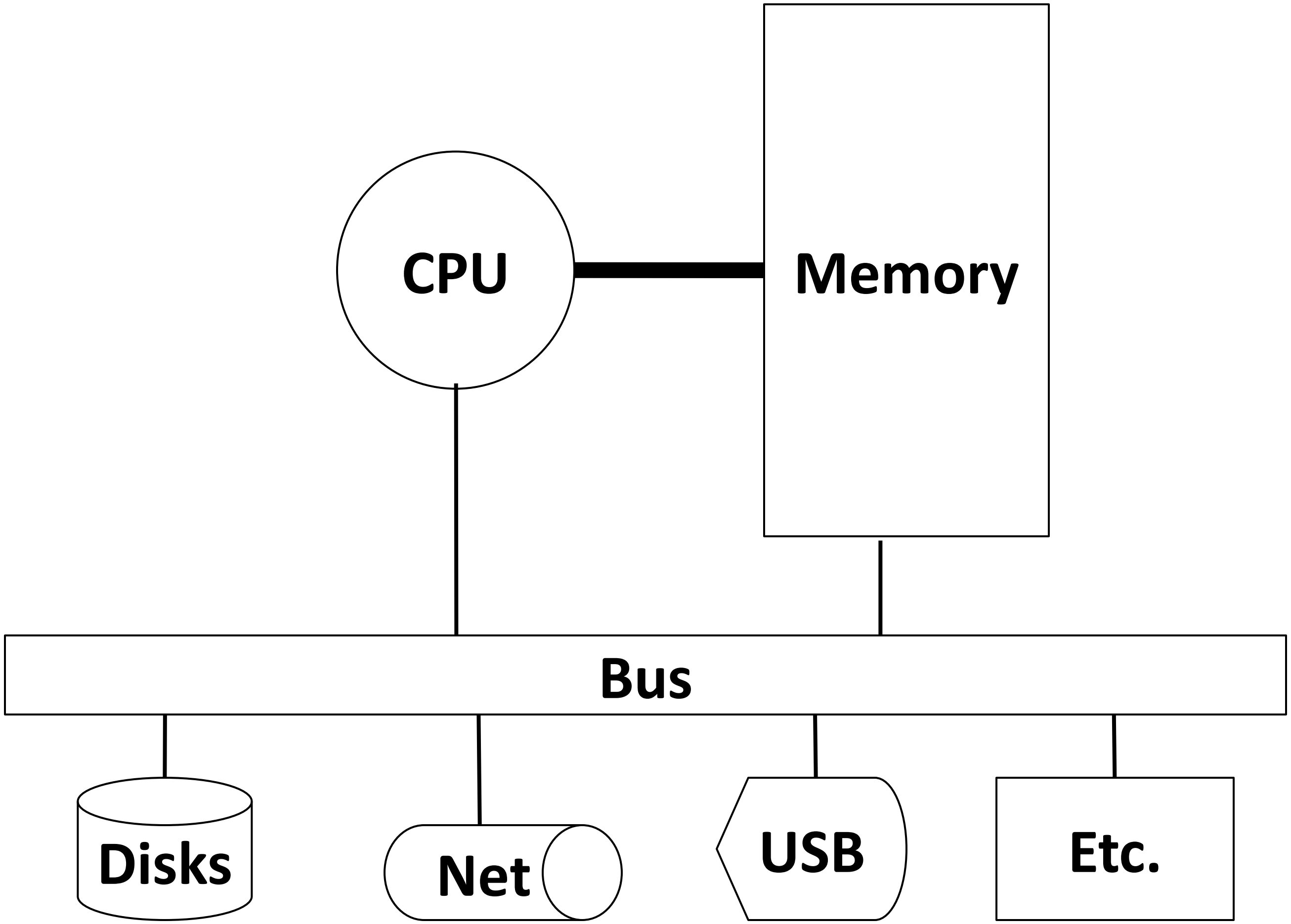
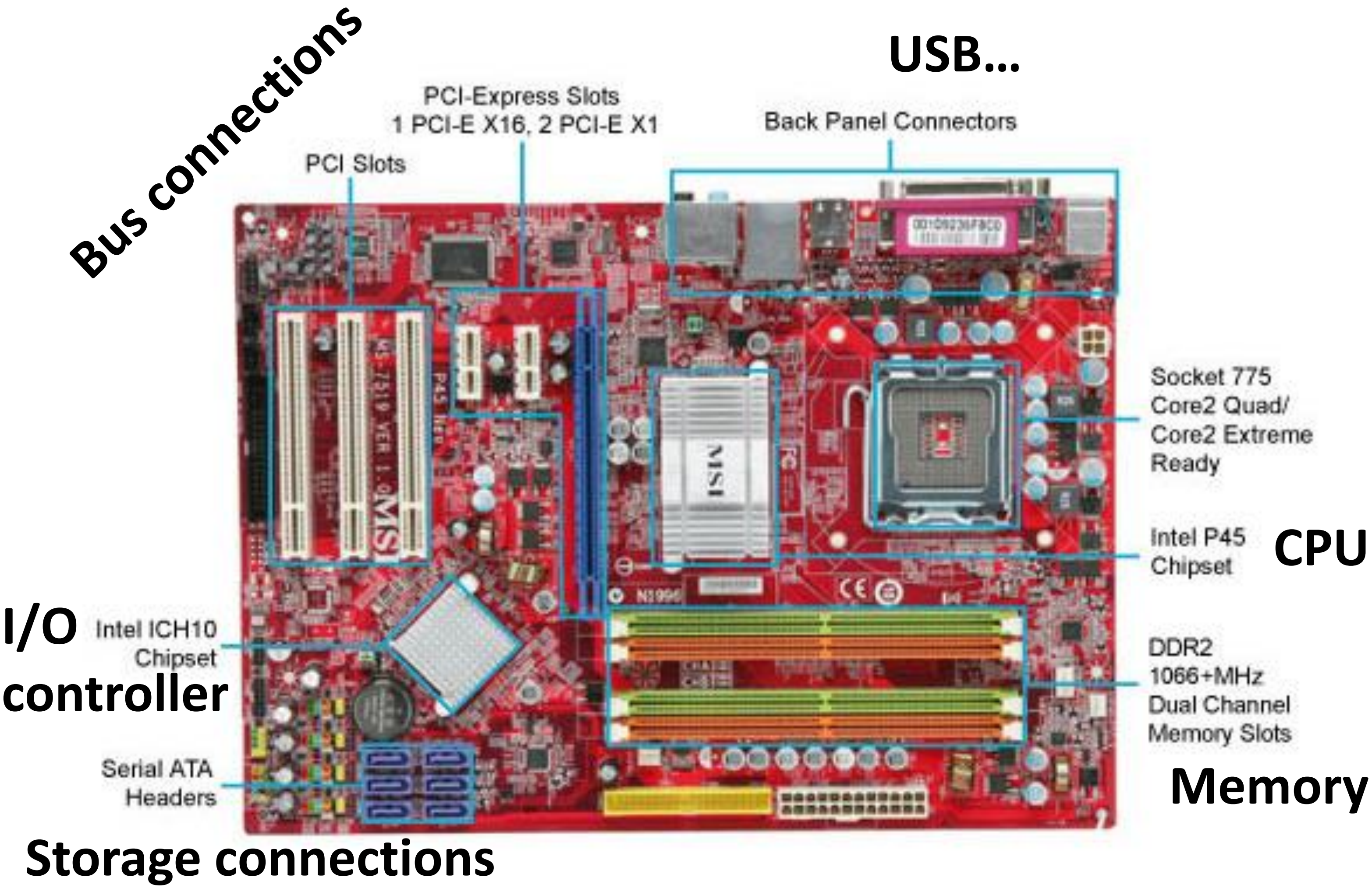
Announcements

- **On the website: cs.uw.edu/351**
  - Anonymous feedback form
  - Need help?
    - Discussion board (aka GoPost) – You can *search* the GoPost!
    - Send email to cse351-staff at cse.uw.edu
    - Office hours: Almost finalized, check the calendar
  - Lecture slides on the web schedule (these will be linked when ready)
  - Lab 0, make sure to start early – due Monday at 5pm
  - Videos for optional reference – not exactly the same slides as we'll use
    - Tips for C, debugging, etc.
    - Lecture content
- **Video Assignment for Monday: (found on schedule)**
  https://courses.cs.washington.edu/courses/cse351/15au/video-assignment-1.html
- **Everyone in cse351 should be able to sign up for cse390a**
  - Show up on Tuesday for first class

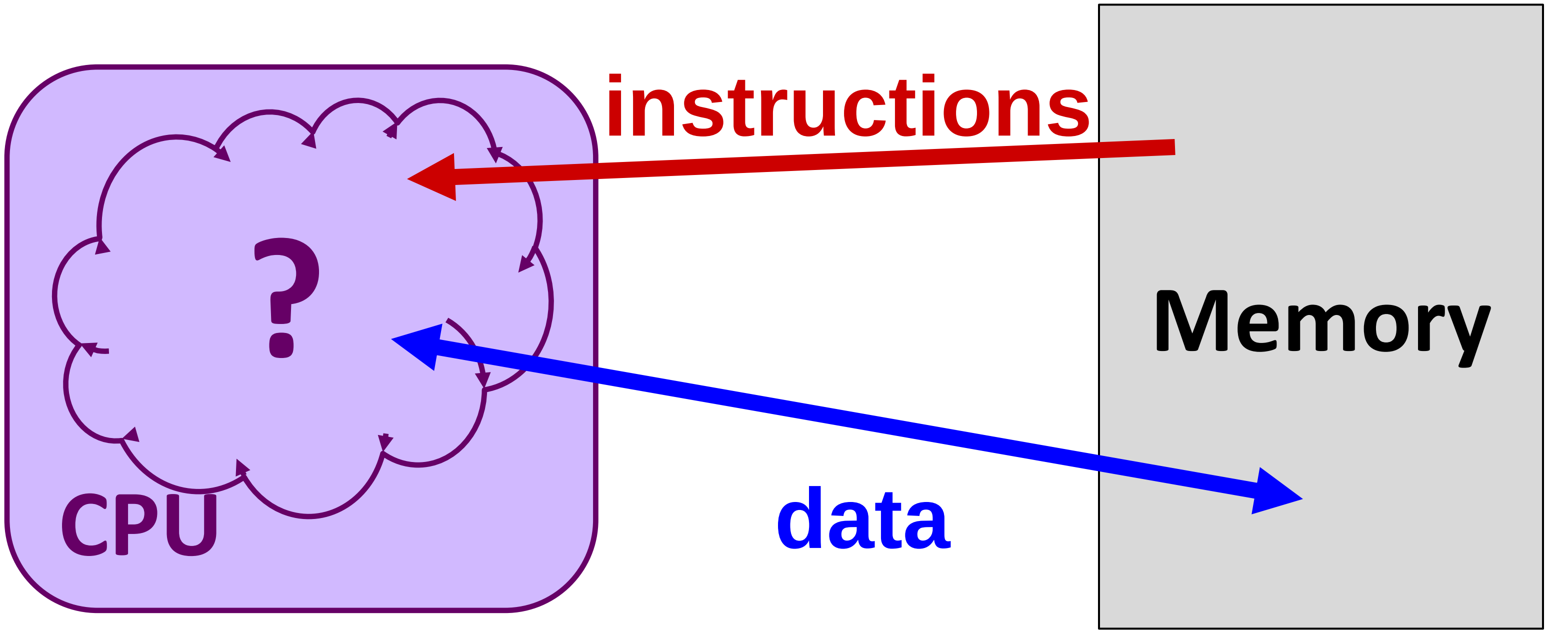
Hardware: Logical View



Hardware: Physical View

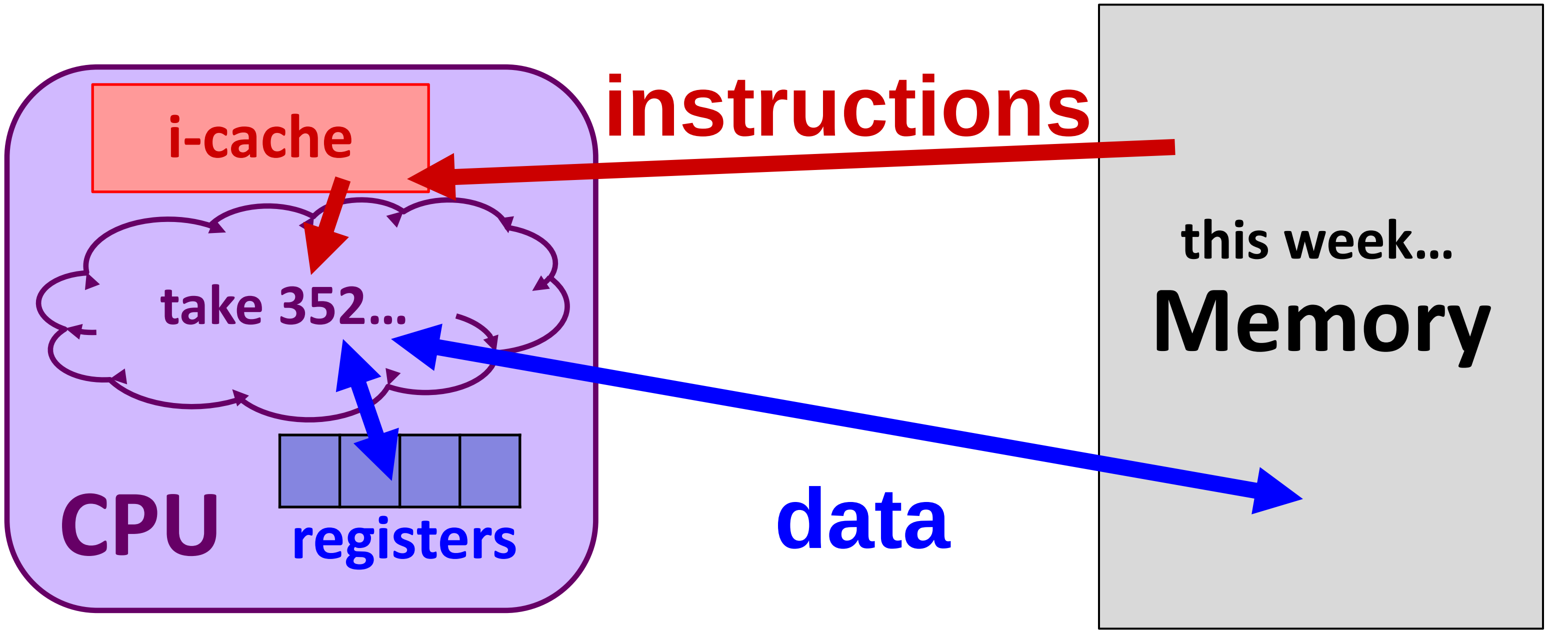


Hardware: 351 View (version 0)



