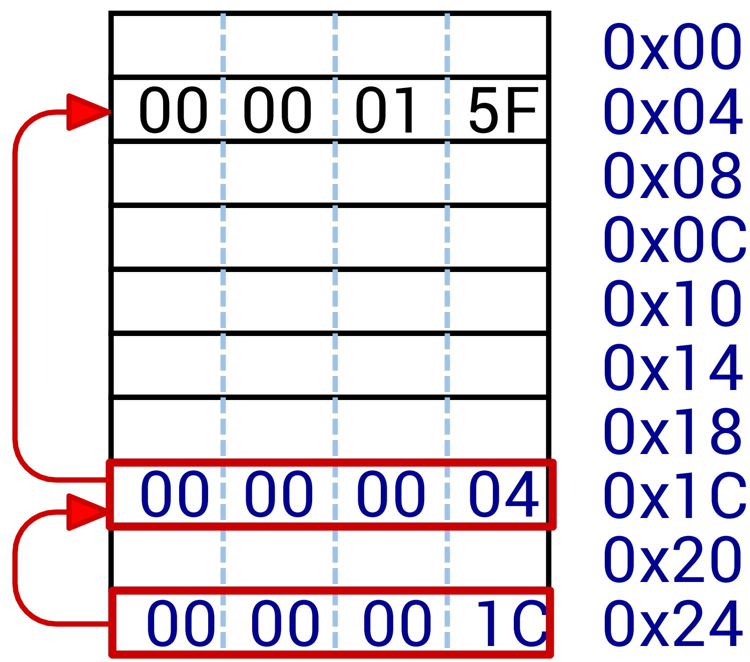
- **An *address* is a location in memory**
- **A *pointer* is a data object that holds an address**
- **The value 351 is stored at address 0x04**
  - $351_{10} = 15F_{16}$ = 0x00 00 01 5F
- **A pointer stored at address 0x1C points to address 0x04**



Addresses and Pointers

32-bit example
(pointers are 32-bits wide)

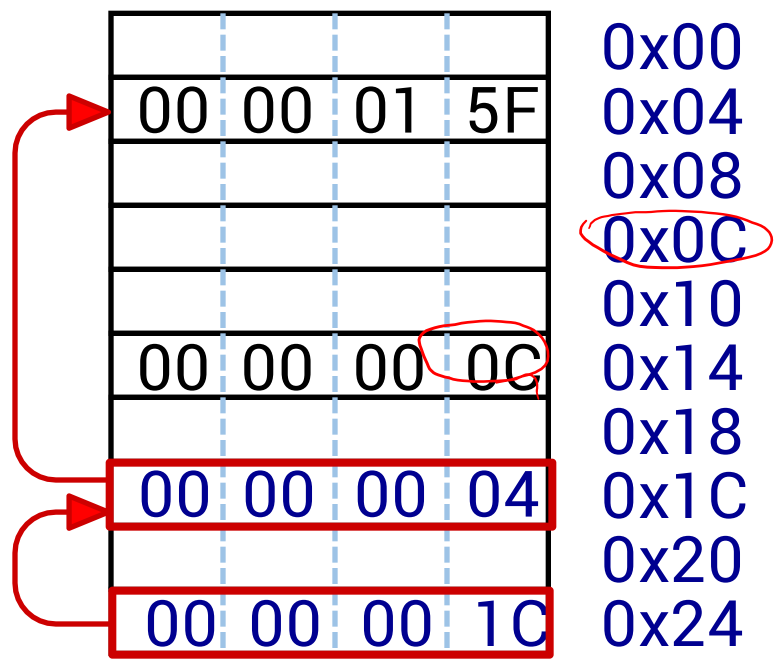
- **An *address* is a location in memory**
- **A *pointer* is a data object that holds an address**
- **The value 351 is stored at address 0x04**
  - $351_{10} = 15F_{16} =$ 0x00 00 01 5F
- **A pointer stored at address 0x1C points to address 0x04**
- **A pointer to a pointer is stored at address 0x24**



Addresses and Pointers

32-bit example
(pointers are 32-bits wide)

- An ***address*** is a location in memory
- A ***pointer*** is a data object that holds an address.
- The value 351 is stored at address **0x04**
  - $351_{10} = 15F_{16}$ = 0x00 00 01 5F
- A pointer stored at address **0x1C** points to address **0x04**
- A pointer to a pointer is stored at address **0x24**
- The value 12 is stored at address **0x14**
  - Is it a pointer?



Addresses and Pointers

64-bit example
(pointers are 64-bits wide)

- **A 64-bit (8-byte) word-aligned view of memory**
- **The value 351 is stored at address 0x08**
  - $351_{10} = 15F_{16} = \text{0x00 00 01 5F}$
- **A pointer stored at address 0x38 points to address 0x08**
- **A pointer to a pointer is stored at address 0x48**

(note hex addresses)

								0x00
00	00	00	00	00	00	01	5F	0x08
								0x10
								0x18
								0x20
								0x28
								0x30
00	00	00	00	00	00	00	08	0x38
								0x40
00	00	00	00	00	00	00	38	0x48

Data Representations

Sizes of data types (in bytes)

Java Data Type	C Data Type	32-bit (old)	x86-64
boolean	bool	1	1
byte	char	1	1
char		2	2
short	short int	2	2
int	int	4	4
float	float	4	4
	long int	4	8
double	double	8	8
long	long	8	8
	long double	8	16
(reference)	**pointer ***	**4**	**8**

To use "bool" in C, you must #include <stdbool.h>

address size = word size

More on Memory Alignment in x86-64

- **For good memory system performance, Intel recommends data be aligned**
  - However the x86-64 hardware will work correctly regardless of alignment of data.
- **Aligned means: Any primitive object of K bytes must have an address that is a multiple of K.**

