# Computer Systems

CSE 410 Autumn 2013

2 – Memory and its Data

# 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
```

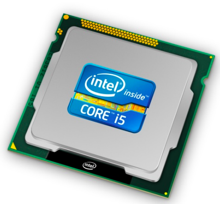
**Machine code:**

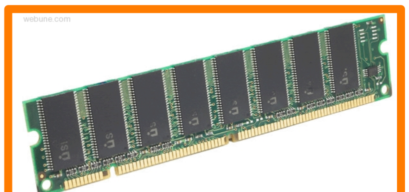
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

**OS:**

Windows 8   Mac

**Computer system:**



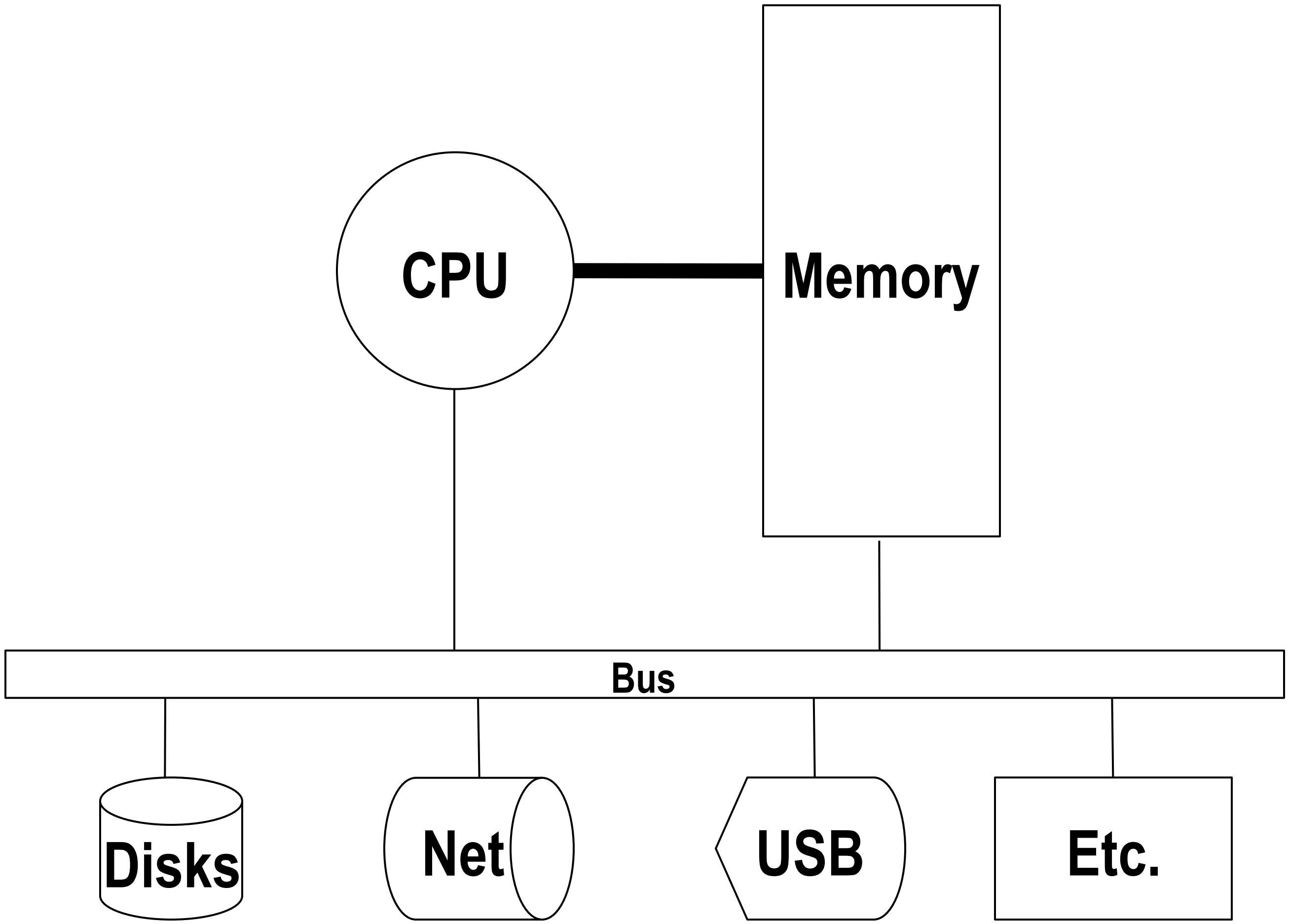



# Memory, Data, and Addressing

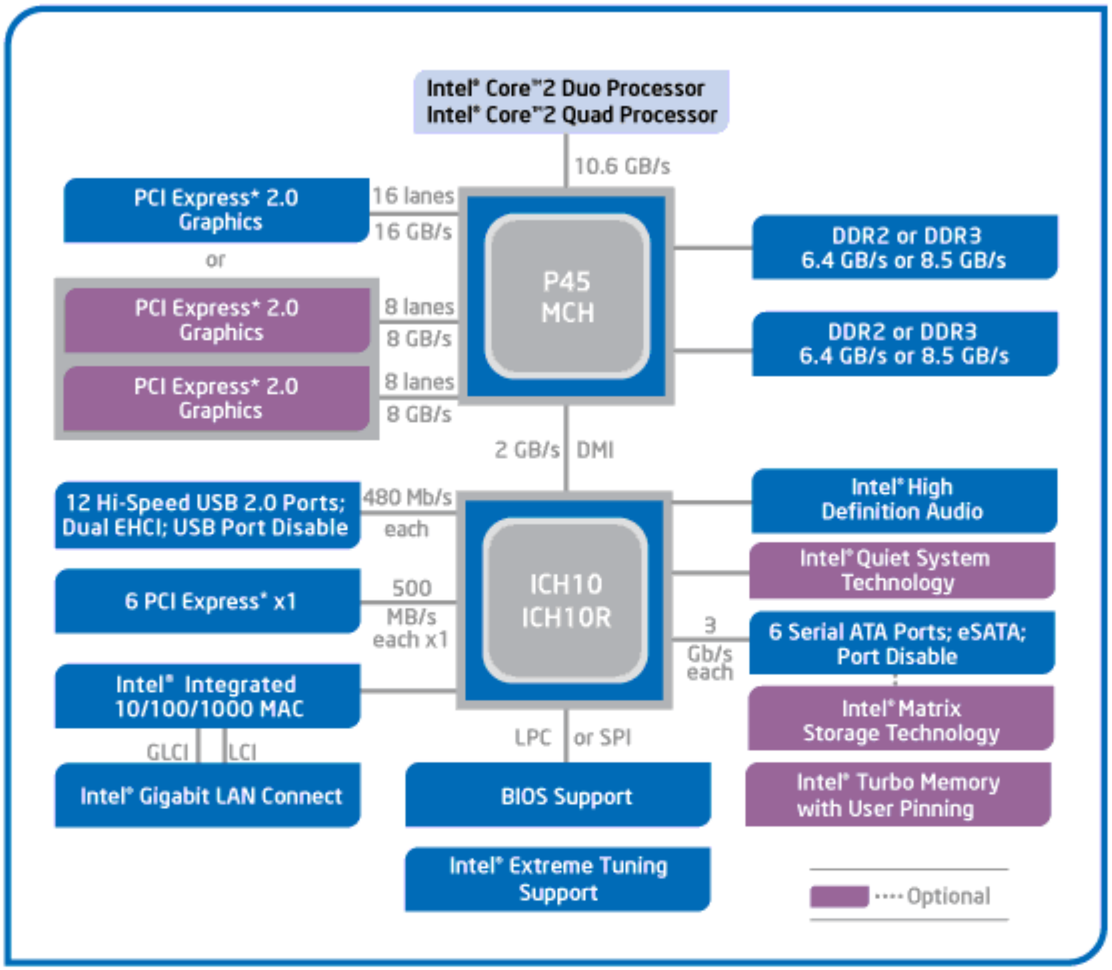
- <u>Preliminaries</u>
- Representing information as bits and bytes
- Organizing and addressing data in memory
- Manipulating data in memory using C
- Boolean algebra and bit-level manipulations

- Reading: Bryant/O'Hallaron sec. 2.1

# Hardware: Logical View

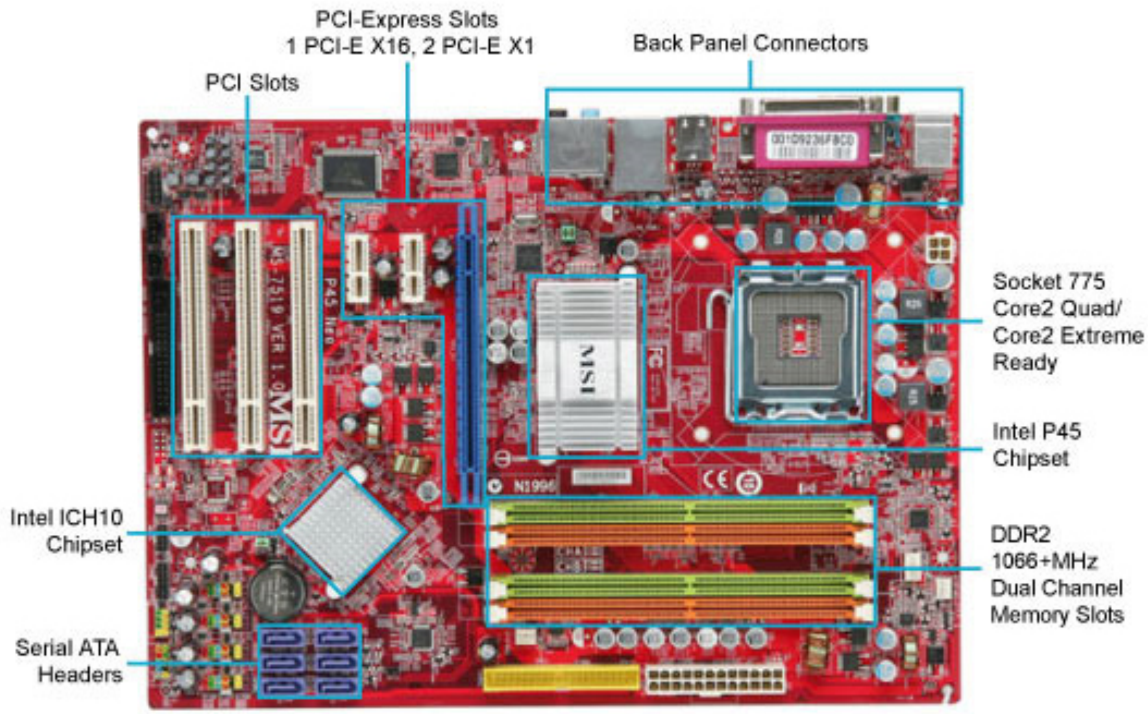


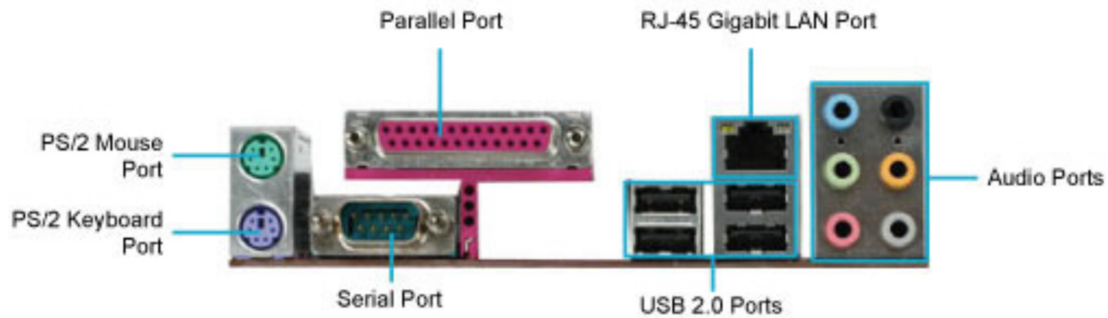
# Hardware: Semi-Logical View



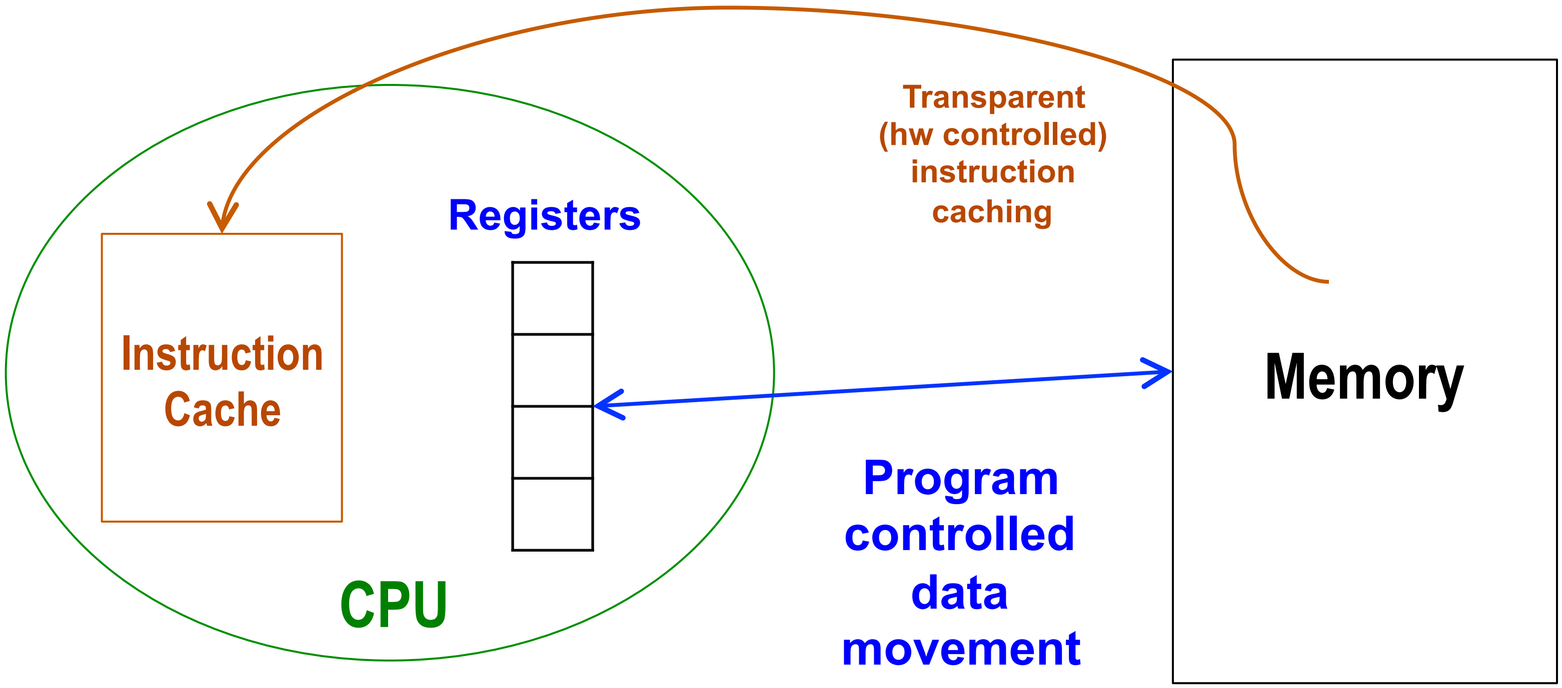

Intel® P45 Express Chipset Block Diagram

# Hardware: Physical View



# CPU "Memory": Registers and Instruction Cache




- **There are a fixed number of <u>registers</u> in the CPU**
  - Registers hold data
- **There is an <u>I-cache</u> in the CPU that holds recently fetched instructions**
  - If you execute a loop that fits in the cache, the CPU goes to memory for those instructions only once, then executes it out of its cache
- ***This slide is just an introduction.***
  ***We'll see a fuller explanation later in the course.***

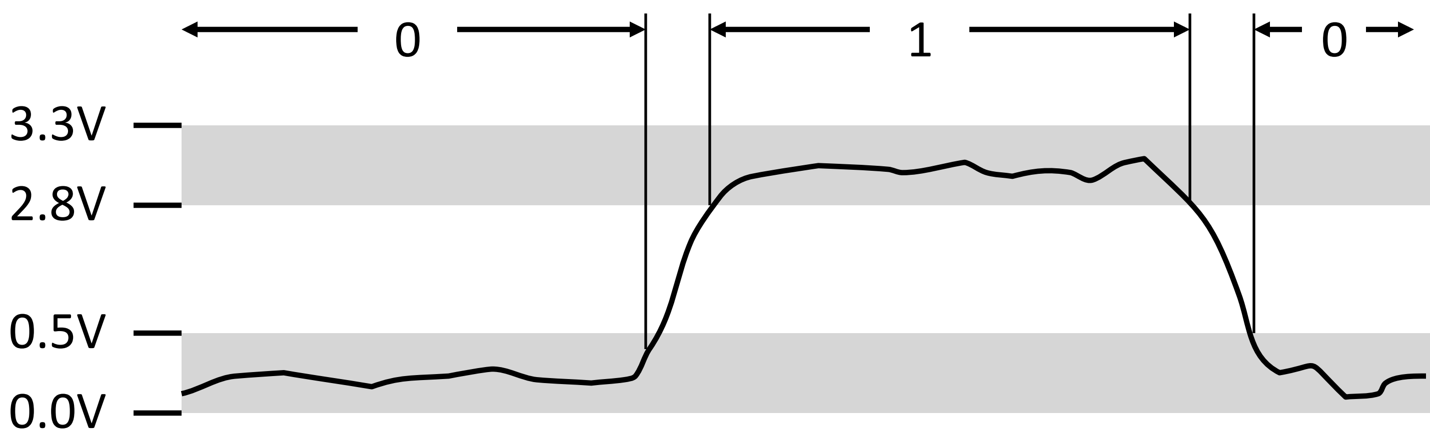
# Performance: It's Not Just CPU Speed

- **Data and instructions reside in memory**
  - To execute an instruction, it must be fetched into the CPU
  - Next, the data on the which the instruction operates must be fetched from memory and brought to the CPU