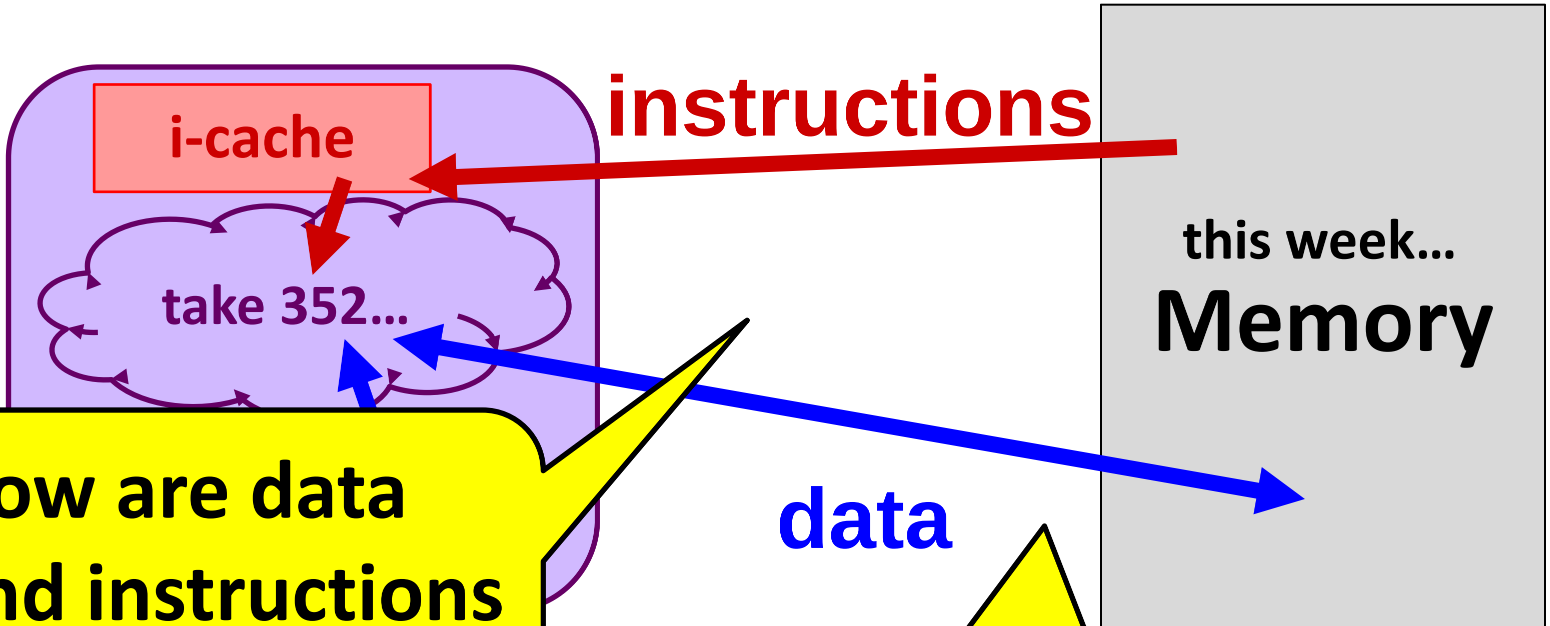
- **CPU executes instructions; memory stores data**
- **To execute an instruction, the CPU must:**
  - fetch an instruction;
  - fetch the data used by the instruction; and, finally,
  - execute the instruction on the data…
  - which may result in writing data back to memory.

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 (assembly language) programmer-controlled
- We'll learn about the instructions the CPU executes – take cse352 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?

- …ctions tem… cache.
- The CPU holds data temporarily… …sters.
- Instruction fetching is HW-cont…
- Data movement is programmer…