K	Type
1	`char`
2	`short`
4	`int, float`
8	`long, double, pointers`

More about alignment later in the course

Byte Ordering

- **How should bytes within a word be ordered in memory?**

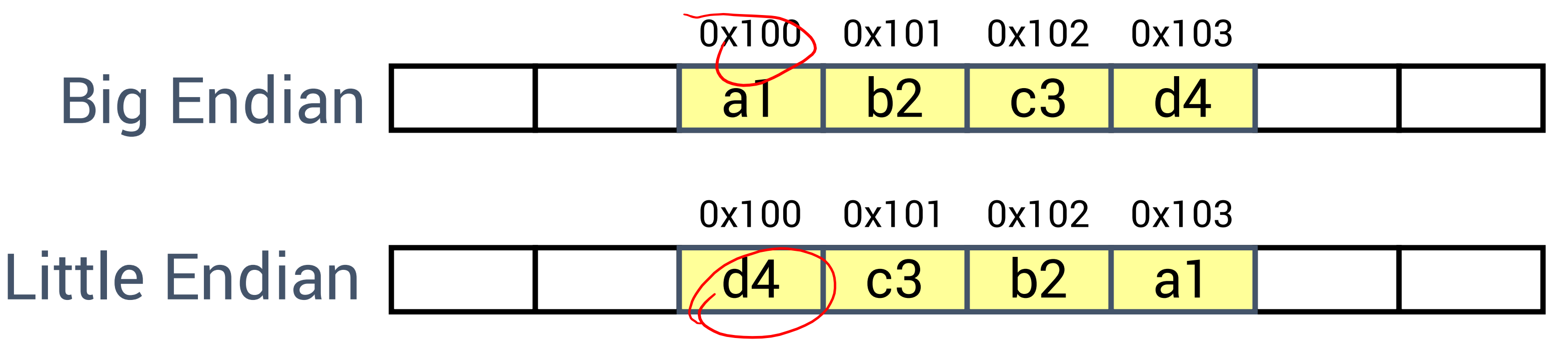
Example:

- **Store the 4-byte (32-bit) word:** 0x a1 b2 c3 d4
  - In what order will the bytes be stored?

- **Conventions!**
  - Big-endian, Little-endian
  - Based on *Gulliver's Travels*: tribes cut eggs on different sides (big, little)

Byte Ordering

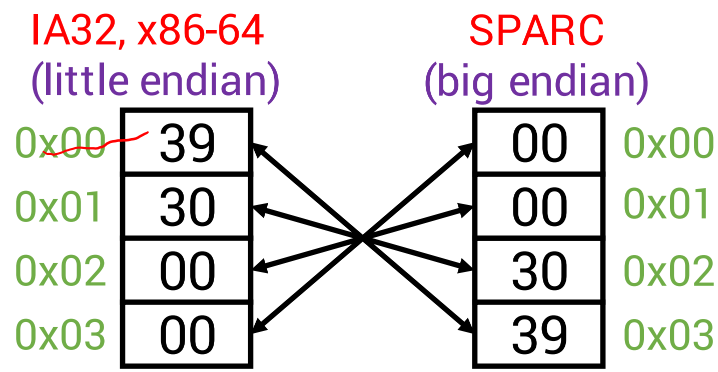
- **Big-Endian** (PowerPC, SPARC, The Internet)
  - Least significant byte has highest address
- **Little-Endian** (x86)
  - Least significant byte has lowest address
- **Example**
  - Variable has 4-byte representation 0xa1b2c3d4
  - Address of variable is 0x100



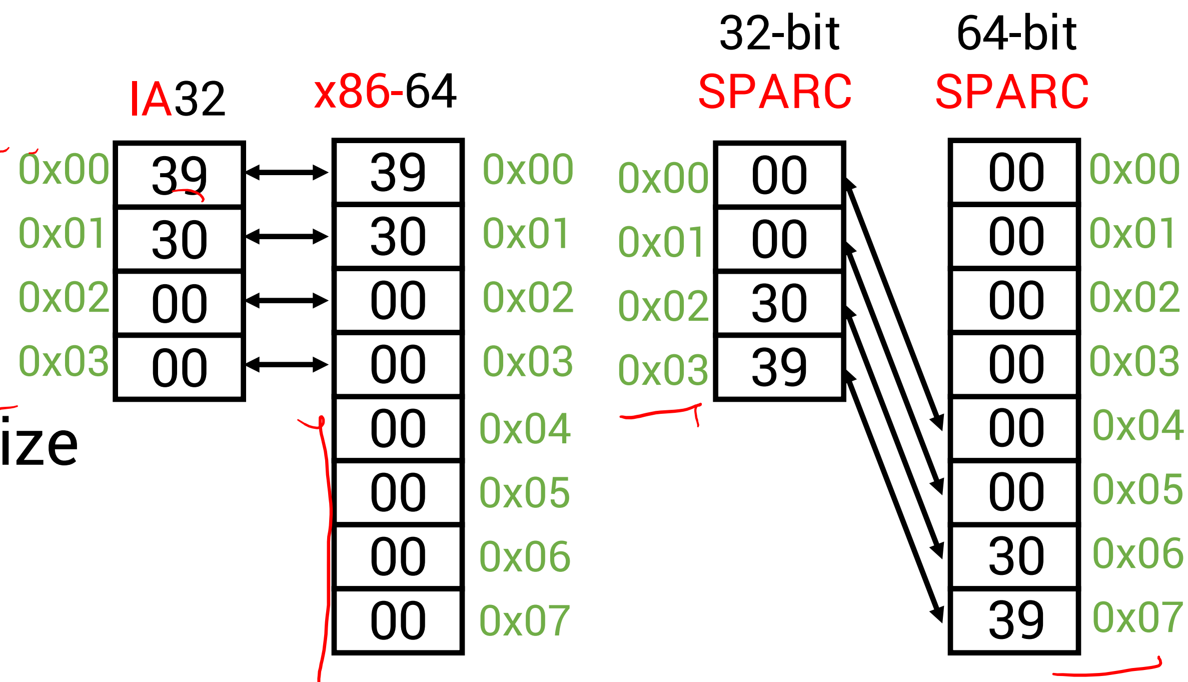
Byte Ordering Examples

Decimal:	12345
Binary:	0011 0000 0011 1001
Hex:	3 0 3 9

```
int x = 12345;
// or x = 0x3039;
```




```
long int y = 12345;
// or y = 0x3039;
```