- **CPU <-> Memory bandwidth can limit performance**
  - Improving performance 1: hardware improvements to increase memory bandwidth (e.g., DDR → DDR2 → DDR3)
  - Improving performance 2: move less data into/out of the CPU
    - Put some "memory" in the CPU chip itself (this is "cache" memory)

# Binary Representations

- **Base 2 number representation**
  - 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



# Memory, Data, and Addressing

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# Encoding Byte Values

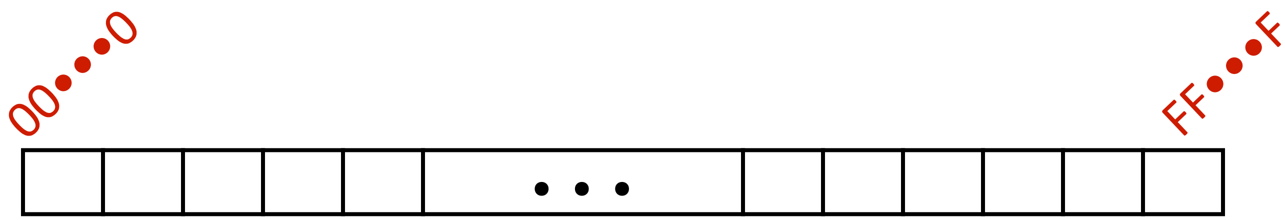
- **Binary** $\mathbf{00000000_2}$ **--** $\mathbf{11111111_2}$
  - Byte = 8 bits (binary digits)
  - Example: $00101011_2 = 32+8+2+1 = 43_{10}$
  - Example: $26_{10} = 16+8+2 = 00101010_2$
- **Decimal** $\mathbf{0_{10}}$ **--** $\mathbf{255_{10}}$
- **Hexadecimal** $\mathbf{00_{16}}$ **--** $\mathbf{FF_{16}}$
  - Groups of 4 binary digits
  - Byte = 2 hexadecimal (hex) or base 16 digits
  - Base-16 number representation
  - Use characters ‘0’ to ‘9’ and ‘A’ to ‘F’
  - Write $FA1D37B_{16}$ in C
    - as `0xFA1D37B` or `0xfa1d37b`

| 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 |

# What is memory, really?

- How do we find data in memory?

# Byte-Oriented Memory Organization



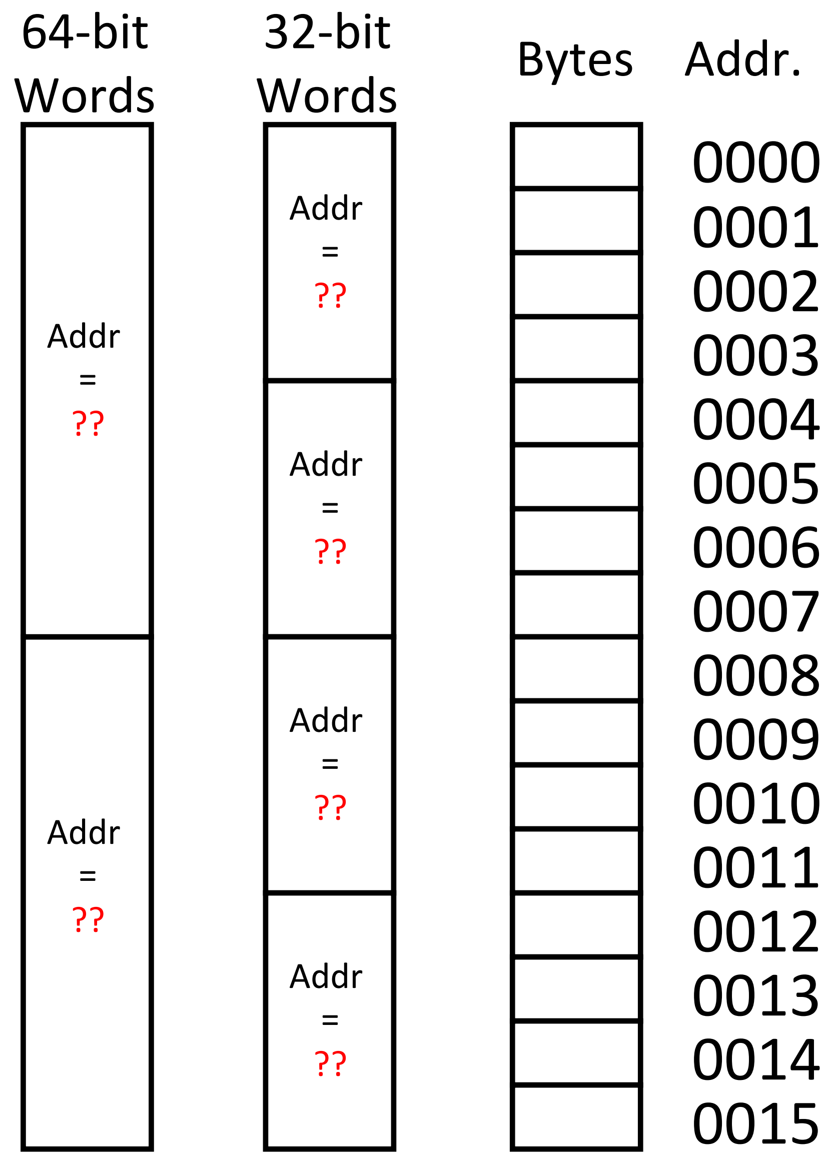

- **Programs refer to addresses**
  - Conceptually, a very large array of bytes, each with an *address* (index)
  - System provides an address space private to each "process"
    - Process = program being executed + its data + its "state"
    - Program can clobber its own data, but not that of others
    - Clobbering code or "state" often leads to crashes (or security holes)
- **Compiler + run-time system control memory allocation**