Roadmap

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

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
```

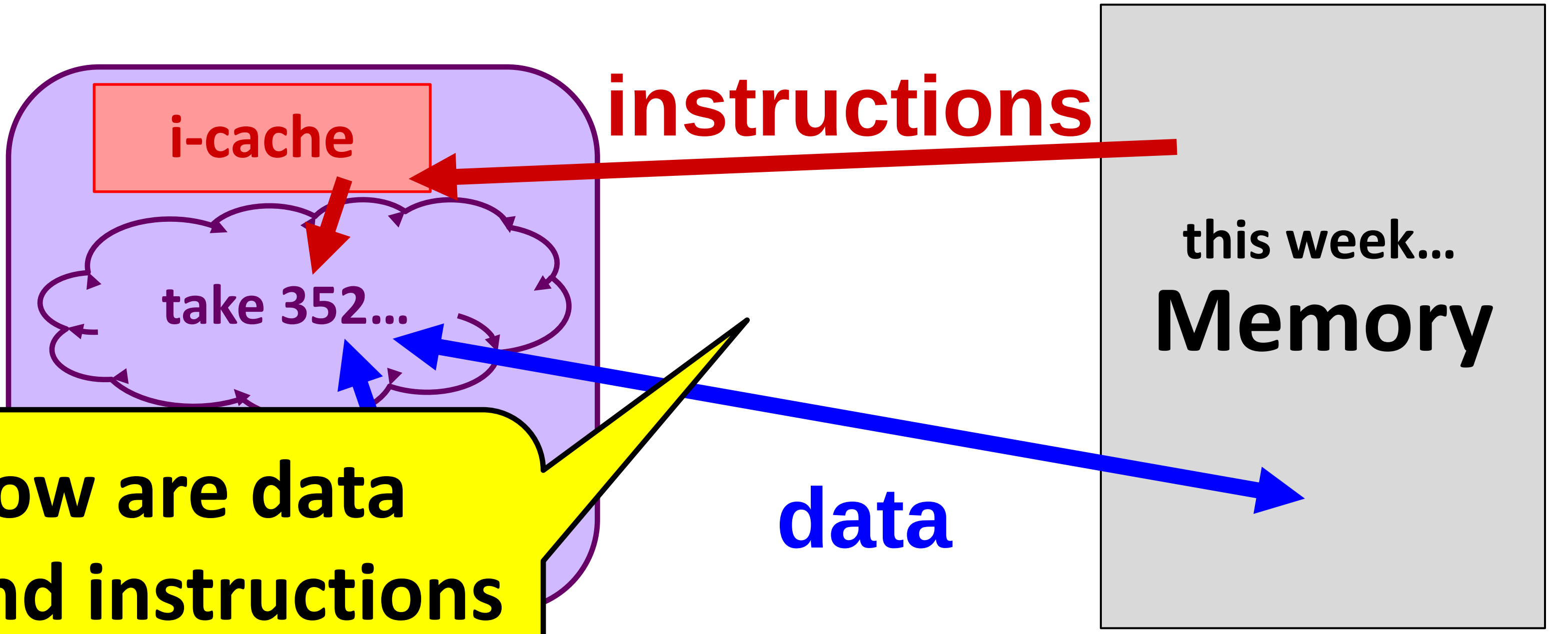
OS:

Windows 8
Mac

Computer system:

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

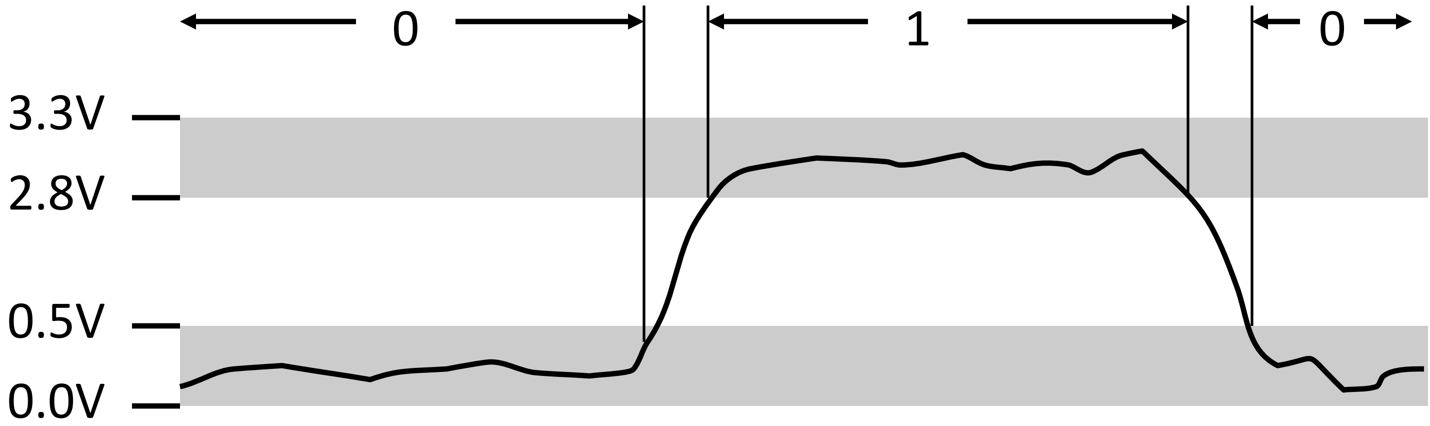


How are data and instructions represented?

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

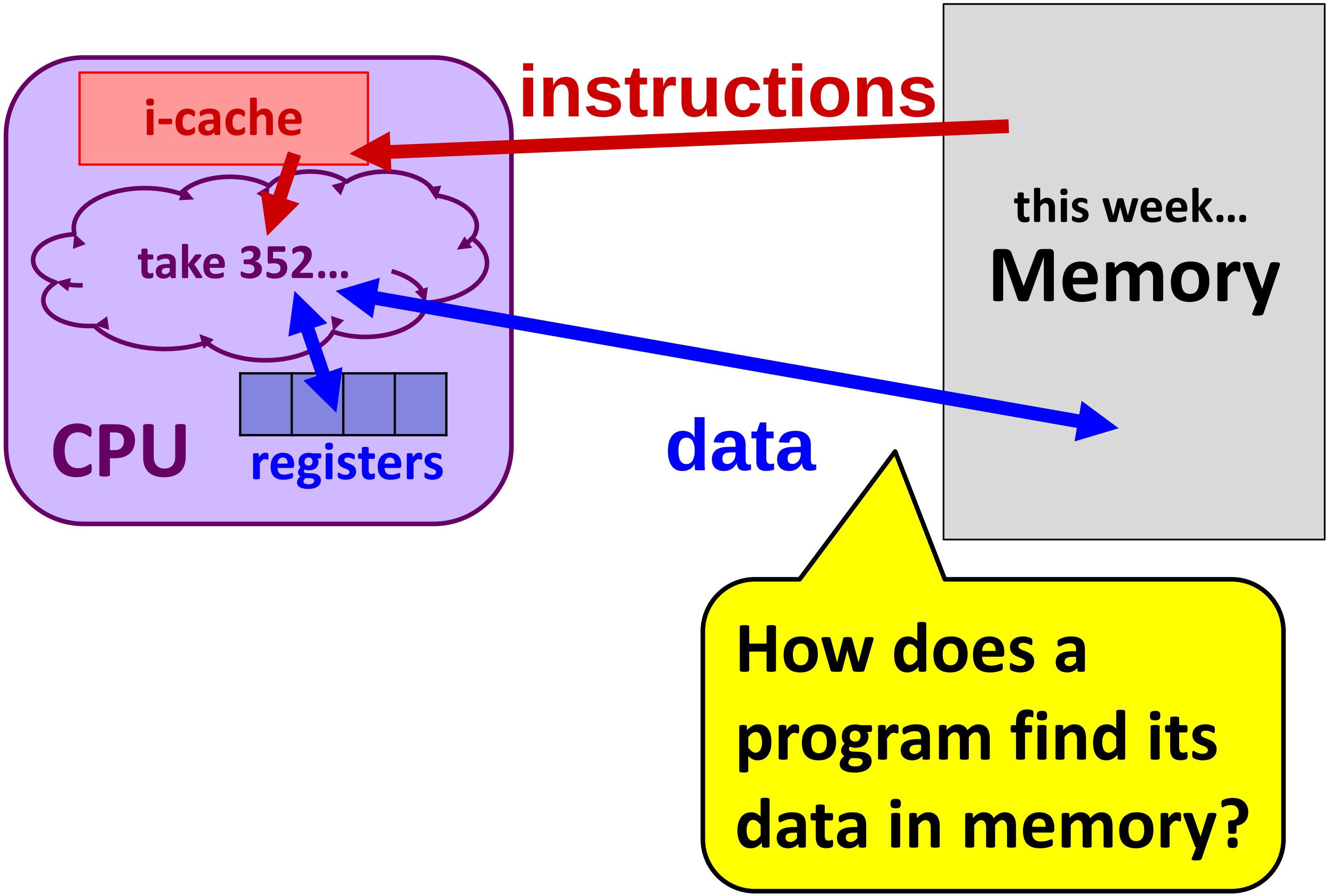
- **Electronic implementation**
  - Easy to store with bi-stable elements
  - Reliably transmitted on noisy and inaccurate wires



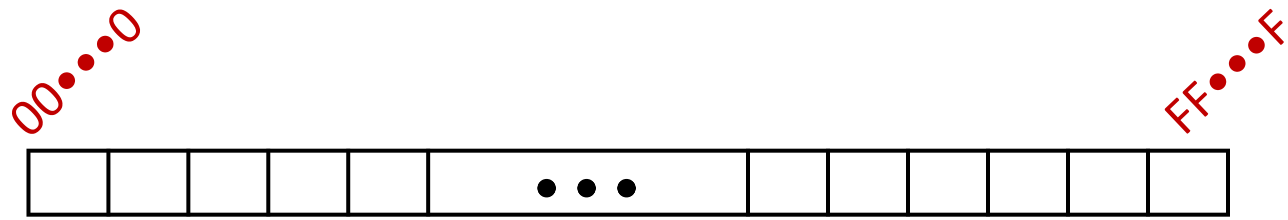
Describing Byte Values

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


i-cache
instructions
take 352…
this week…
Memory
CPU
registers
data
How does a program find its data in memory?

Byte-Oriented Memory Organization



- **Conceptually, memory is a single, large array of bytes, each with an 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**

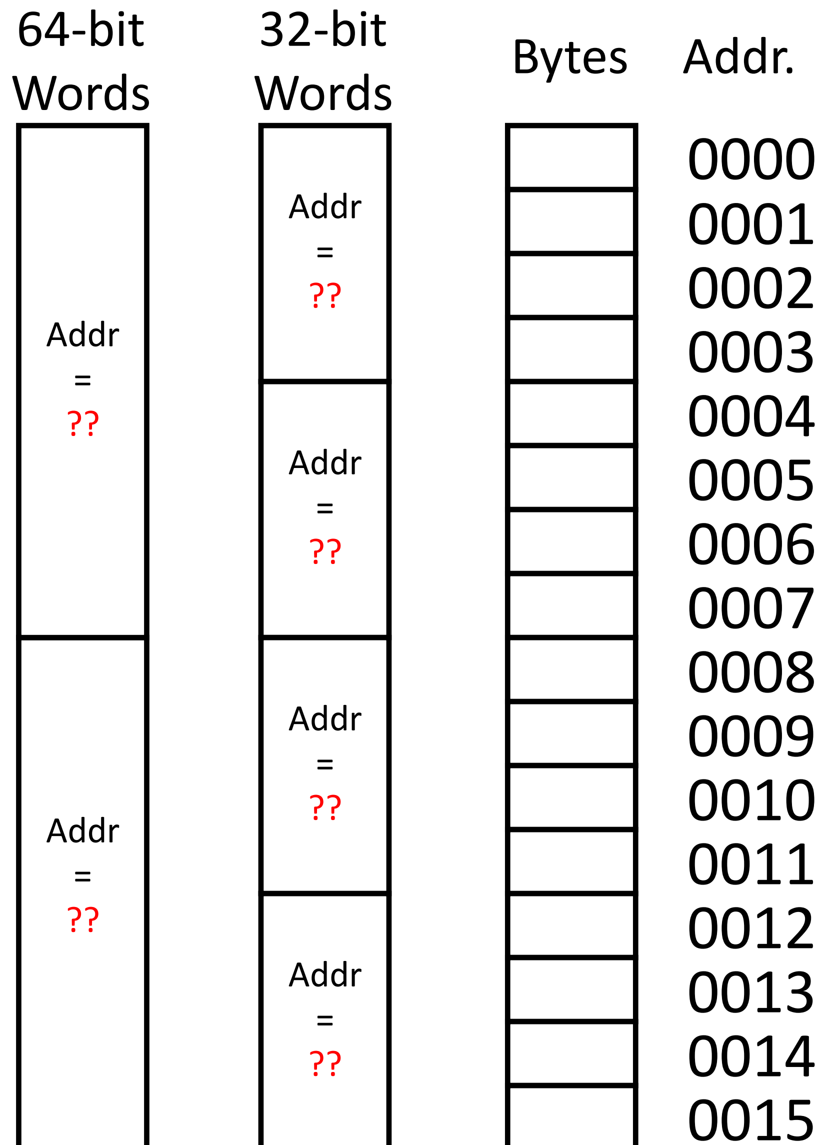
Machine Words

- **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 ≈ $\mathbf{4 \times 10^9}$ **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 ≈ $\mathbf{1.8 \times 10^{19}}$ **bytes** = 18 billion billion bytes = **18 EB** (exabytes)

Word-Oriented Memory Organization

(note: decimal addresses)

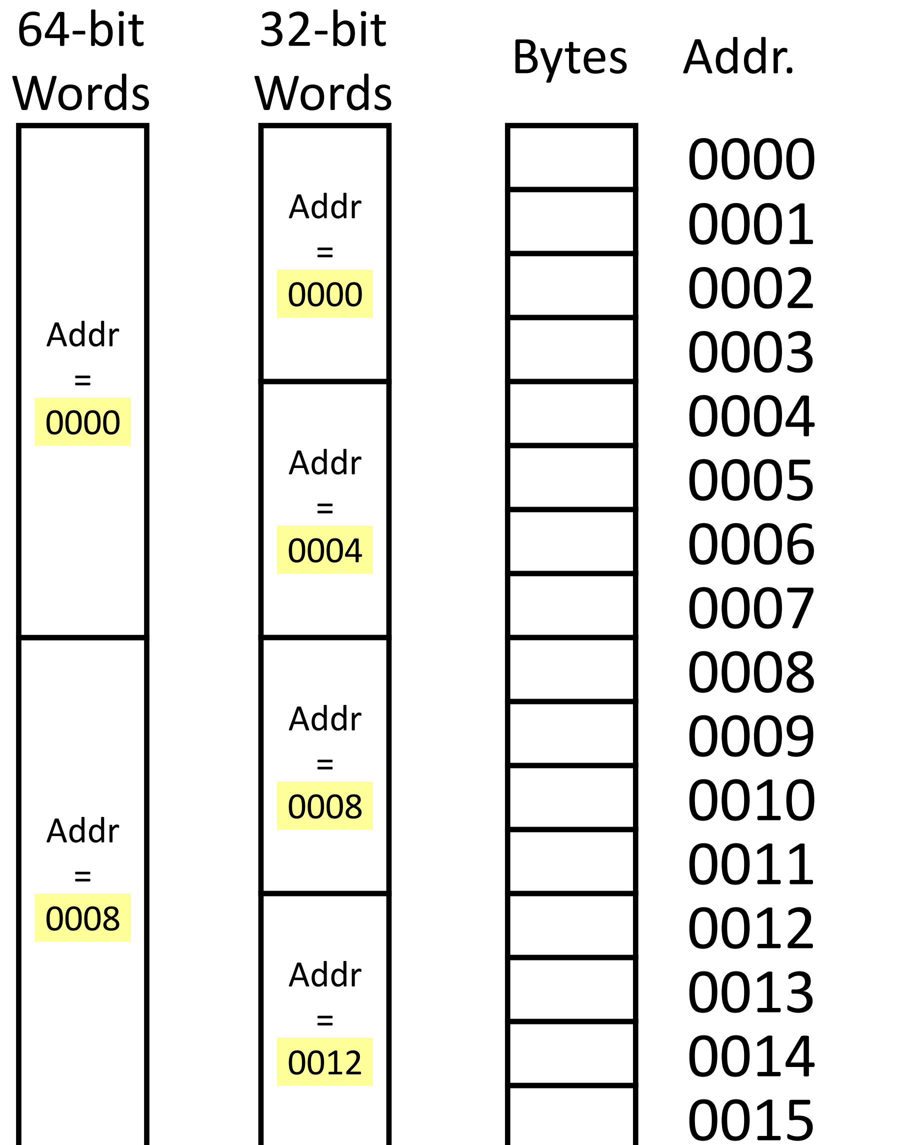
- **Addresses specify locations of bytes in memory**
  - Address of word
    = address of first byte in word
  - Addresses of successive words differ by word size (in bytes): *e.g.*, 4 (32-bit) or 8 (64-bit)
  - Address of word 0, 1, .. 10?



Word-Oriented Memory Organization

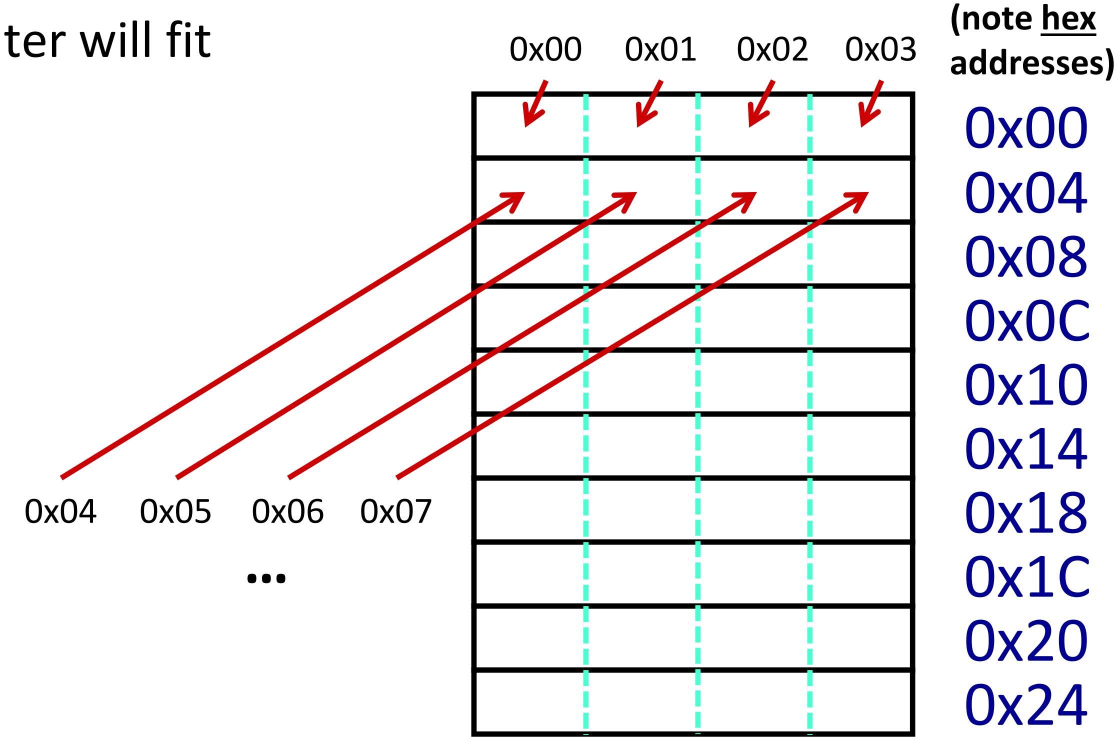
(note: decimal addresses)