(A `long int` is the size of a word)

Reading Byte-Reversed Listings

- **Disassembly**
  - Take binary machine code and generate an assembly code version
  - Does the reverse of the assembler
- **Example instruction in memory**
  - add value 0x12ab to register ‘ebx’ *(a special location in the CPU)*

Address	Instruction Code	Assembly Rendition
8048366:	81 c3 ab 12 00 00	add $0x12ab,%ebx

Reading Byte-Reversed Listings

- **Disassembly**
  - Take binary machine code and generate an assembly code version
  - Does the reverse of the assembler
- **Example instruction in memory**
  - add value 0x12ab to register 'ebx' *(a special location in the CPU)*

Address	Instruction Code	Assembly Rendition
8048366:	81 c3 ab 12 00 00	add $0x12ab,%ebx

Deciphering numbers

- Value: 0x12ab
- Pad to 32 bits: 0x000012ab
- Split into bytes: 00 00 12 ab
- Reverse (little-endian): ab 12 00 00

Memory, Data, and Addressing

- **Representing information as bits and bytes**
- **Organizing and addressing data in memory**
- **Manipulating data in memory using C**
- **Boolean algebra and bit-level manipulations**

Addresses and Pointers in C

& = ‘address of’
* = ‘value at address’ or ‘dereference’

int *ptr

```
int* ptr;
```

Declares a variable, `ptr`, that is a pointer to (i.e., holds the address of) an `int` in memory

* is also used with variable declarations

```
int x = 5;
int y = 2;
```

Declares two variables, `x` and `y`, that hold `int`s, and sets them to 5 and 2, respectively

```
ptr = &x;
```

x

a

Sets `ptr` to the address of `x`. Now, “`ptr` points to `x`”

“Dereference `ptr`”

```
y = 1 + *ptr;
```

5

Sets `y` to “1 plus the value stored at the address held by `ptr`, because `ptr` points to `x`, this is equivalent to `y=1+x;`

What is `*(&y)` ?

CSE351: April 1

- **Notes**
  - Slides are posted on the **schedule** (pdf before lecture, ppt w/ scribbles after) (https://courses.cs.washington.edu/courses/cse351/16sp/schedule.html)
- **Survey**
  - C vs Java (in your words!)
    - Lower level language
    - Not object-oriented,
    - Allocate memory manually / manual garbage collections
    - Have to do more things on your own like defining of arrays
    - Pointers are a big issue and easier to mess up compared to Java
    - A lot more tedious than Java
  - Concerns
    - Have no idea what the assignments will look like
    - Fast-paced
    - Missing necessary background
    - Not familiar with C or Linux

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = ‘address of’
* = ‘value at address’
or ‘dereference’

- **A variable is represented by a memory location**
- **Initially, it may hold any value**
- **int x, y;**
  - x is at location 0x04, y is at 0x18

0x00	0x01	0x02	0x03		
A7	00	32	00	0x00	
00	01	29	F3	0x04	x
EE	EE	EE	EE	0x08	
FA	CE	CA	FE	0x0C	
26	00	00	00	0x10	
00	00	10	00	0x14	
01	00	00	00	0x18	y
FF	00	F4	96	0x1C	
00	00	00	00	0x20	
00	42	17	34	0x24	

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = ‘address of’
* = ‘value at address’
or ‘dereference’

- **A variable is represented by a memory location**
- **Initially, it may hold any value**
- **int x, y;**
  - x is at location 0x04, y is at 0x18

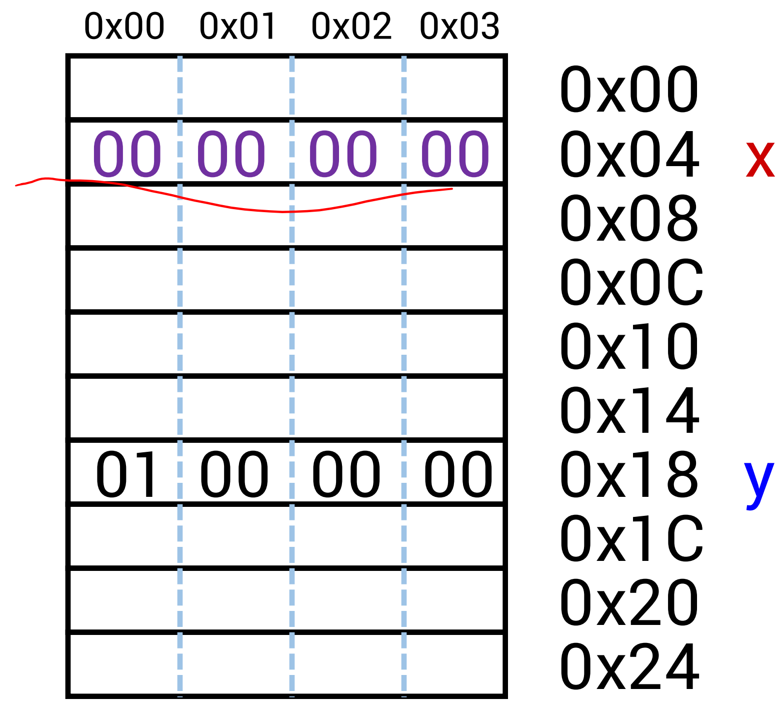
0x00	0x01	0x02	0x03		
				0x00	
00	01	29	F3	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
01	00	00	00	0x18	y
				0x1C	
				0x20	
				0x24	

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = ‘address of’
* = ‘value at address’
or ‘dereference’

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**



Assignment in C

32-bit example
(pointers are 32-bits wide)

& = 'address of'
* = 'value at address'
or 'dereference'

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD02700;**

0x00	0x01	0x02	0x03		
				0x00	
00	00	00	00	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	y
				0x1C	
				0x20	
				0x24	

little endian!