  - Where different program objects should be stored
  - All allocation within a single address space

# Machine Words

- **Machine has a "word size"**
  - Nominal size of integer-valued data
    - *Including addresses*
  - Until recently, most machines used 32 bits (4 bytes) words
    - Limits addresses to 4GB
    - Became too small for memory-intensive applications
  - More recent and high-end systems use 64 bits (8 bytes) words
    - Potential address space ≈ 1.8 X $10^{19}$ bytes (18 EB – exabytes)
    - x86-64 supports 48-bit physical addresses: 256 TB (terabytes)
  - For backward-compatibility, many CPUs support different word sizes
    - Always a power-of-2 in the number of bytes: 1, 2, 4, 8, …

# Word-Oriented Memory Organization

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



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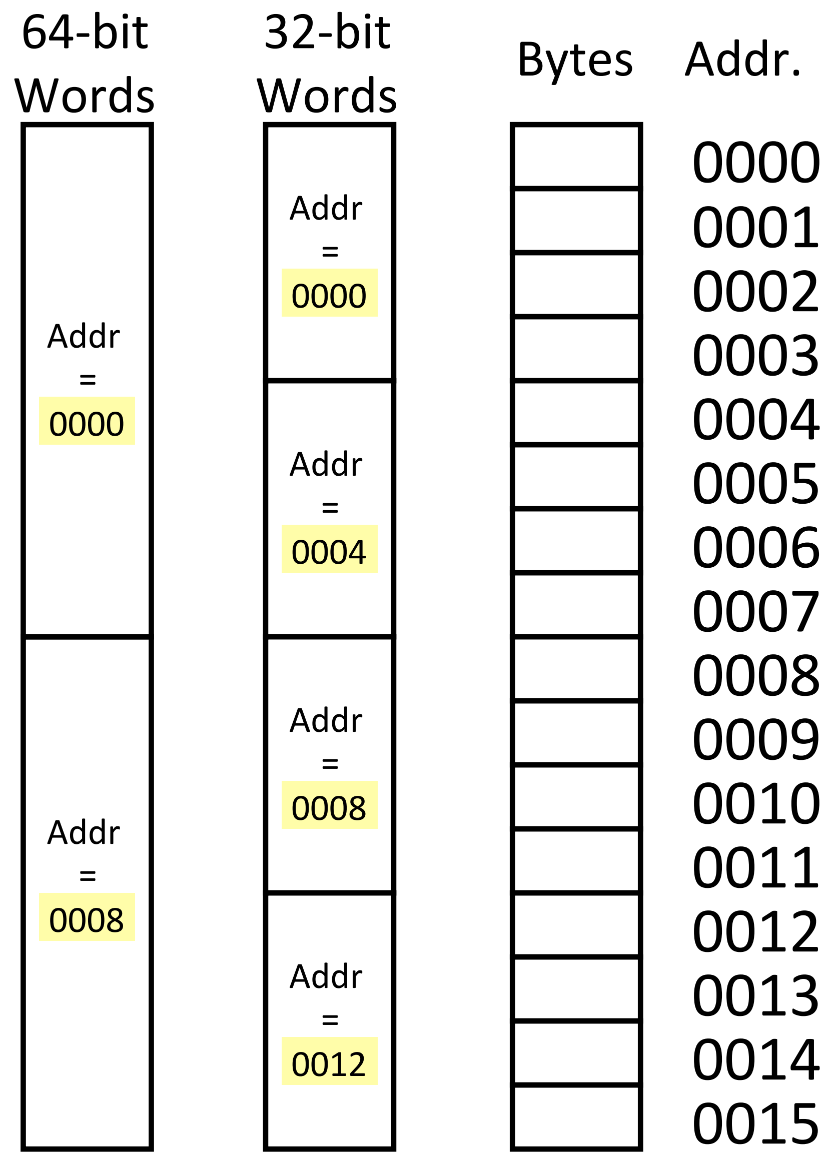

# Memory, Data, and Addressing

- Preliminaries
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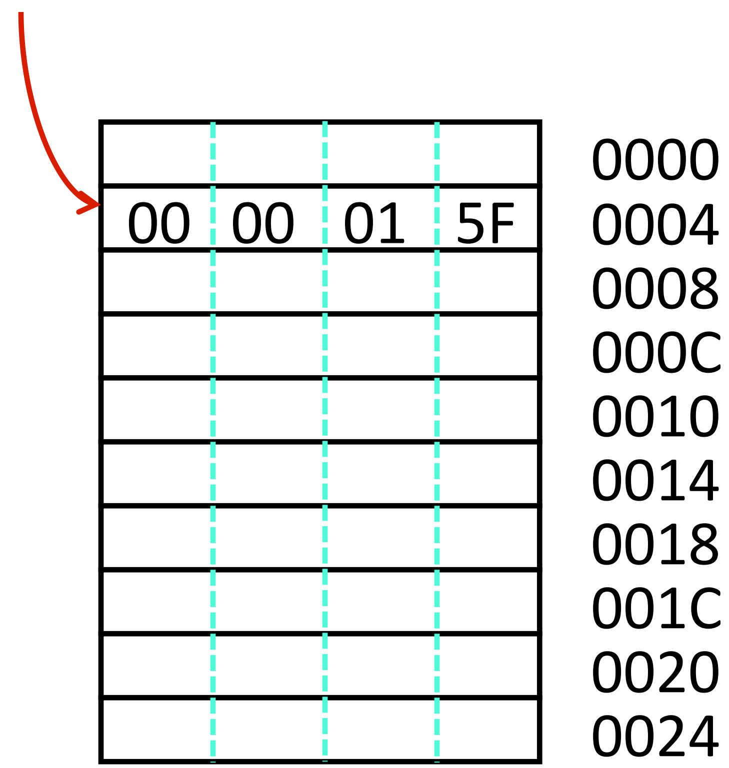
# Addresses and Pointers

- **Address is a *location* in memory**
- **Pointer is a data object that *contains an address***
- **Address 0004 stores the value 351 (or $15F_{16}$)**



# Addresses and Pointers

- **Address is a *location* in memory**
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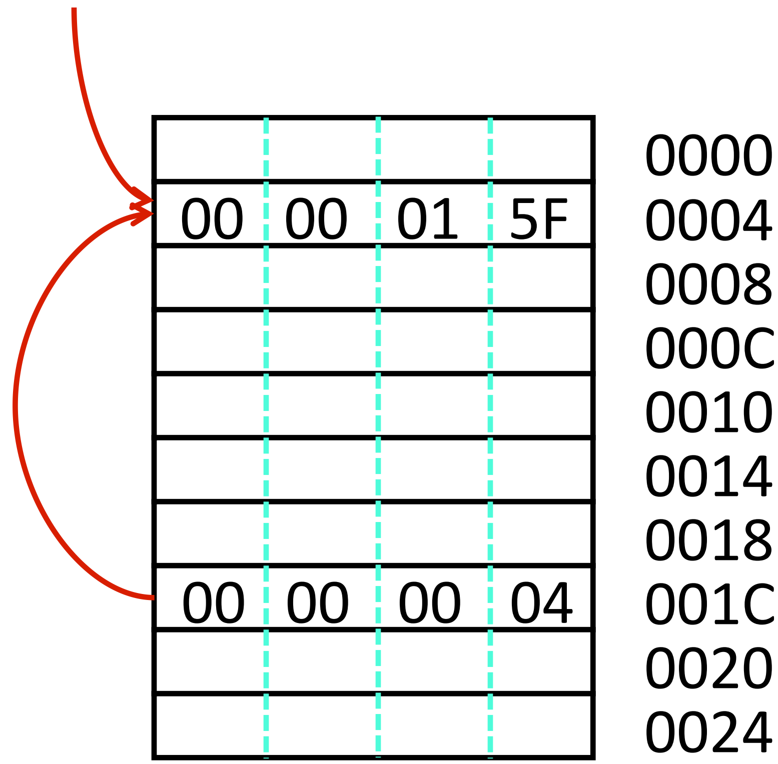
- **Pointer to address 0004 stored at address 001C**



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- Address is a *location* in memory
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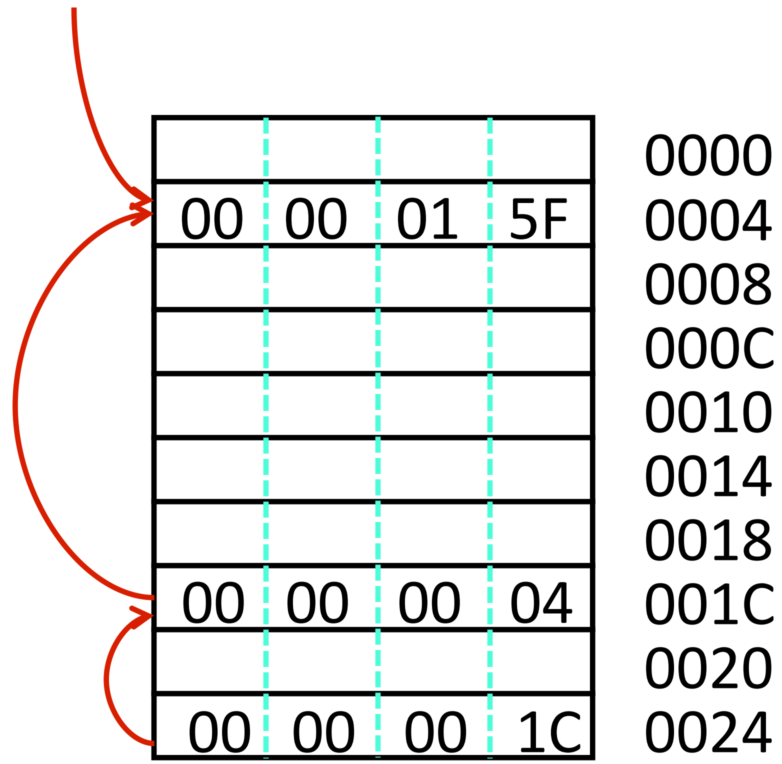
- Address 0004 stores the value 351 (or $15F_{16}$)
- Pointer to address 0004 stored at address 001C