- **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***



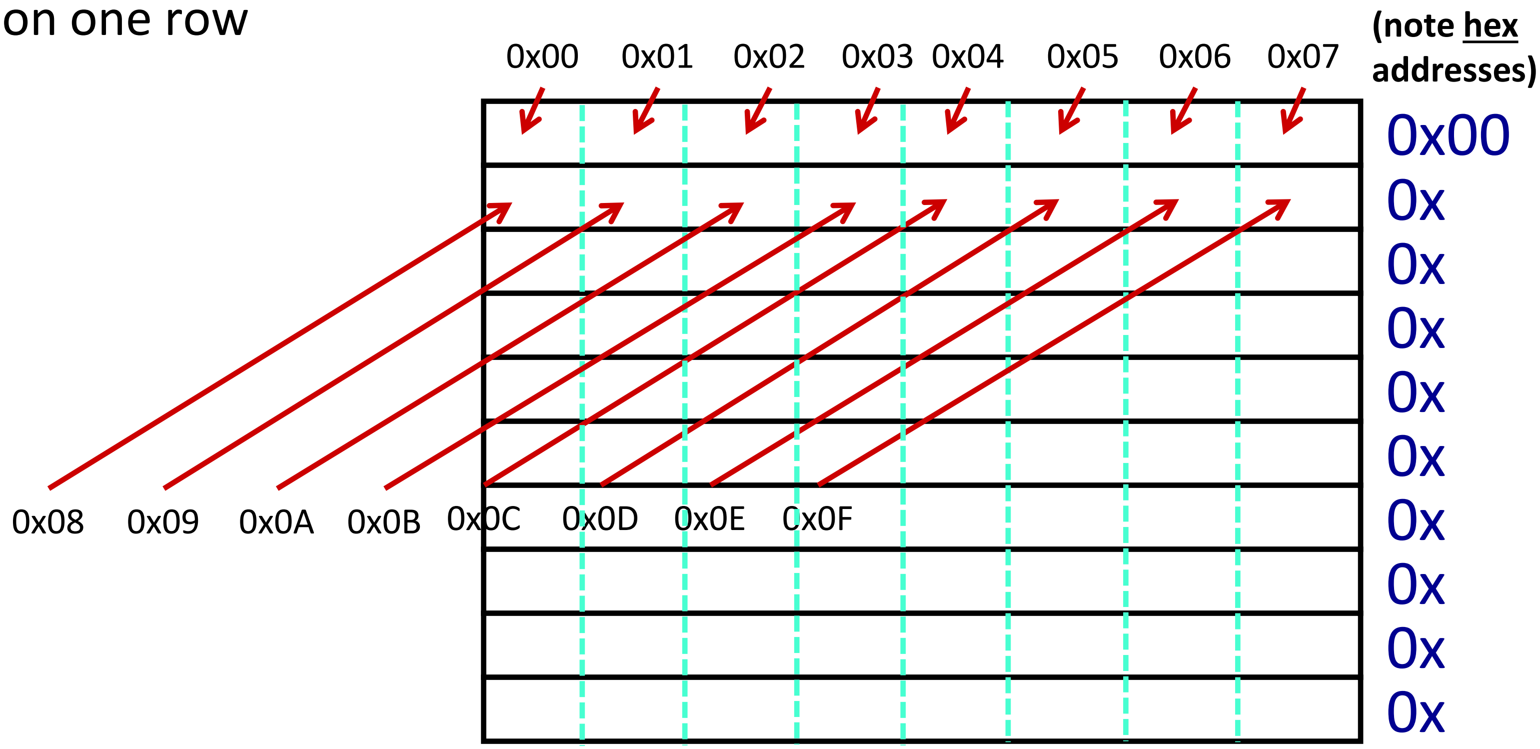
A Picture of Memory (32-bit view)

- **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



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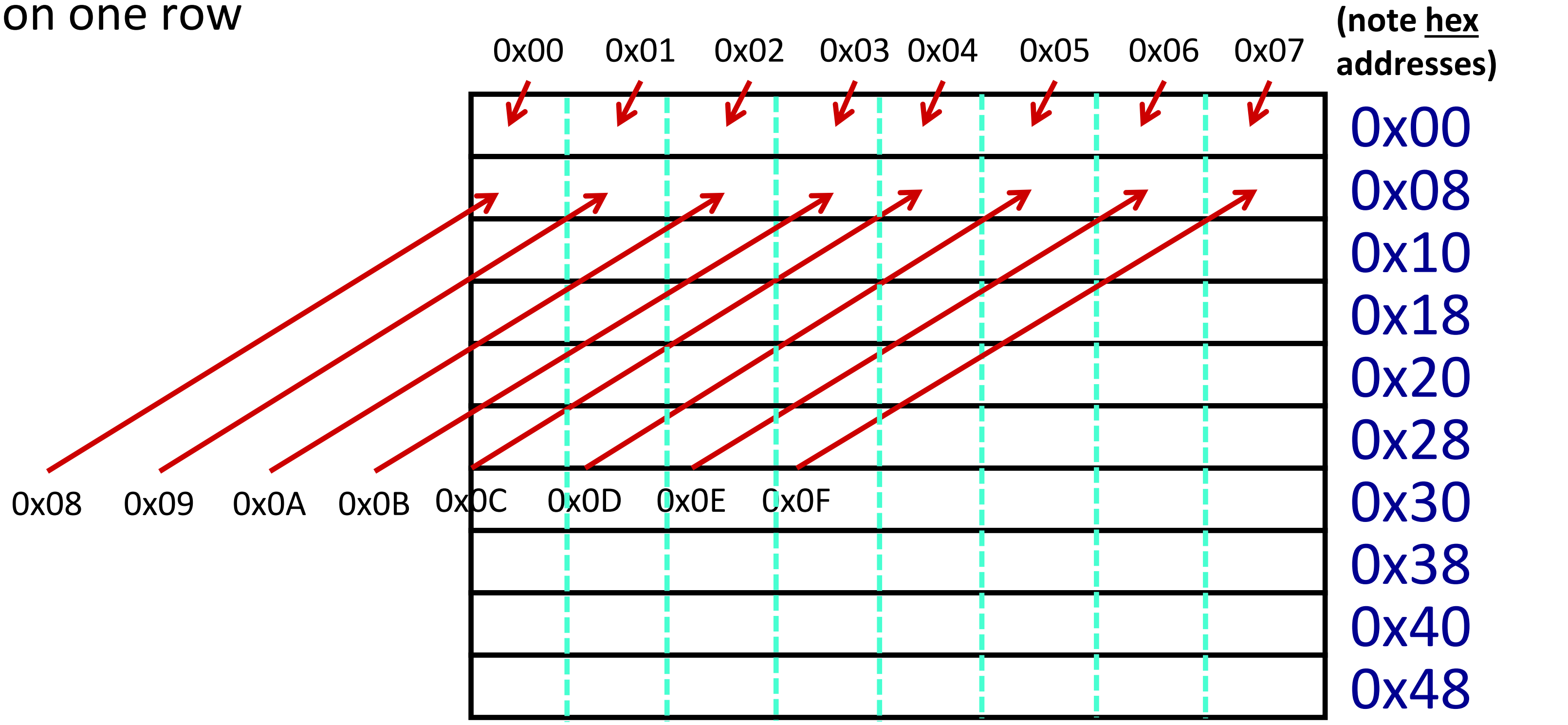


Addresses and Pointers

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

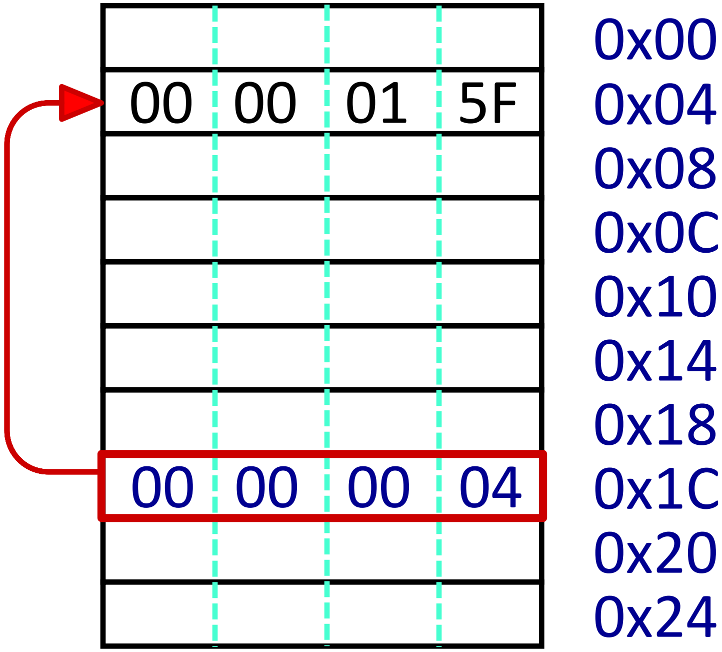
- An ***address*** is a location in memory
- A ***pointer*** is a data object that holds an address
- The value 351 is stored at address **0x04**
  - $351_{10} = 15F_{16} = \text{0x00 00 01 5F}$

				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)

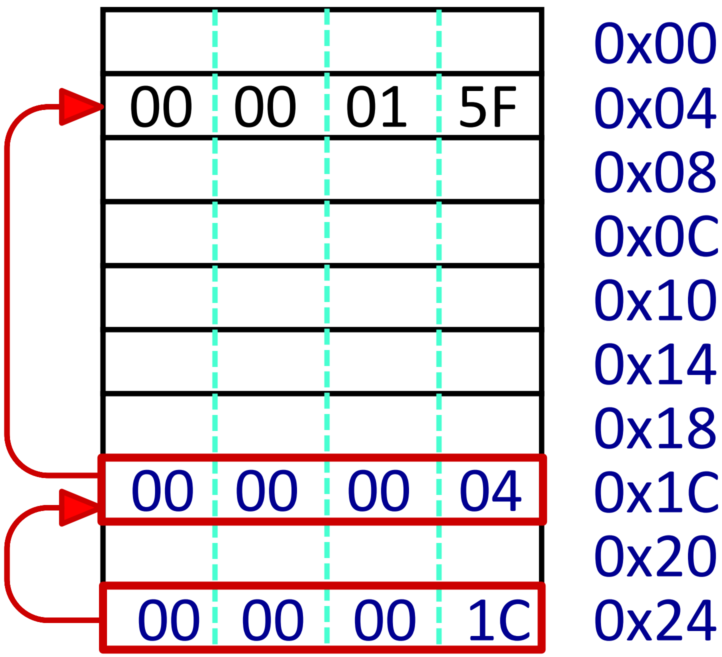
- **An *address* is a location in memory**
- **A *pointer* is a data object that holds an address**
- **The value 351 is stored at address 0x04**
  - $351_{10} = 15F_{16}$ = 0x00 00 01 5F
- **A pointer stored at address 0x1C points to address 0x04**



Addresses and Pointers

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

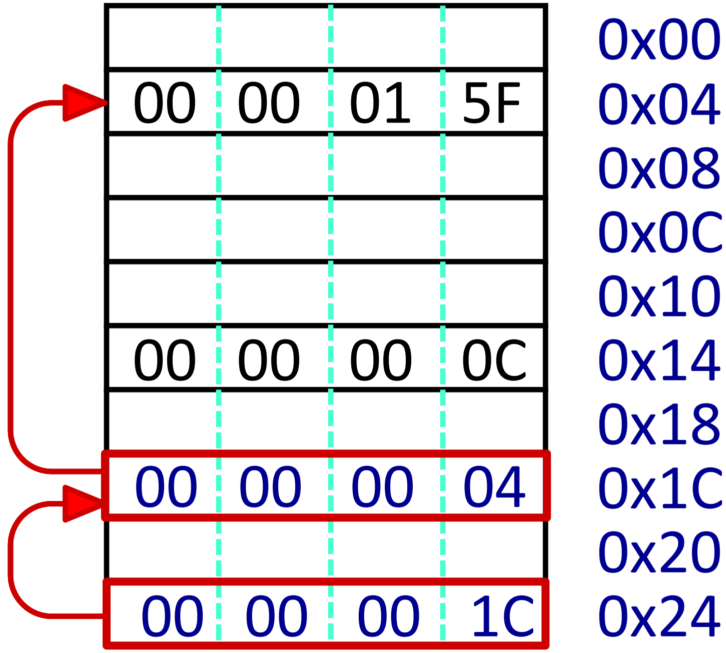
- An ***address*** is a location in memory
- A ***pointer*** is a data object that holds an address
- The value 351 is stored at address **0x04**
  - $351_{10} = 15F_{16}$ = 0x00 00 01 5F
- A pointer stored at address **0x1C** points to address **0x04**
- A pointer to a pointer is stored at address **0x24**



Addresses and Pointers

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

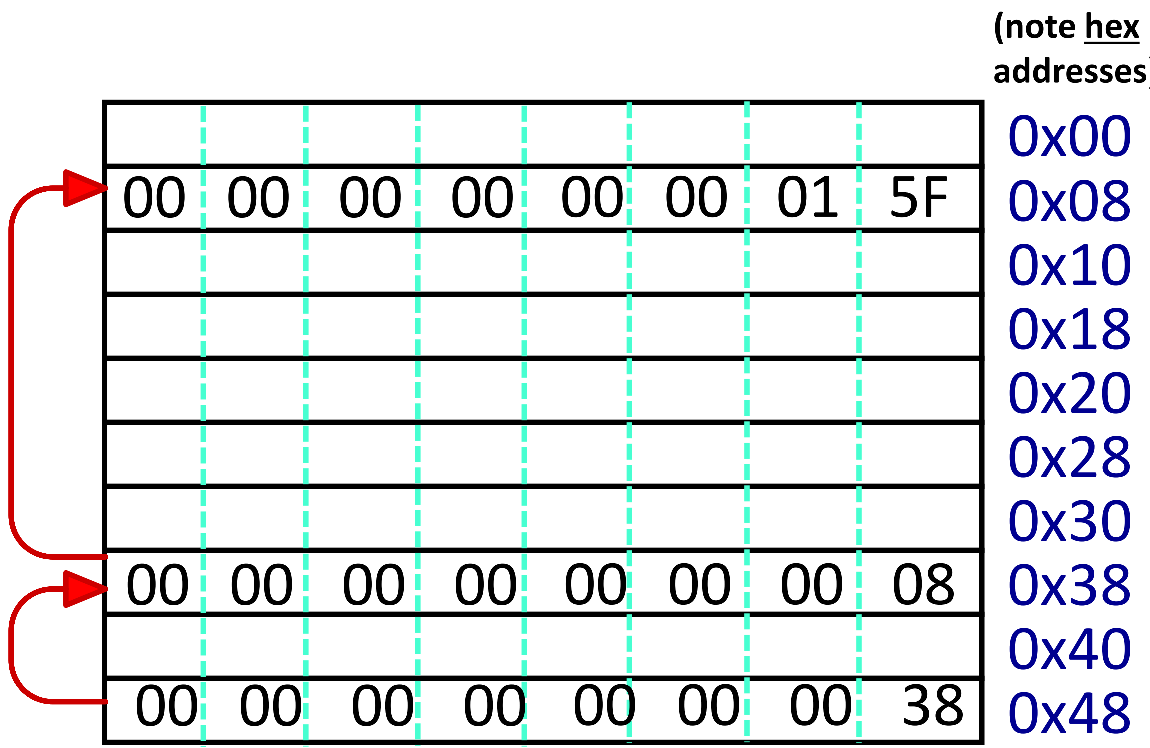
- **An *address* is a location in memory**
- **A *pointer* is a data object that holds an address.**
- **The value 351 is stored at address 0x04**
  - $351_{10} = 15F_{16}$ = 0x00 00 01 5F
- **A pointer stored at address 0x1C points to address 0x04**