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = 'address of'
* = 'value at address'
or 'dereference'

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD02700;**
- **x = y + 3;**
  - Get value at y, add 3, put it in x

	0x00	0x01	0x02	0x03		
					0x00	
	03	27	D0	3C	0x04	x
					0x08	
					0x0C	
					0x10	
					0x14	
	00	27	D0	3C	0x18	y
					0x1C	
					0x20	
					0x24	

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = 'address of'
* = 'value at address'
or 'dereference'

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD02700;**
- **x = y + 3;**
  - Get value at y, add 3, put it in x
- **int* z**

0x00	0x01	0x02	0x03		
				0x00	
03	27	D0	3C	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	y
				0x1C	
				0x20	z
				0x24	

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = 'address of'
* = 'value at address'
or 'dereference'

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD02700;**
- **x = y + 3;**
  - Get value at y, add 3, put it in x
- **int* z = &y + 3;**
  - Get address of y, add **???**, put it in z

Pointer arithmetic

	0x00	0x01	0x02	0x03		
					0x00	
	03	27	D0	3C	0x04	x
					0x08	
					0x0C	
					0x10	
					0x14	
	00	27	D0	3C	0x18	y
					0x1C	
					0x20	z
					0x24	

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = 'address of'
* = 'value at address'
or 'dereference'

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD027**
- **x = y + 3;**
  - Get value at y, ad put it in x
- **int* z = &y + 3;**
  - Get address of y, add **12**, put it in z

Pointer arithmetic
can be dangerous

0x00	0x01	0x02	0x03		
				0x00	
03	27	D0	3C	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	y
				0x1C	
24	00	00	00	0x20	z
				0x24	

&y = 0x18 = 24 (decimal)
+ 12
36 = 0x24

Pointer arithmetic is scaled by size of target type

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = 'address of'
* = 'value at address'
or 'dereference'

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD02700;**
- **x = y + 3;**
  - Get value at y, add 3, put it in x
- **int* z = &y + 3;**
  - Get address of y, add **12**, put it in z
- ***z = y;**
  - What does this do?

0x00	0x01	0x02	0x03		
				0x00	
03	27	D0	3C	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	y
				0x1C	
24	00	00	00	0x20	z
				0x24	

Assignment in C

32-bit example
(pointers are 32-bits wide)

& = 'address of'
* = 'value at address' or 'dereference'

- **Left-hand-side = right-hand-side;**
  - LHS must evaluate to a memory *location*
  - RHS must evaluate to a *value* (could be an address!)
  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD**
- **x = y + 3;**
  - Get value at … 3, put it in x
- **int* z = … + 3;**
  - G… address of y, add **12**, put it in z
- ***z = y;**
  - **Get value of y, put it at the address stored in z**

The target of a pointer is also a memory location

0x00	0x01	0x02	0x03		
				0x00	
03	27	D0	3C	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	y
				0x1C	
24	00	00	00	0x20	z
00	27	D0	3C	0x24	

Arrays in C

Declaration: int a[6];