- Pointer to a pointer in 0024



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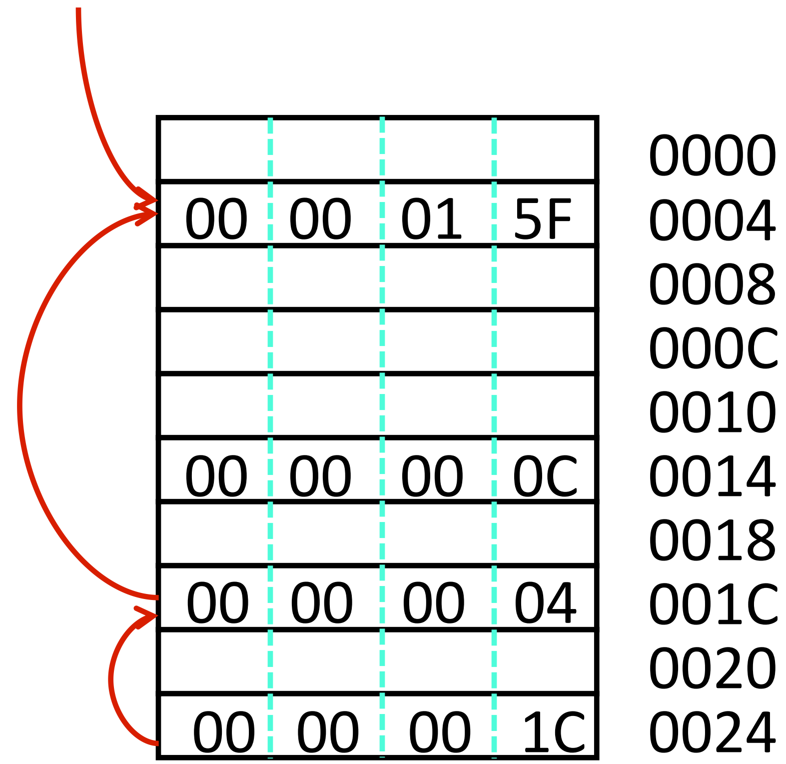
- **Address 0004 stores the value 351 (or $15F_{16}$)**
- **Pointer to address 0004 stored at address 001C**
- **Pointer to a pointer in 0024**
- **Address 0014 stores the value 12**
  - Is it a pointer?



# Data Representations

- **Sizes of objects (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 |

# Byte Ordering

- **How should bytes within multi-byte word be ordered in memory?**
- **Say you want to store 0xaabbccdd**
  - What order will the *bytes* be stored?

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- ***Endianness:* big endian vs. little endian**
  - Two different conventions, used by different architectures
  - Origin: *Gulliver's Travels* (see CS:APP2 textbook, section 2.1)

# Byte Ordering Example

- **Big-Endian** (PowerPC, Sun, Internet)
  - Least significant byte has highest address
- **Little-Endian** (x86)
  - Least significant byte has lowest address
- **Example**
  - Variable has 4-byte representation `0x01234567`
  - Address of variable is `0x100`

| | | | 0x100 | 0x101 | 0x102 | 0x103 | | |
|---|---|---|---|---|---|---|---|---|
| **Big Endian** | | | 01 | 23 | 45 | 67 | | |

| | | | 0x100 | 0x101 | 0x102 | 0x103 | | |
|---|---|---|---|---|---|---|---|---|
| **Little Endian** | | | 67 | 45 | 23 | 01 | | |

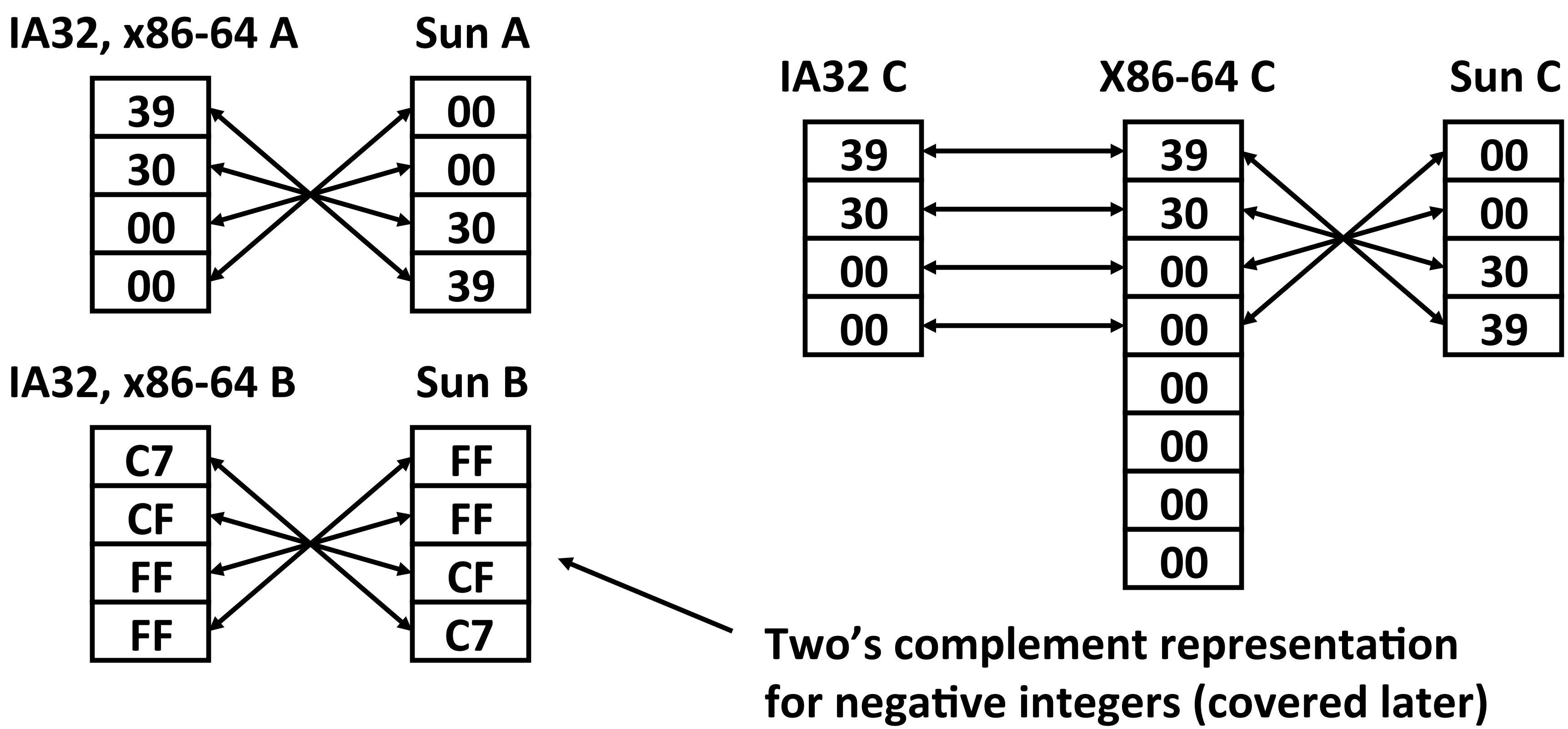
# Representing Integers

- `int A = 12345;`
- `int B = -12345;`
- `long int C = 12345;`

**Decimal:** 12345

**Binary:** 0011 0000 0011 1001

**Hex:** 3 0 3 9



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# Addresses and Pointers in C

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