- **A pointer to a pointer is stored at address 0x24**
- **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**
  - $351_{10} = 15F_{16}$ = 0x00 00 01 5F
- **A pointer stored at address 0x38 points to address 0x08**
- **A pointer to a pointer is stored at address 0x48**



Data Representations

Sizes of data types (in bytes)

Java Data Type	C Data Type	Typical 32-bit	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 long	8	8
	long double	8	16
(reference)	pointer *	4	8

address size = word size

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

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.**
- **This means we could expect these types to have starting addresses that are the following multiples:**

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?**

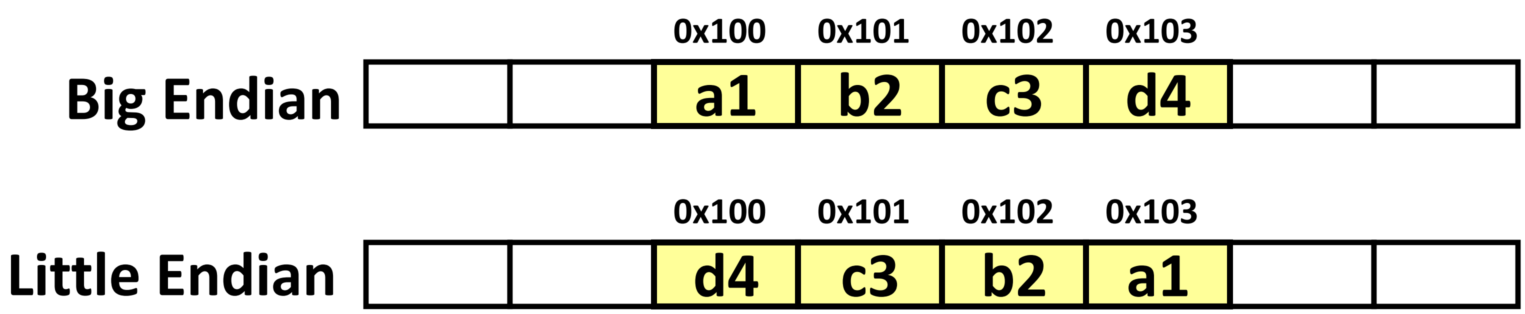
Example:

- **Store the 4-byte (32-bit) word: 0xa1 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

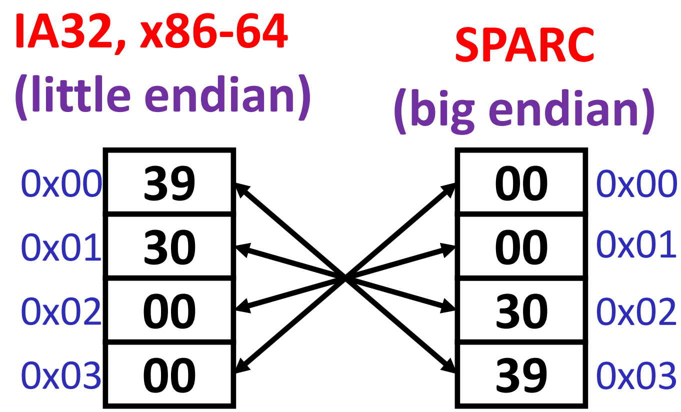
- **Big-Endian** (PowerPC, SPARC, The Internet)
  - Least significant byte has highest address
- **Little-Endian** (x86)
  - Least significant byte has lowest address
- **Example**
  - Variable has 4-byte representation **0xa1b2c3d4**
  - Address of variable is **0x100**



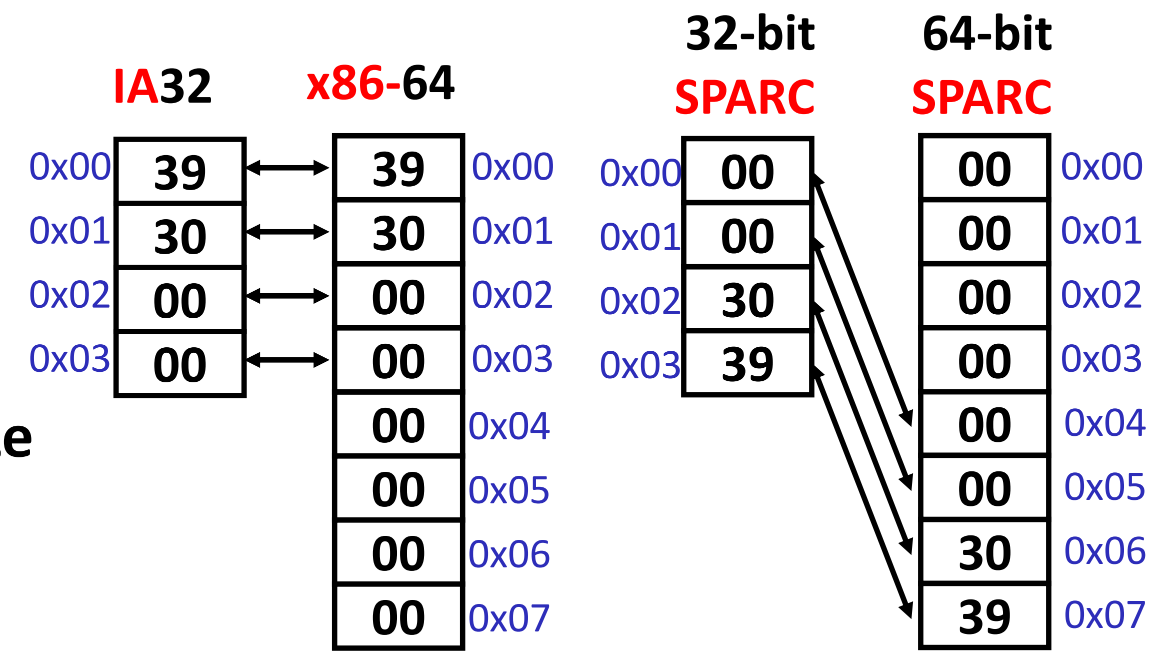
Byte Ordering Examples

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 CPU's memory)*

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
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  - add value 0x12ab to register 'ebx' *(a special location in CPU's memory)*

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**

Addresses and Pointers in C

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