element type

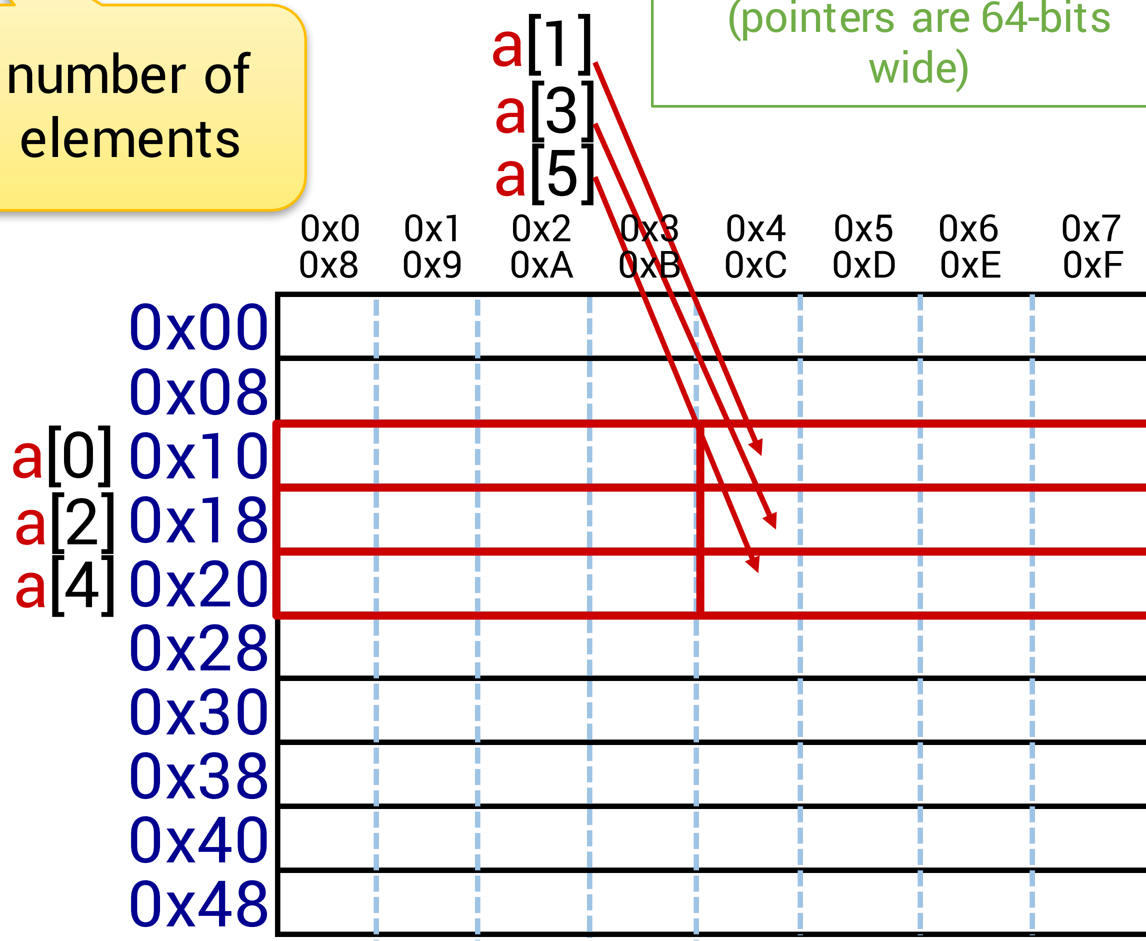
name

number of elements

Arrays are adjacent locations in memory storing the same type of data object

a is a name for the array's address

64-bit example
(pointers are 64-bits wide)



Arrays in C

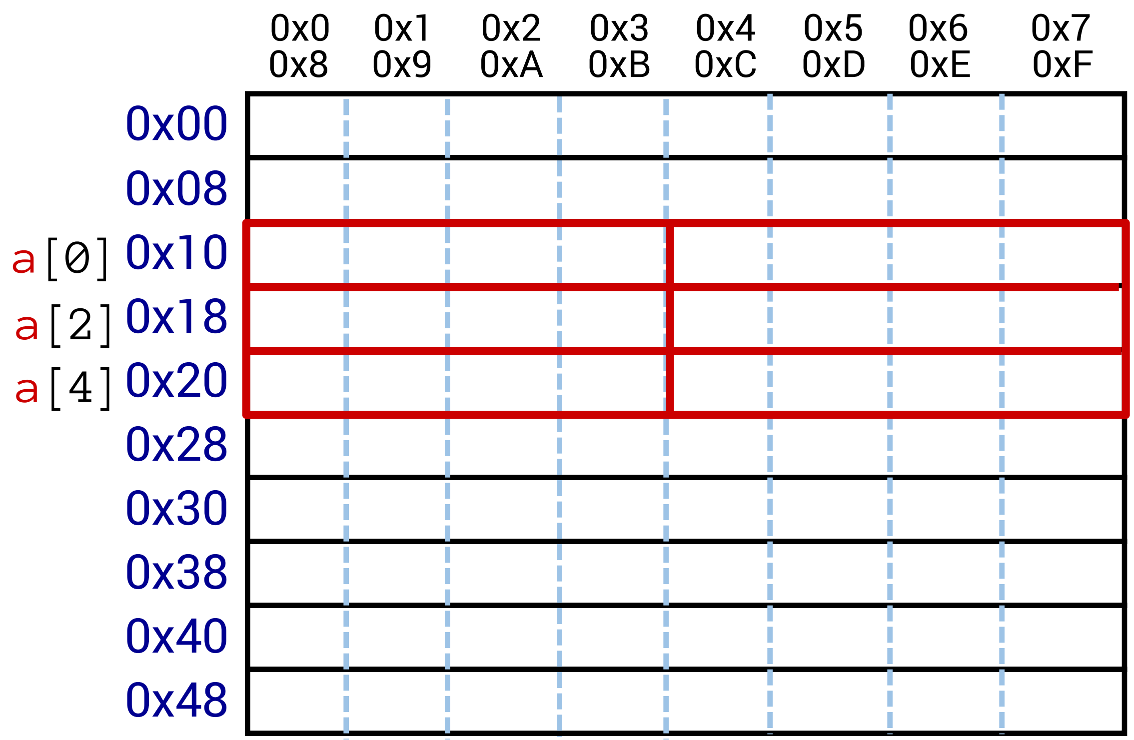
Arrays are adjacent locations in memory storing the same type of data object