- **Variable declarations**
  - int x, y;
  - Finds two locations in memory in which to store 2 integers (1 word each)
- **Pointer declarations use ***
  - int *ptr;
  - Declares a variable ptr that is a pointer to a data item that is an integer
- **Assignment to a pointer**
  - ptr = &x;
  - Assigns ptr to point to the address where x is stored
    - (stores the address of x in ptr)

# Addresses and Pointers in C

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

- **To use the value pointed to by a pointer we use *dereference (*)***
  - Given a pointer, we can get the value it points to by using the * operator
  - *ptr is the value at the memory address given by the value of ptr
- **Examples**
  - If ptr = &x then y = *ptr + 1 is the same as y = x + 1
  - If ptr = &y then y = *ptr + 1 is the same as y = y + 1
  - What is *(&x) equivalent to?

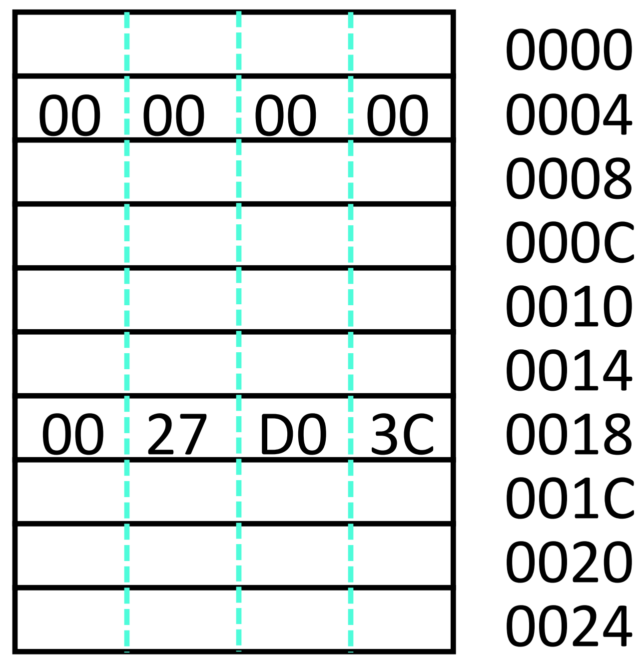
# Addresses and Pointers in C

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

- **We can do arithmetic on pointers**
  - ptr = ptr + 1; *// really adds 4: type of ptr is int*, and an int uses 4 bytes!*
  - Changes the value of the pointer so that it now points to the next data item in memory (that may be y, or it may not – this is dangerous!)

# Assignment in C

- **Left-hand-side = right-hand-side**
  - LHS must evaluate to a memory LOCATION
  - RHS must evaluate to a VALUE (could be an address)
- **E.g., x at location 0x04, y at 0x18**
  - x originally 0x0, y originally 0x3CD02700



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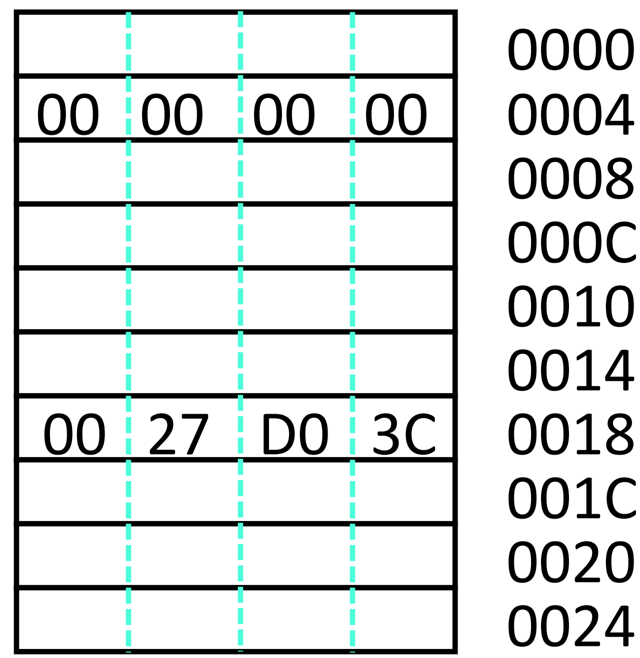
- **E.g., x at location 0x04, y at 0x18**
  - x originally 0x0, y originally 0x3CD02700
  - int x, y;