```
int* ptr;
```

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

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

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

```
ptr = &x;
```

Sets **`ptr`** to the address of **`x`**. Now, "*`ptr` points to `x`*"

"Dereference `ptr`"

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

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)` ?

Assignment in C

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

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

* is also used with variable declarations

- **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

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& = 'address of'
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- **A variable is represented by a memory location**
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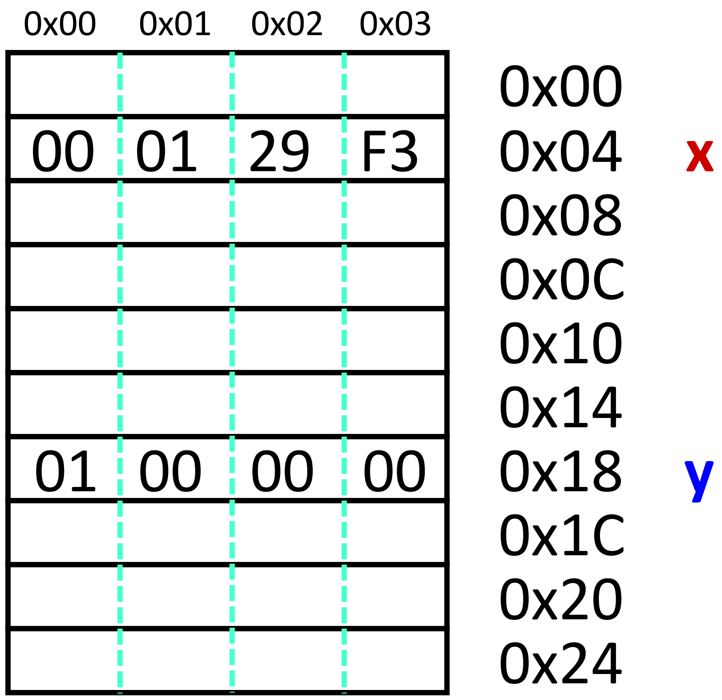

Assignment in C

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;**

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

Assignment in C

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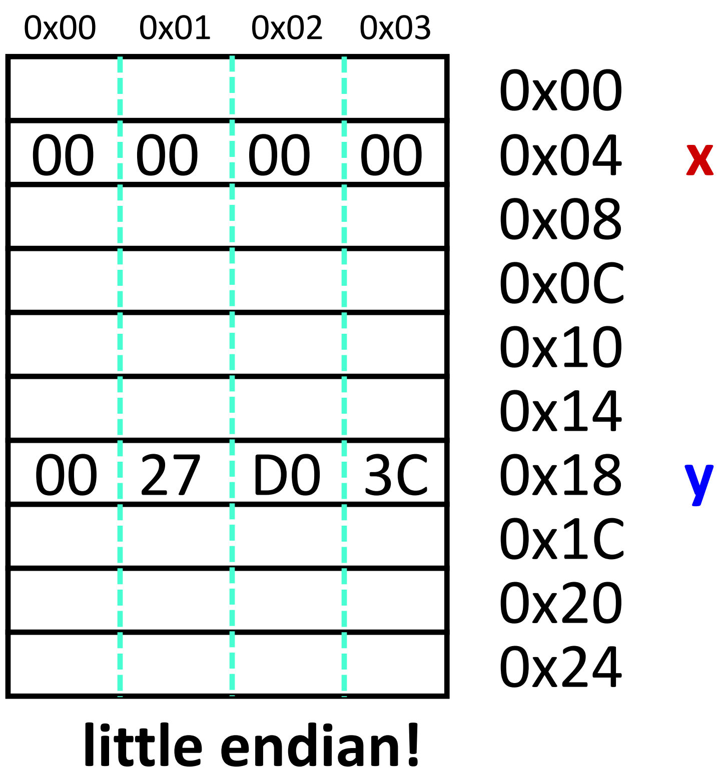
- **int x, y;**
- **x = 0;**
- **y = 0x3CD02700;**



Assignment in C

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  - 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

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(pointers are 32-bits wide)

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- **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

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- **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

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

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  - Store RHS value at LHS location
- **int x, y;**
- **x = 0;**
- **y = 0x3CD02**
- **x = y + 3;**
  - Get value at y … d 3, 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	

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

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(pointers are 32-bits wide)

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

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  - 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 ... add 3, put it in x
- **int* z = ... y + 3;**
  - G...t 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

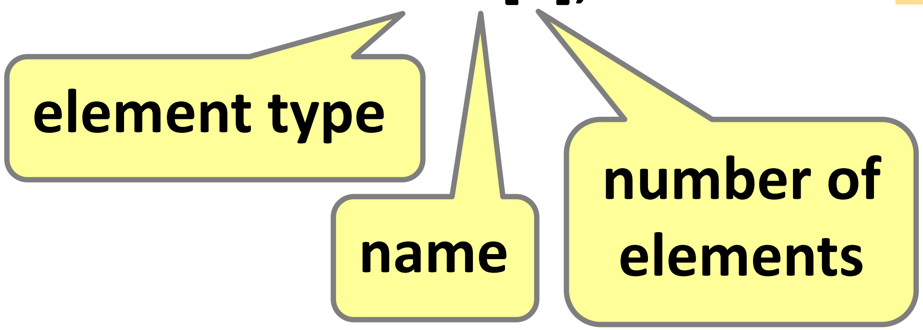
0x00	0x01	0x02	0x03		
				0x00	
03	27	D0	3C	0x04	x
				0x08	
				0x0C	
				0x10	
				0x14	
00	27	D0	3C	0x18	y
				0x1C	
24	00	00	00	0x20	z
00	27	D0	3C	0x24	

Arrays in C

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

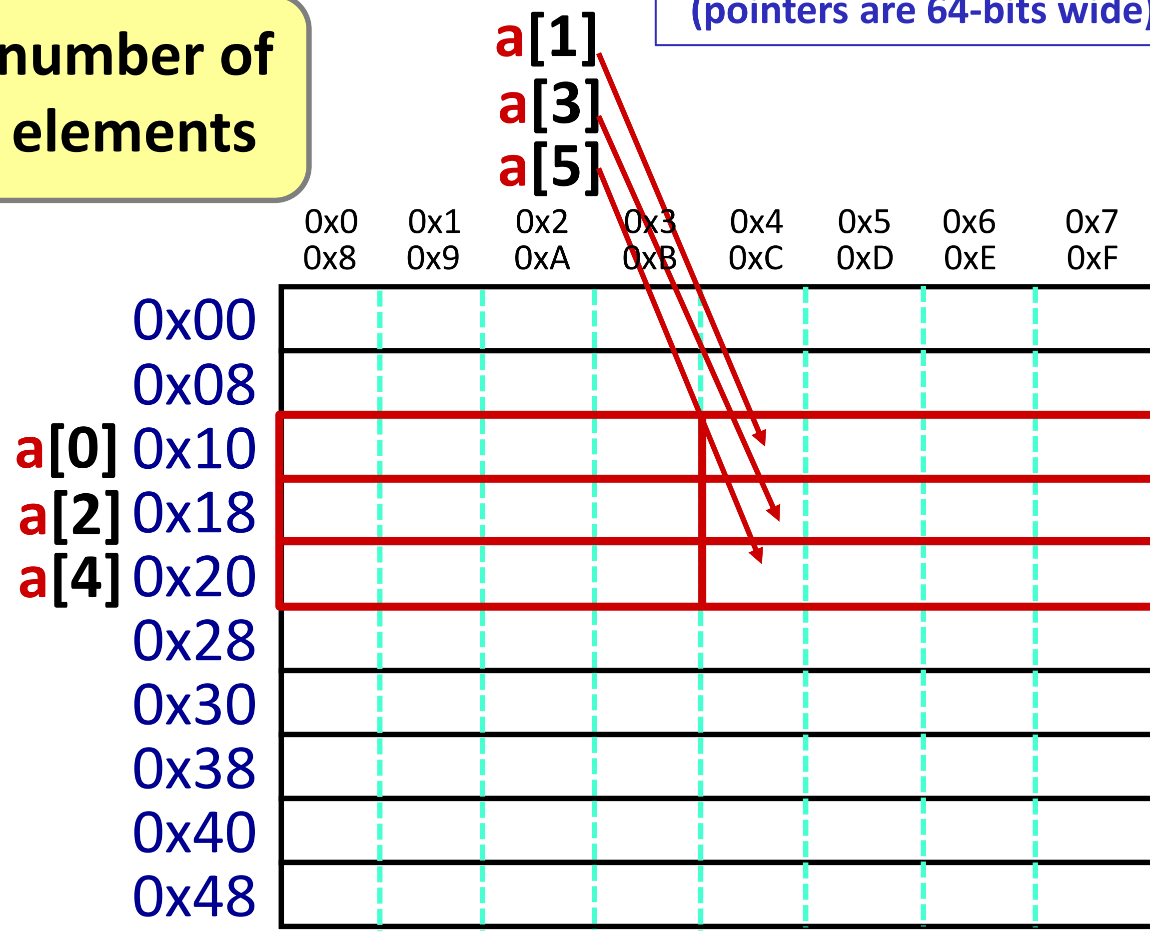
a is a name for the array's address

Declaration: int a[6];



64-bit example

(pointers are 64-bits wide)



Arrays in C

Declaration: int a[6];

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

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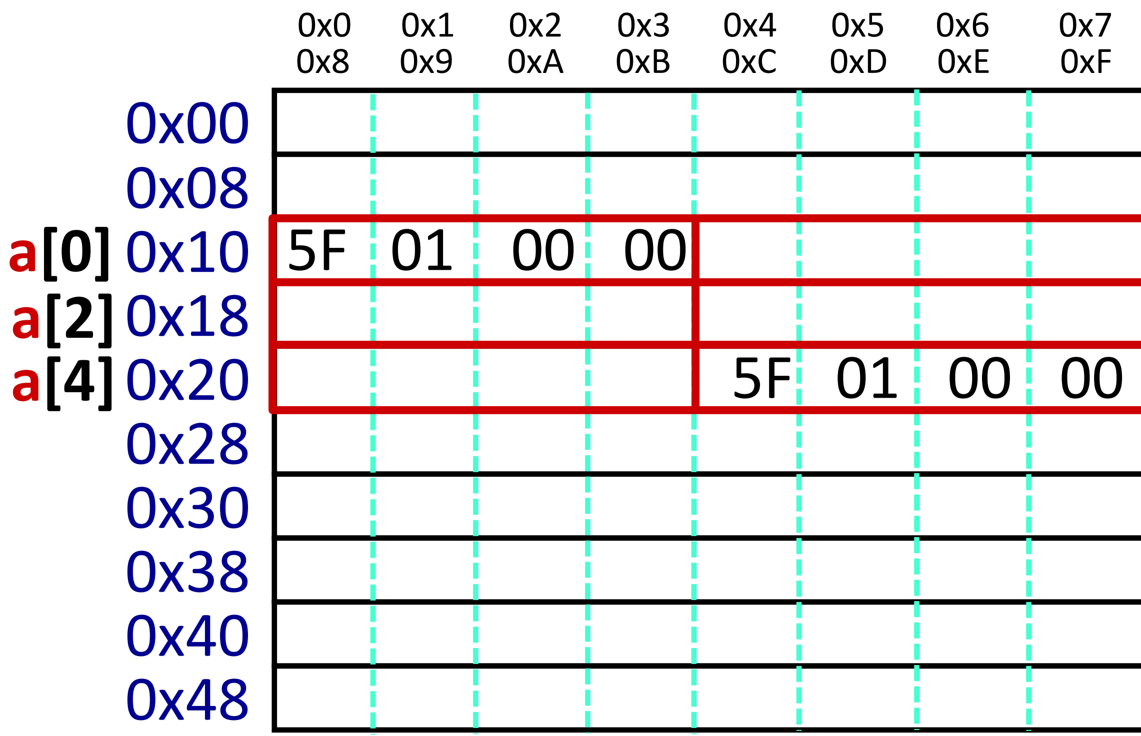
The address of a[i] is the address of a[0] plus i times the element size in bytes



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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

		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	5F	01	00	00				
a[2]	0x18								
a[4]	0x20					5F	01	00	00
	0x28	AD	0B	00	00				
	0x30								
	0x38								
	0x40								
	0x48								

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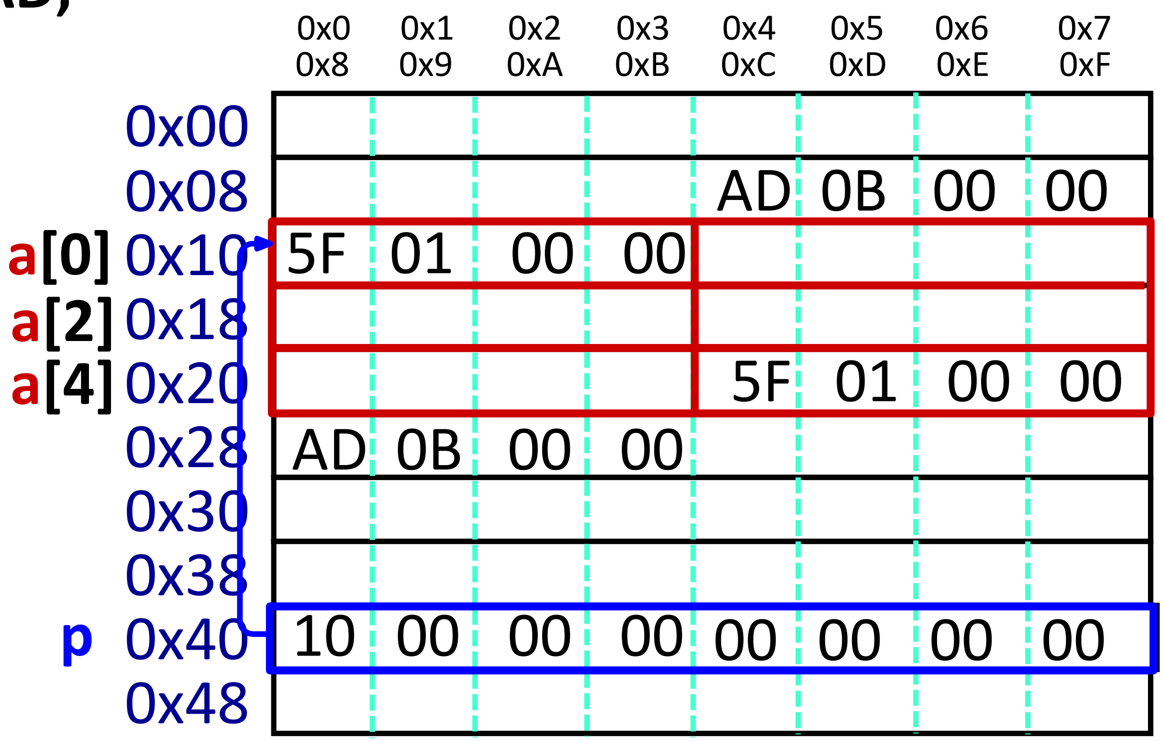
Pointers: `int* p;`

equivalent { `p = a;`
`p = &a[0];`

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



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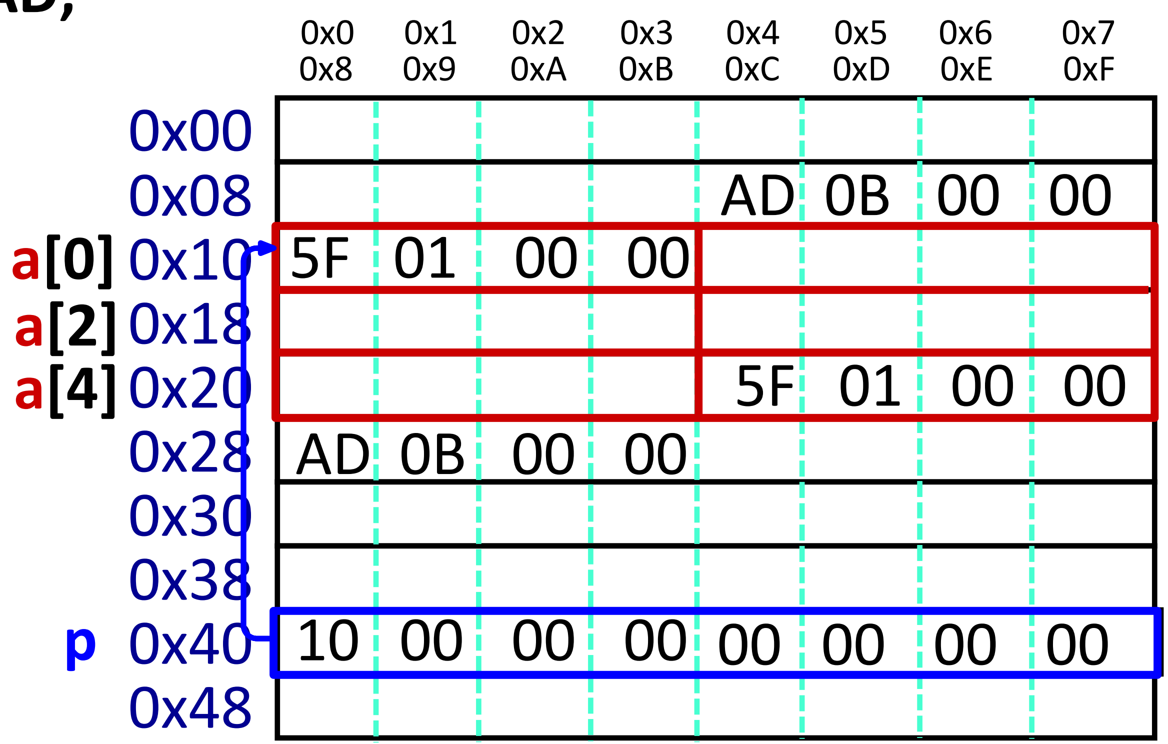

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```

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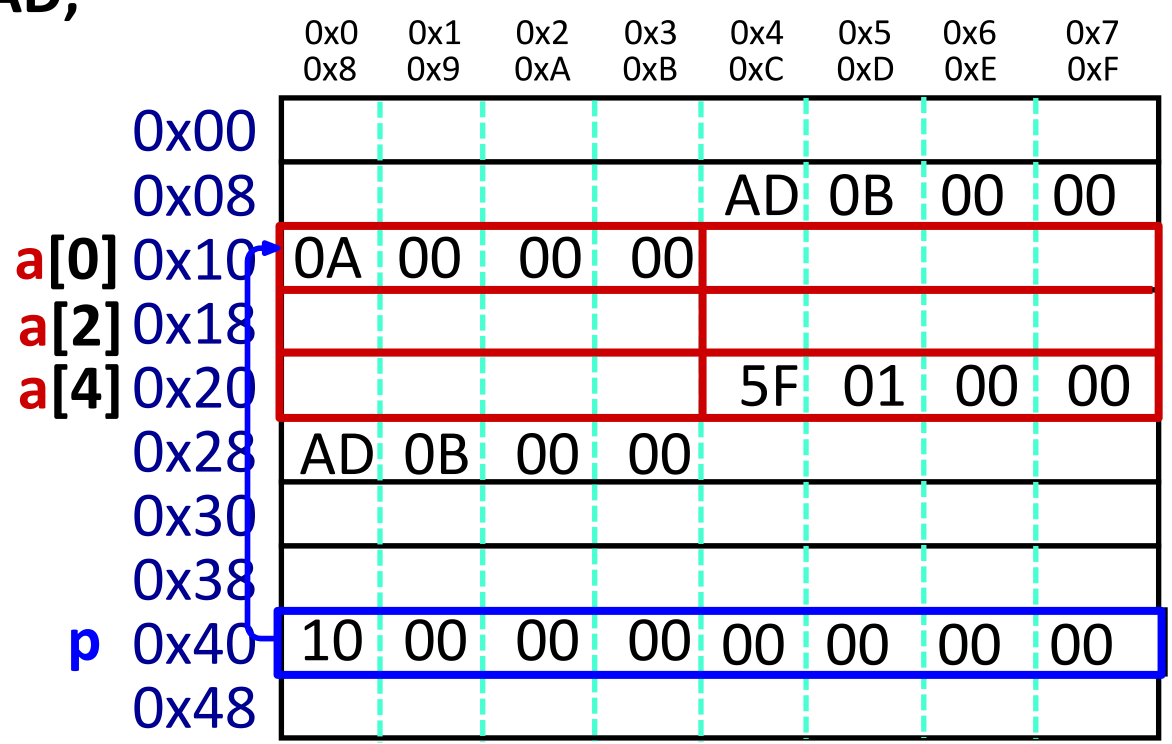
```