a is a name for the array's address

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes



Arrays in C

Arrays are adjacent locations in memory storing the same type of data object

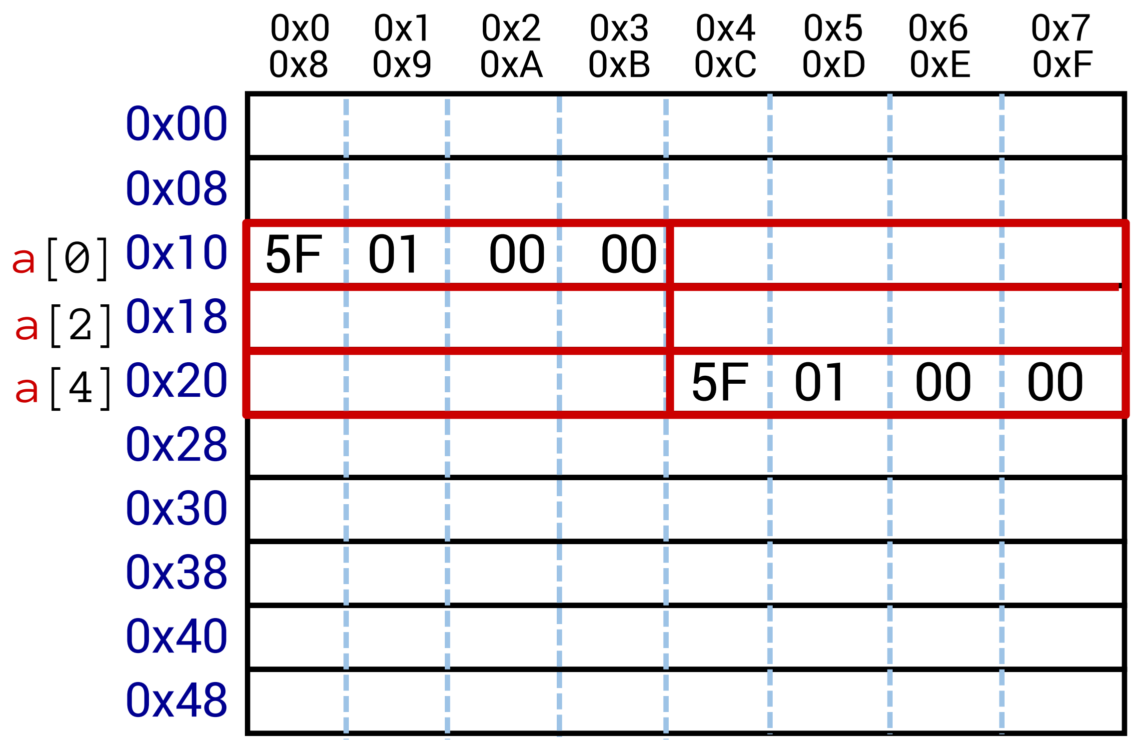
`a` is a name for the array's address

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes



Arrays in C

Arrays are adjacent locations in memory storing the same type of data object

a is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

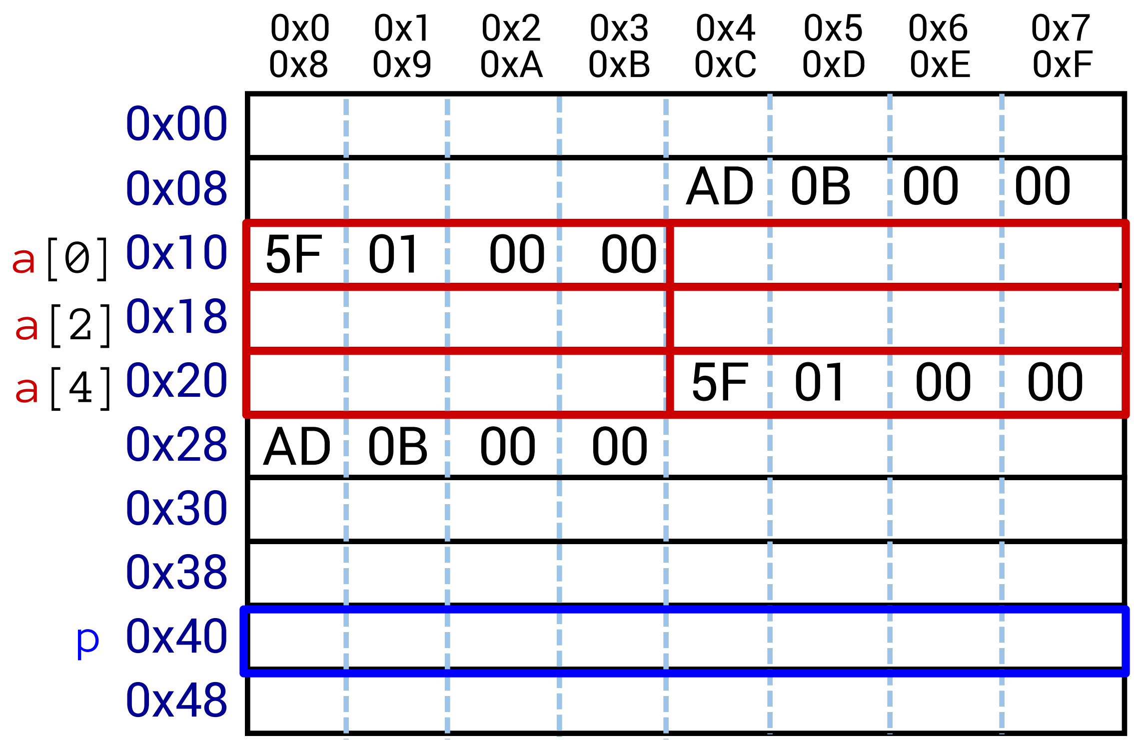
Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers:
```
int* p;
p = a;
p = &a[0];
*p = 0xA;
```

equivalent



Arrays in C

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration:
```
int a[6];
```

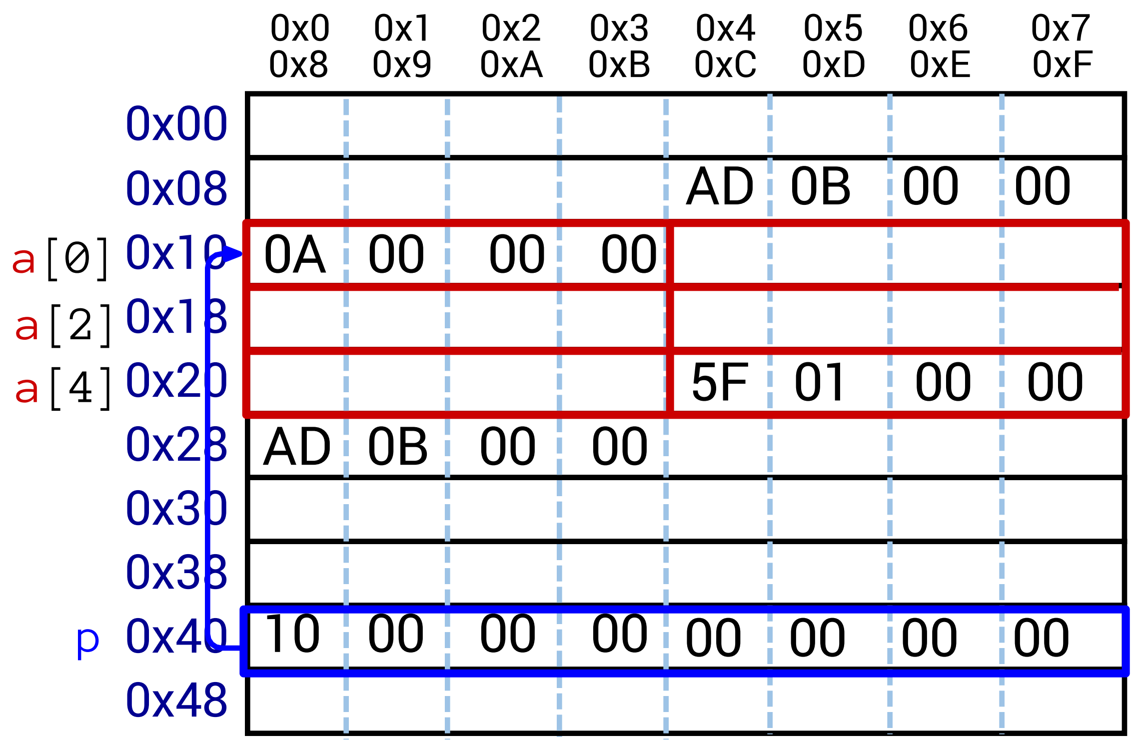
Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers:
```
int* p;
```
equivalent {
```
p = a;
p = &a[0];
```
```
*p = 0xA;
```