    x = y + 3; //get value at y, add 3, put it in x



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| | | | | |
|---|---|---|---|---|
| | | | | 0000 |
| 03 | 27 | D0 | 3C | 0004 |
| | | | | 0008 |
| | | | | 000C |
| | | | | 0010 |
| | | | | 0014 |
| 00 | 27 | D0 | 3C | 0018 |
| | | | | 001C |
| | | | | 0020 |
| | | | | 0024 |

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  - int * x; int y;
    x = &y + 3; // get address of y add ??

| | | | | |
|---|---|---|---|---|
| | | | | 0000 |
| 00 | 00 | 00 | 00 | 0004 |
| | | | | 0008 |
| | | | | 000C |
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  - int * x; int y;
    x = &y + 3; // get address of y add 12
    // 0x0018 + 0x000C = 0x0024

| | | | | |
|---|---|---|---|---|
| | | | | 0000 |
| 24 | 00 | 00 | 00 | 0004 |
| | | | | 0008 |
| | | | | 000C |
| | | | | 0010 |
| | | | | 0014 |
| 00 | 27 | D0 | 3C | 0018 |
| | | | | 001C |
| | | | | 0020 |
| | | | | 0024 |

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    *x = y; // value of y copied to
    // location to which x points

| | | | | |
|---|---|---|---|---|
| | | | | 0000 |
| 24 | 00 | 00 | 00 | 0004 |
| | | | | 0008 |
| | | | | 000C |
| | | | | 0010 |
| | | | | 0014 |
| 00 | 27 | D0 | 3C | 0018 |
| | | | | 001C |
| | | | | 0020 |
| | | | | 0024 |

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    x = &y + 3; // get address of y add 12
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| | | | | |
|---|---|---|---|---|
| | | | | 0000 |
| 24 | 00 | 00 | 00 | 0004 |
| | | | | 0008 |
| | | | | 000C |
| | | | | 0010 |
| | | | | 0014 |
| 00 | 27 | D0 | 3C | 0018 |
| | | | | 001C |
| | | | | 0020 |
| 00 | 27 | D0 | 3C | 0024 |