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



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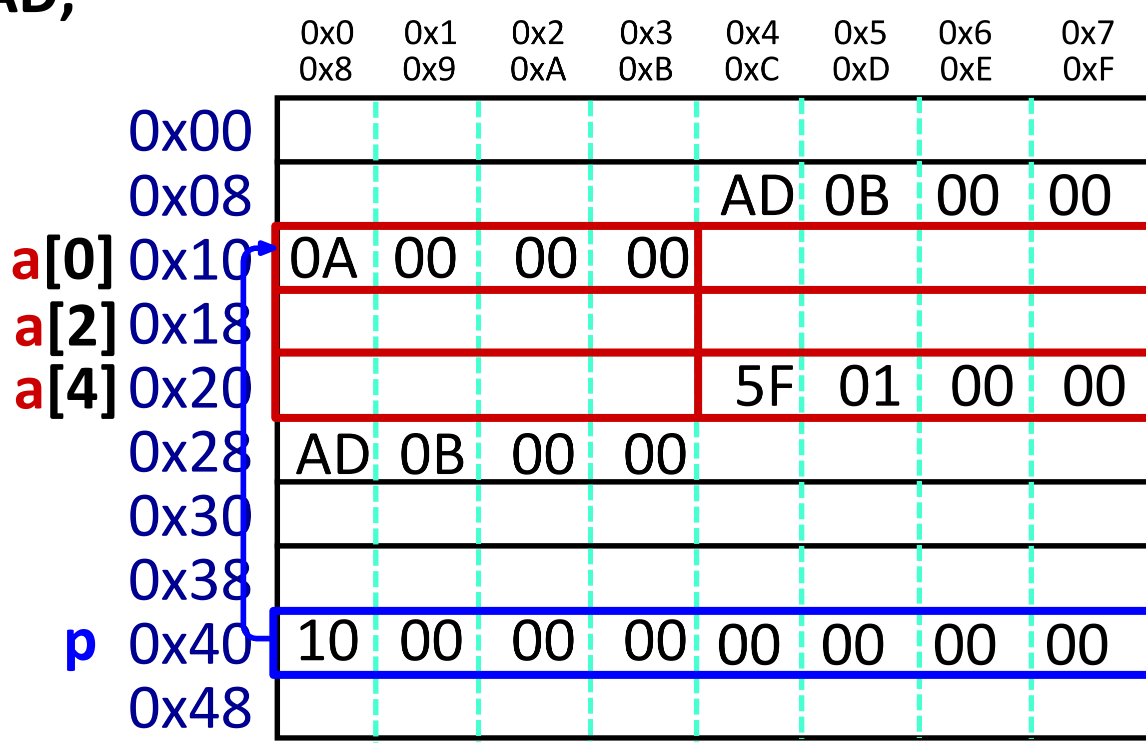
Indexing:
```
a[0] = 0x015f;
a[5] = a[0];
```

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

Pointers:
```
int* p;
p = a;
p = &a[0];
*p = 0xA;
p[1] = 0xB;
```

equivalent: `p = a;` and `p = &a[0];`



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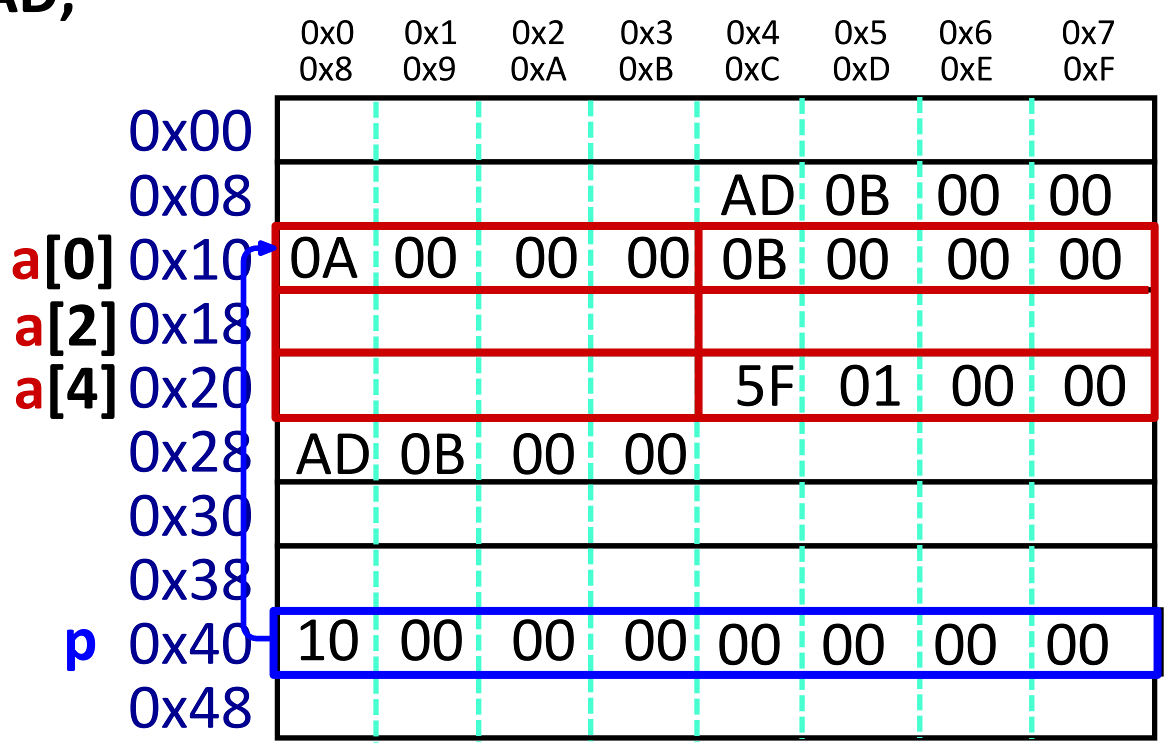
a[-1] = 0xBAD;
```

Pointers: `int* p;`

equivalent {
```
p = a;
p = &a[0];
```
}
```
*p = 0xA;
p[1] = 0xB;
```



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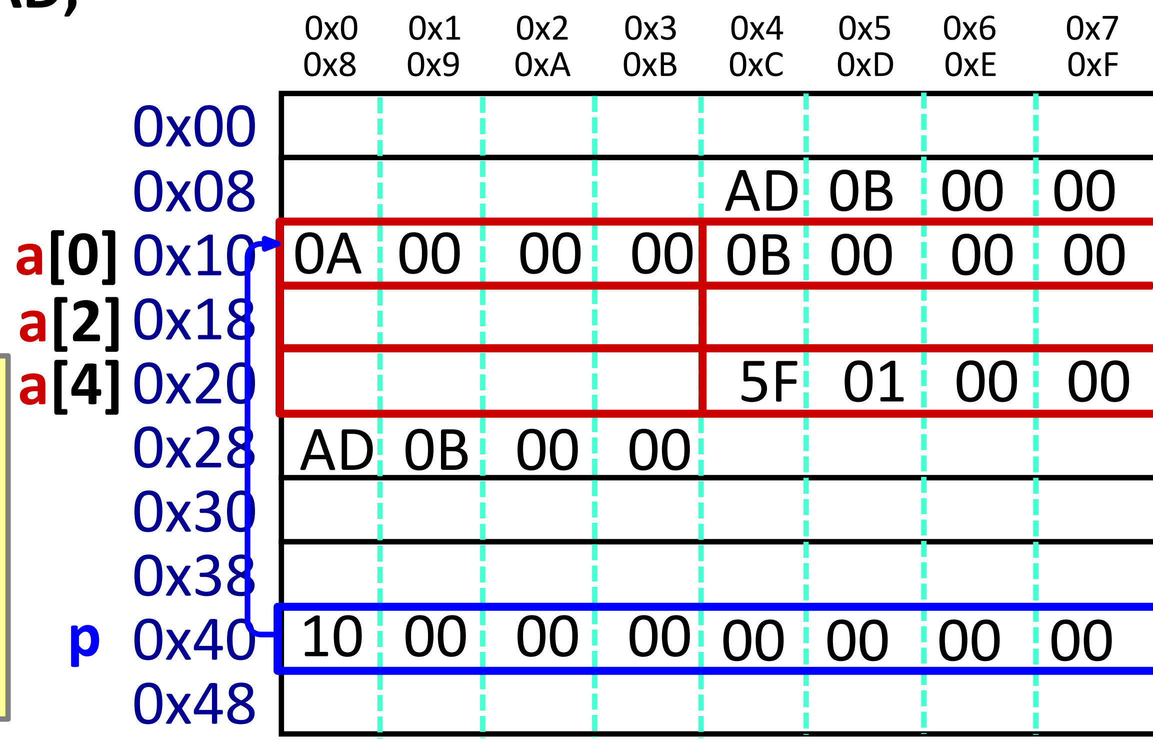
No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers:
```
int* p;
```

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

```
p[1] = 0xB;
```

array indexing = address arithmetic
Both are scaled by the size of the type



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equivalent { `p = a;` / `p = &a[0];` }

`*p = 0xA;`

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

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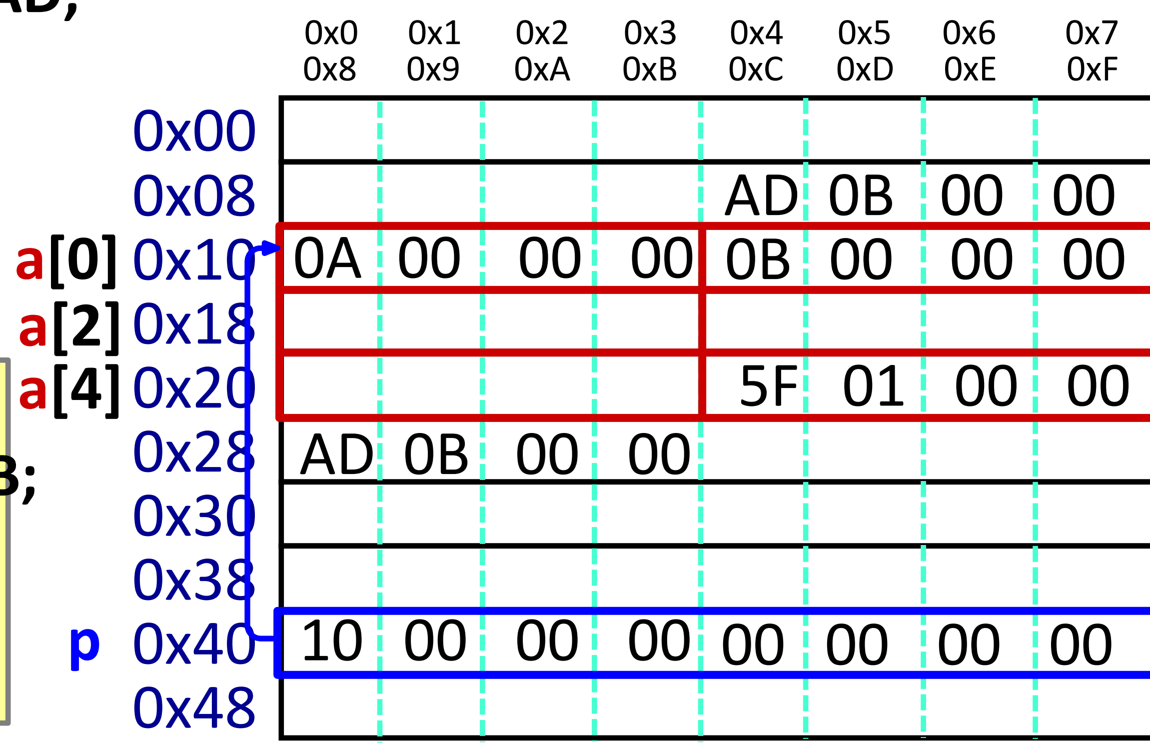

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```
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```

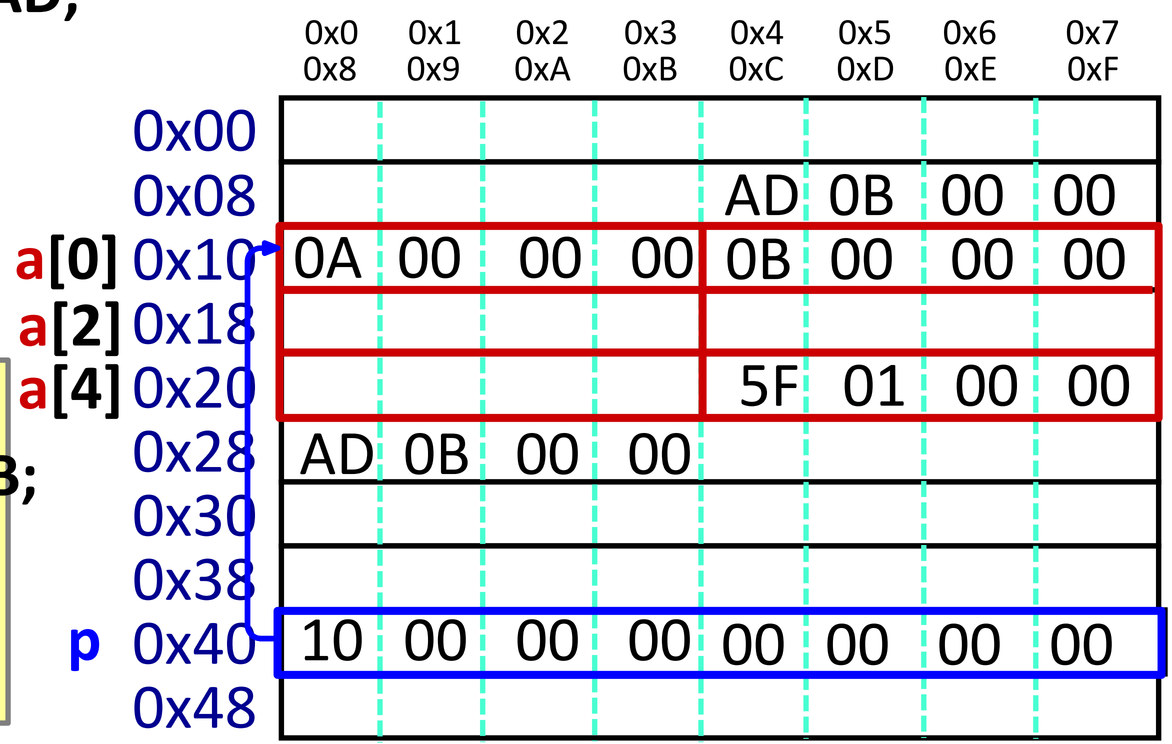
No bounds check:
```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers: `int* p;`