array indexing = address arithmetic
(both scaled by the size of the type)

equivalent {
```
p[1] = 0xB;
*(p + 1) = 0xB;
```
```
p = p + 2;
```



Arrays in C

Arrays are adjacent locations in memory storing the same type of data object

`a` is a name for the array's address

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Declaration:
```
int a[6];
```

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers:
```
int* p;
```
equivalent {
```
p = a;
p = &a[0];
```
}
```
*p = 0xA;
```

array indexing = address arithmetic
(both scaled by the size of the type)

equivalent {
```
p[1] = 0xB;
*(p + 1) = 0xB;
```
}
```
p = p + 2;
```

```
*p = a[1] + 1;
```

		0x0 0x8	0x1 0x9	0x2 0xA	0x3 0xB	0x4 0xC	0x5 0xD	0x6 0xE	0x7 0xF
	0x00								
	0x08					AD	0B	00	00
a[0]	0x10	0A	00	00	00	0B	00	00	00
a[2]	0x18								
a[4]	0x20					5F	01	00	00
	0x28	AD	0B	00	00				
	0x30								
	0x38								
p	0x40	18	00	00	00	00	00	00	00
	0x48								

Arrays in C

Arrays are adjacent locations in memory storing the same type of data object

a is a name for the array's address

Declaration: `int a[6];`

Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

The address of `a[i]` is the address of `a[0]` plus `i` times the element size in bytes

Pointers:
```
int* p;
p = a;
p = &a[0];
*p = 0xA;
```
equivalent: `p = a;` / `p = &a[0];`

array indexing = address arithmetic
(both scaled by the size of the type)

equivalent:
```
p[1] = 0xB;
*(p + 1) = 0xB;
```

```
p = p + 2;
```

```
*p = a[1] + 1;
```

		0x0 0x8	0x1 0x9	0x2 0xA	0x3 0xB	0x4 0xC	0x5 0xD	0x6 0xE	0x7 0xF
	0x00								
	0x08					AD	0B	00	00
a[0]	0x10	0A	00	00	00	0B	00	00	00
a[2]	0x18	0C	00	00	00				
a[4]	0x20					5F	01	00	00
	0x28	AD	0B	00	00				
	0x30								
	0x38								
p	0x40	18	00	00	00	00	00	00	00
	0x48								

Representing strings

- A C-style string is represented by an array of bytes (`char`)
  - Elements are one-byte ASCII codes for each character
  - ASCII = American Standard Code for Information Interchange

32	space	48	0	64	@	80	P	96	`	112	p
33	!	49	1	65	A	81	Q	97	a	113	q
34	”	50	2	66	B	82	R	98	b	114	r
35	#	51	3	67	C	83	S	99	c	115	s
36	$	52	4	68	D	84	T	100	d	116	t
37	%	53	5	69	E	85	U	101	e	117	u
38	&	54	6	70	F	86	V	102	f	118	v
39	’	55	7	71	G	87	W	103	g	119	w
40	(	56	8	72	H	88	X	104	h	120	x
41	)	57	9	73	I	89	Y	105	I	121	y
42	*	58	:	74	J	90	Z	106	j	122	z
43	+	59	;	75	K	91	[	107	k	123	{
44	,	60	<	76	L	92	\	108	l	124	|
45	-	61	=	77	M	93	]	109	m	125	}
46	.	62	>	78	N	94	^	110	n	126	~
47	/	63	?	79	O	95	_	111	o	127	del

Null-terminated Strings

- For example, "Harry Potter" can be stored as a 13-byte array

72	97	114	114	121	32	80	111	116	116	101	114	0
H	a	r	r	y		P	o	t	t	e	r	\0

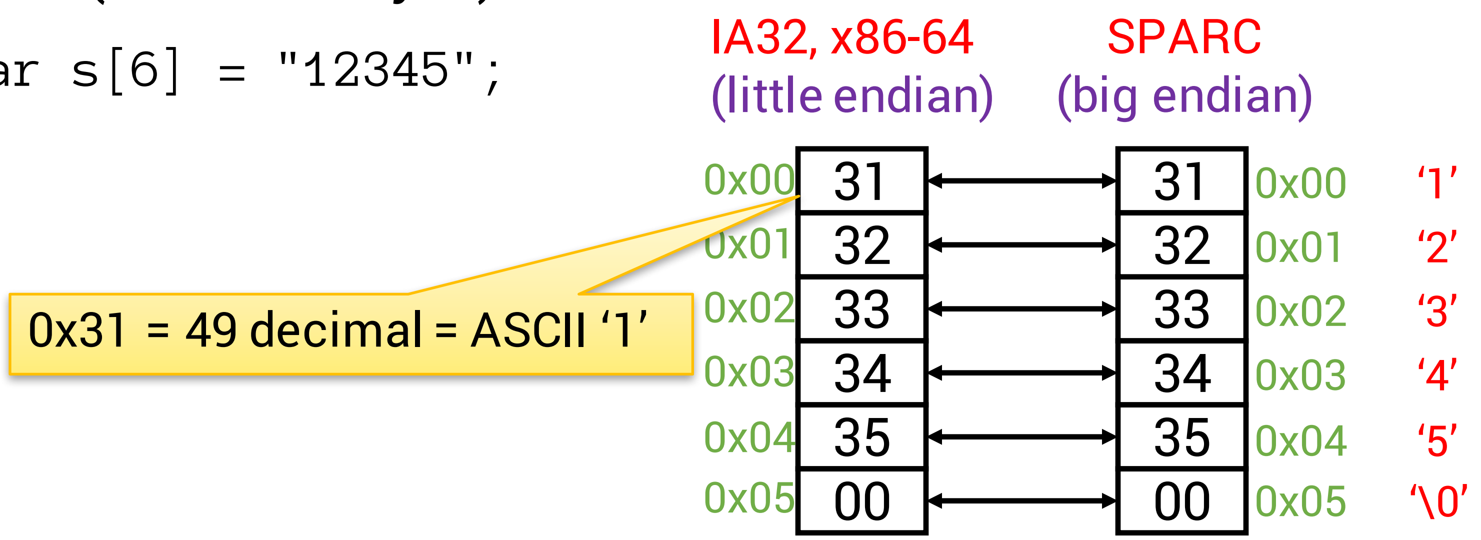
- Why do we put a 0, or null zero, at the end of the string?
  - Note the special symbol: string[12] = '\0';