# Arrays

- **Arrays represent adjacent locations in memory storing the same type of data object**
  - e.g., int big_array[128];
    allocates 512 adjacent bytes in memory starting at 0x00ff0000
- **Pointer arithmetic can be used for array indexing in C (if pointer and array have the same type!):**
  - int *array_ptr;
    array_ptr = big_array; 0x00ff0000
    array_ptr = &big_array[0]; 0x00ff0000
    array_ptr = &big_array[3]; 0x00ff000c
    array_ptr = &big_array[0] + 3; 0x00ff000c *(adds 3 * size of int)*
    array_ptr = big_array + 3; 0x00ff000c *(adds 3 * size of int)*
    *array_ptr = *array_ptr + 1; 0x00ff000c *(but big_array[3] is incremented)*
    array_ptr = &big_array[130]; 0x00ff0208 *(out of bounds, C doesn't check)*
  - In general: &big_array[i] is the same as (big_array + i),
    which implicitly computes: *&bigarray[0] + i*sizeof(bigarray[0]);*

# Representing strings

- **A C-style string is represented by an array of bytes.**
  - Elements are one-byte ASCII codes for each character.
  - A 0 value marks the end of the array.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 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.**

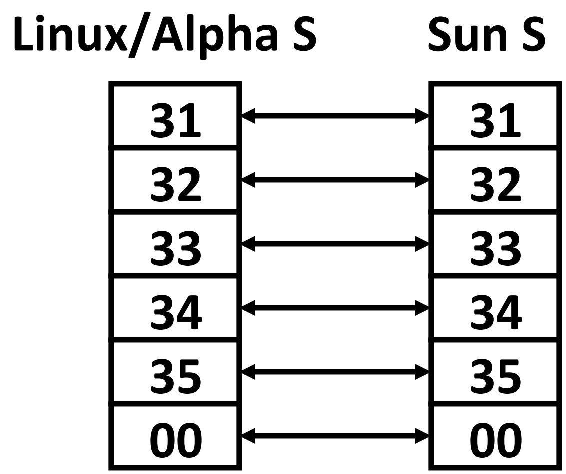
| 72 | 97 | 114 | 114 | 121 | 32 | 80 | 111 | 116 | 116 | 101 | 114 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | a | r | r | y | | P | o | t | t | e | r | \0 |

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

- **How do we compute the string length??**

# Compatibility

**char S[6] = "12345";**




- **Byte ordering (endianness) is not an issue for standard C strings (char arrays)**
- **Unicode characters – up to 4 bytes/character**
  - ASCII codes still work (leading 0 bit) but 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`