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

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

array indexing = address arithmetic
Both are scaled by the size of the type



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```
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p = &a[0];
```
}
```
*p = 0xA;
```

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

array indexing = address arithmetic

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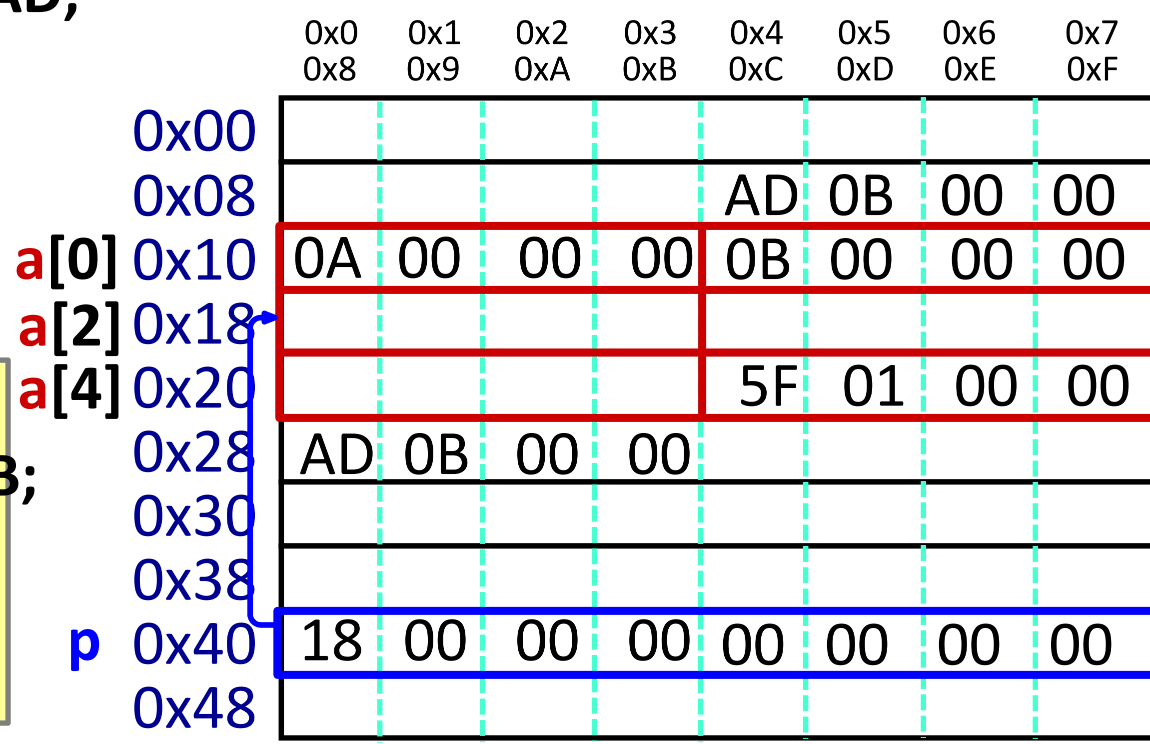

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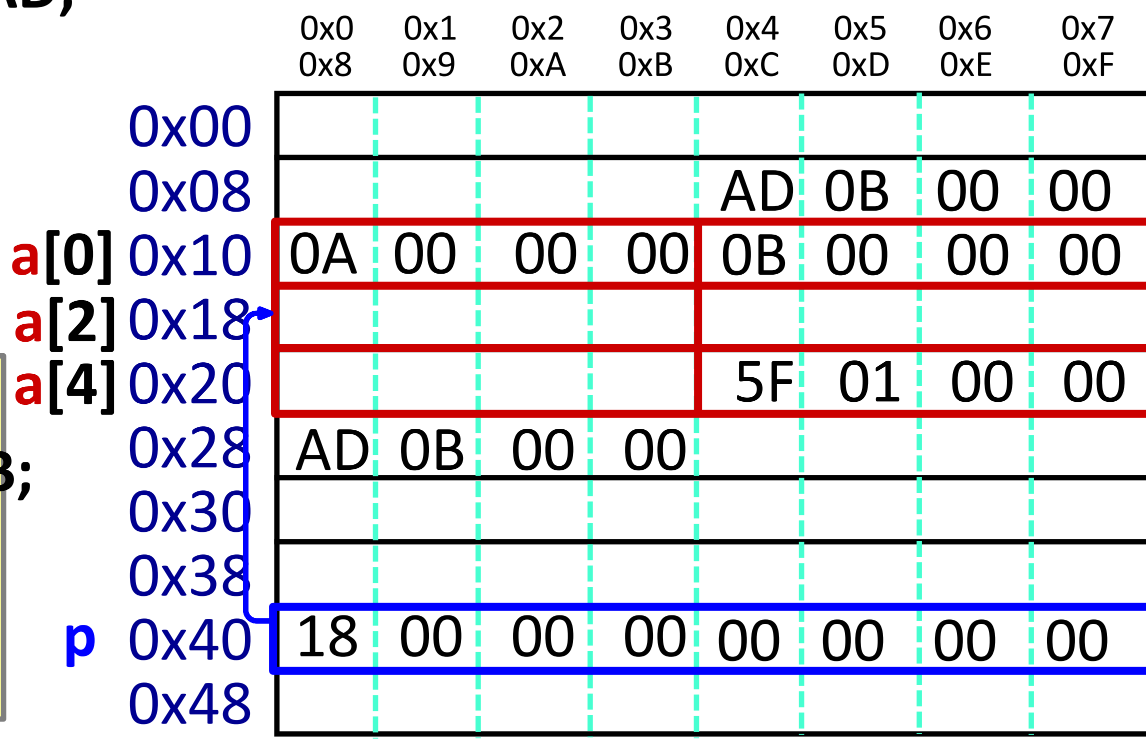
equivalent {
```
p = a;
p = &a[0];
```
```
*p = 0xA;
```

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

array indexing = address arithmetic
Both are scaled by the size of the type

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



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Indexing:

```
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a[5] = a[0];
```

No bounds check:

```
a[6] = 0xBAD;
a[-1] = 0xBAD;
```

Pointers: `int* p;`

equivalent {

```
p = a;
p = &a[0];
```

```
*p = 0xA;
```

equivalent {

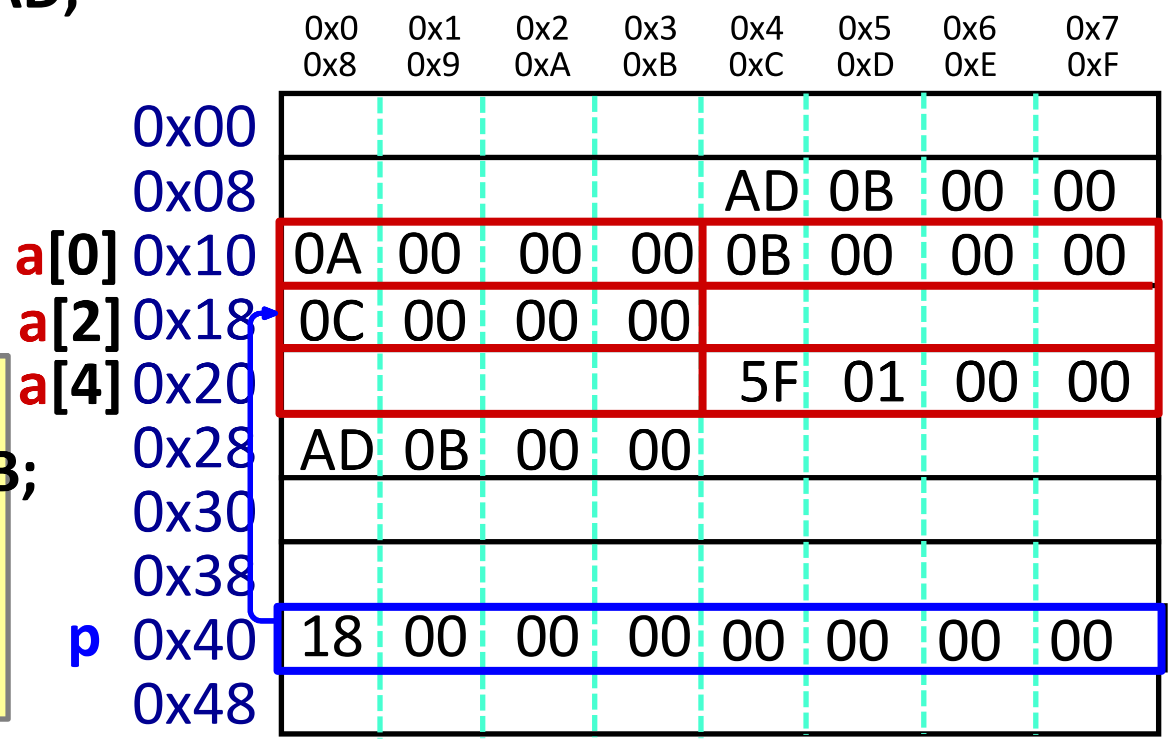
```
p[1] = 0xB;
*(p + 1) = 0xB;
```

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

array indexing = address arithmetic

Both are scaled by the size of the type

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



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

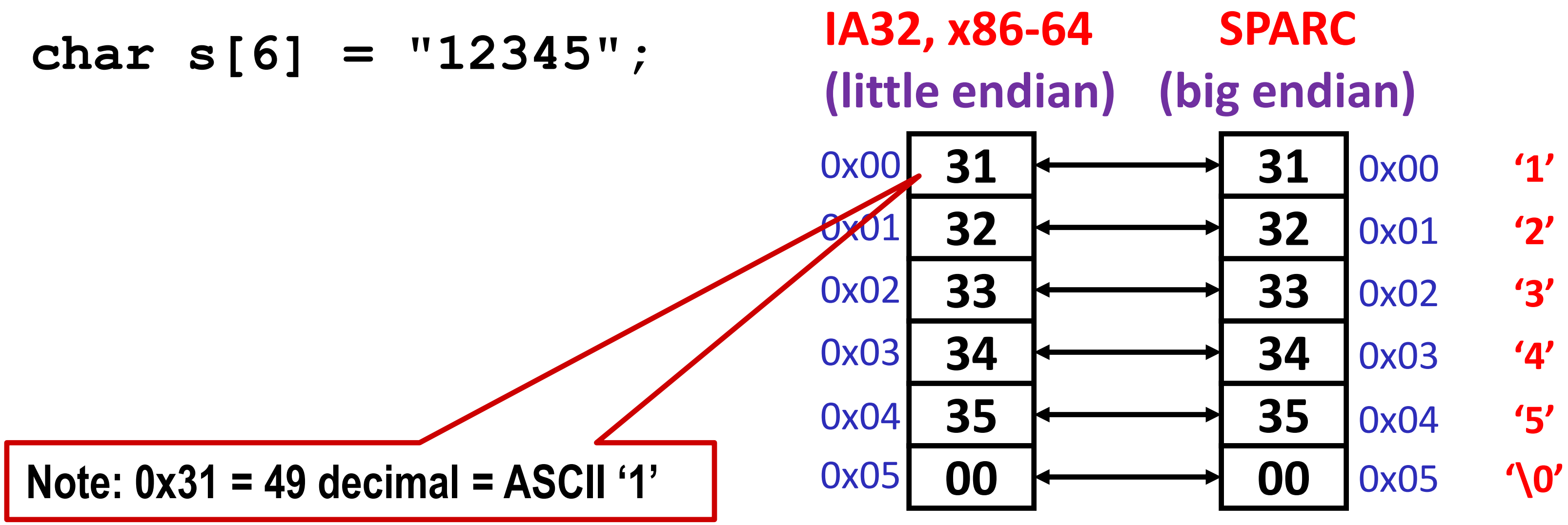
- Why do we put a 0, or null zero, at the end of the string?
  - Note the special symbol: string[12] = '\0';

- 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
```

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

&	0	1
0	0	0
1	0	1

~	
0	1
1	0

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    ~(A & B) = ~A | ~B

&	0	1
0	0	0
1	0	1

|	0	1
0	0	1
1	1	1

^	0	1
0	0	1
1	1	0

~	
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, …, *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`

    $\sim 01000001_2 \texttt{-->} 10111110_2$
  - `~0x00 -->  0xFF`

    $\sim 00000000_2 \texttt{-->} 11111111_2$
  - `0x69 & 0x55  -->  0x41`

    $01101001_2 \;\&\; 01010101_2 \texttt{-->} 01000001_2$
  - `0x69 | 0x55  -->  0x7D`

    $01101001_2 \mid 01010101_2 \texttt{-->} 01111101_2$
- **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`

  - `0x69 && 0x55   -->   0x01`
  - `0x69 || 0x55   -->   0x01`
  - `p && *p++` (avoids null pointer access, null pointer = 0x0000 0000 0000 0000)