- How do we compute the string length?

Endianness and Strings

C (char = 1 byte)

```
char s[6] = "12345";
```



- **Byte ordering (endianness) is not an issue for 1-byte values**
  - The whole array does not constitute a single value
  - Individual elements are values; chars are single bytes
- **Unicode characters – up to 4 bytes/character**
  - ASCII codes still work (just add leading zeros)
  - Unicode can support the many characters in all languages in the world
  - Java and C have libraries for Unicode (Java commonly uses 2 bytes/char)

Examining Data Representations

- **Code to print byte representation of data**
  - Any data type can be treated as a *byte array* by **casting** it to `char`
  - C has unchecked casts. << DANGER >>

```
void show_bytes(char* start, int len) {
  int i;
  for (i = 0; i < len; i++)
    printf("%p\t0x%.2x\n", start+i, *(start+i));
  printf("\n");
}
```

```
void show_int (int x) {
  show_bytes( (char *) &x, sizeof(int));
}
```

printf directives:

%p	Print pointer
\t	Tab
%x	Print value as hex
\n	New line

show_bytes Execution Example

```
int a = 12345; // represented as 0x00003039
printf("int a = 12345;\n");
show_int(a);   // show_bytes((char *) &a, sizeof(int));
```

Result (Linux x86-64):

```
int a = 12345;
0x7fffb7f71dbc  0x39
0x7fffb7f71dbd  0x30
0x7fffb7f71dbe  0x00
0x7fffb7f71dbf  0x00
```

Memory, Data, and Addressing

- **Representing information as bits and bytes**
- **Organizing and addressing data in memory**
- **Manipulating data in memory using C**
- **Boolean algebra and bit-level manipulations**

Boolean Algebra

- Developed by George Boole in 19th Century
  - Algebraic representation of logic
    - Encode "True" as 1 and "False" as 0
  - AND: `A & B = 1` when both A is 1 and B is 1
  - OR: `A | B = 1` when either A is 1 or B is 1
  - XOR: `A ^ B = 1` when either A is 1 or B is 1, but not both
  - NOT: `~A = 1` when A is 0 and vice-versa
  - DeMorgan's Law: `~(A | B) = ~A & ~B`
    `~(A & B) = ~A | ~B`

AND

&	0	1
0	0	0
1	0	1

OR

|	0	1
0	0	1
1	1	1

XOR

^	0	1
0	0	1
1	1	0

NOT

~	
0	1
1	0

General Boolean Algebras

- **Operate on bit vectors**
  - Operations applied bitwise

```
  01101001     01101001     01101001
& 01010101   | 01010101   ^ 01010101   ~ 01010101
  01000001     01111101     00111100     10101010
```

- **All of the properties of Boolean algebra apply**

```
  01010101
^ 01010101
  00000000
```

- **How does this relate to set operations?**

Representing & Manipulating Sets

- **Representation**
  - A w-bit vector represents subsets of $\{0, \ldots, w-1\}$
  - $a_j = 1$ iff $j \in A$

    `01101001` { 0, 3, 5, 6 }
    `76543210`

    `01010101` { 0, 2, 4, 6 }
    `76543210`

- **Operations**

&	Intersection	`01000001`	{ 0, 6 }
|	Union	`01111101`	{ 0, 2, 3, 4, 5, 6 }
^	Symmetric difference	`00111100`	{ 2, 3, 4, 5 }
~	Complement	`10101010`	{ 1, 3, 5, 7 }

Bit-Level Operations in C

- `&   |   ^   ~`
  - Apply to any “integral” data type
    - `long`, `int`, `short`, `char`, `unsigned`
  - View arguments as bit vectors
- **Examples (char data type)**
  - `~0x41` --> `0xBE`
    $\sim 01000001_2$ --> 10111110_2
  - `~0x00` --> `0xFF`
    $\sim 00000000_2$ --> 11111111_2
  - `0x69 & 0x55` --> `0x41`
    01101001_2 & 01010101_2 --> 01000001_2
  - `0x69 | 0x55` --> `0x7D`
    01101001_2 | 01010101_2 --> 01111101_2
- **Some bit-twiddling puzzles in Lab 1**

Contrast: Logic Operations in C

- **Contrast to logical operators**
  - `&&` `||` `!`
    - 0 is "False"
    - **Anything nonzero** is "True"
    - **Always** return 0 or 1
    - Early termination a.k.a. short-circuit evaluation
- **Examples (char data type)**
  - `!0x41 --> 0x00`
  - `!0x00 --> 0x01`
  - `!!0x41 --> 0x01`
  - `0x68 && 0x55 --> 0x01`
  - `0x68 || 0x55 --> 0x01`
  - `p && *p++` (avoids null pointer access, null pointer = 0x0000 0000 0000 0000)