```
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((pointer) &a, sizeof(int));
```

**Result (Linux):**

```
int a = 12345;
0x11ffffcb8    0x39
0x11ffffcb9    0x30
0x11ffffcba    0x00
0x11ffffcbb    0x00
```

# Memory, Data, and Addressing

- Preliminaries
- Representing information as bits and bytes
- Organizing and addressing data in memory
- Manipulating data in memory using C
- <u>Boolean algebra and bit-level manipulations</u>

# 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

| & | 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 |

# Manipulating Bits

- **Boolean operators can be applied to *bit vectors*: operations are applied *bitwise***

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

# Bit-Level Operations in C

- **Bitwise operators &, |, ^, ~ are available in C**
  - Apply to any “integral” data type
    - `long, int, short, char`
  - Arguments are treated as bit vectors
  - Operations applied bitwise
- **Examples:**

`char a, b, c;`

`a = (char)0x41;      // 0x41 -> 01000001`$_2$

`b = ~a;              //         10111110`$_2$ `-> 0xBE`

`a = (char)0;         // 0x00 -> 00000000`$_2$

`b = ~a;              //         11111111`$_2$ `-> 0xFF`

`a = (char)0x69;      // 0x41 -> 01101001`$_2$

`b = (char)0x55;      // 0x55 -> 01010101`$_2$

`c = a & b;           //         01000001`$_2$ `-> 0x41`

# Contrast: Logic Operations in C

- **Logical operators in C: &&, ||, !**
  - Behavior:
    - View 0 as "False"
    - Anything nonzero as "True"
    - Always return 0 or 1
    - Early termination (&& and ||)
- **Examples (char data type)**
  - `!0x41          -->   0x00`
  - `!0x00          -->   0x01`
  - `0x69 && 0x55   -->   0x01`
  - `0x00 && 0x55   -->   0x00`
  - `0x69 || 0x55   -->   0x01`
  - `p && *p++` (avoids null pointer access: null pointer = 0x00000000)
    short for: `if (p) { *p++; }`

# Representing & Manipulating Sets

- **Bit vectors can be used to represent *sets***
  - Width *w* bit vector represents subsets of {0, …, *w*–1}
  - $a_j = 1$ if $j \in A$ – each bit in the vector represents the absence (0) or presence (1) of an element in the set

```
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 }

- Slides past this point not used

# Reading Byte-Reversed Listings

- **Disassembly**
  - Text representation of binary machine code
  - Generated by program that reads the machine code
- **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 |

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| Address | Instruction Code | Assembly Rendition |
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**Deciphering numbers**

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

# Representing Pointers

- `int B = -12345;`
- `int *P = &B;`

| Sun P | IA32 P | x86-64 P |
|---|---|---|
| EF | D4 | 0C |
| FF | F8 | 89 |
| FB | FF | EC |
| 2C | BF | FF |
| | | FF |
| | | 7F |
| | | 00 |
| | | 00 |

*Different compilers & machines assign different locations to objects*