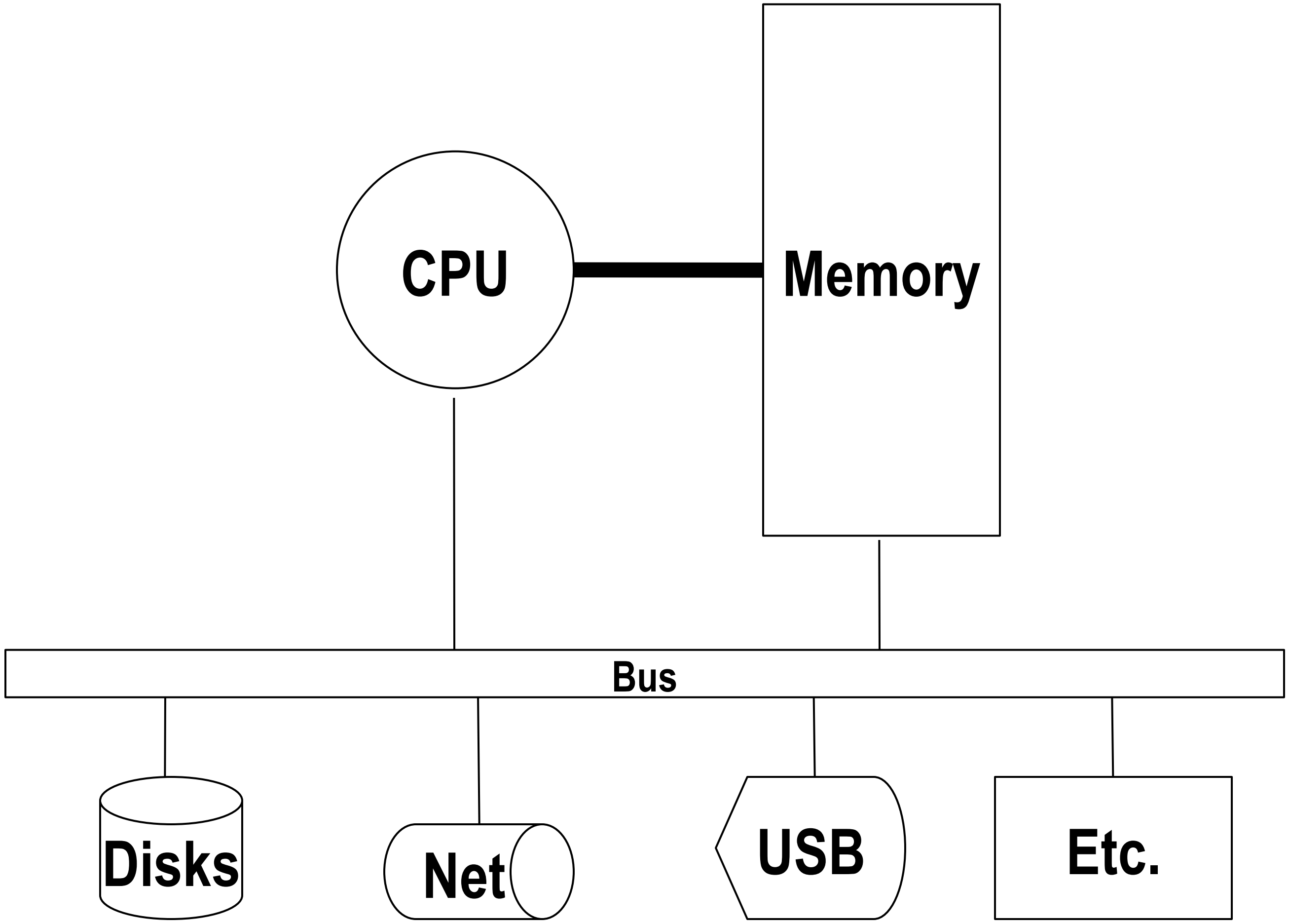
CSE351

- **Announcements:**
  - HW0, having fun?
  - Use discussion boards!
  - Sign up for cse351@cs mailing list
    - If you enrolled recently, you might not be on it

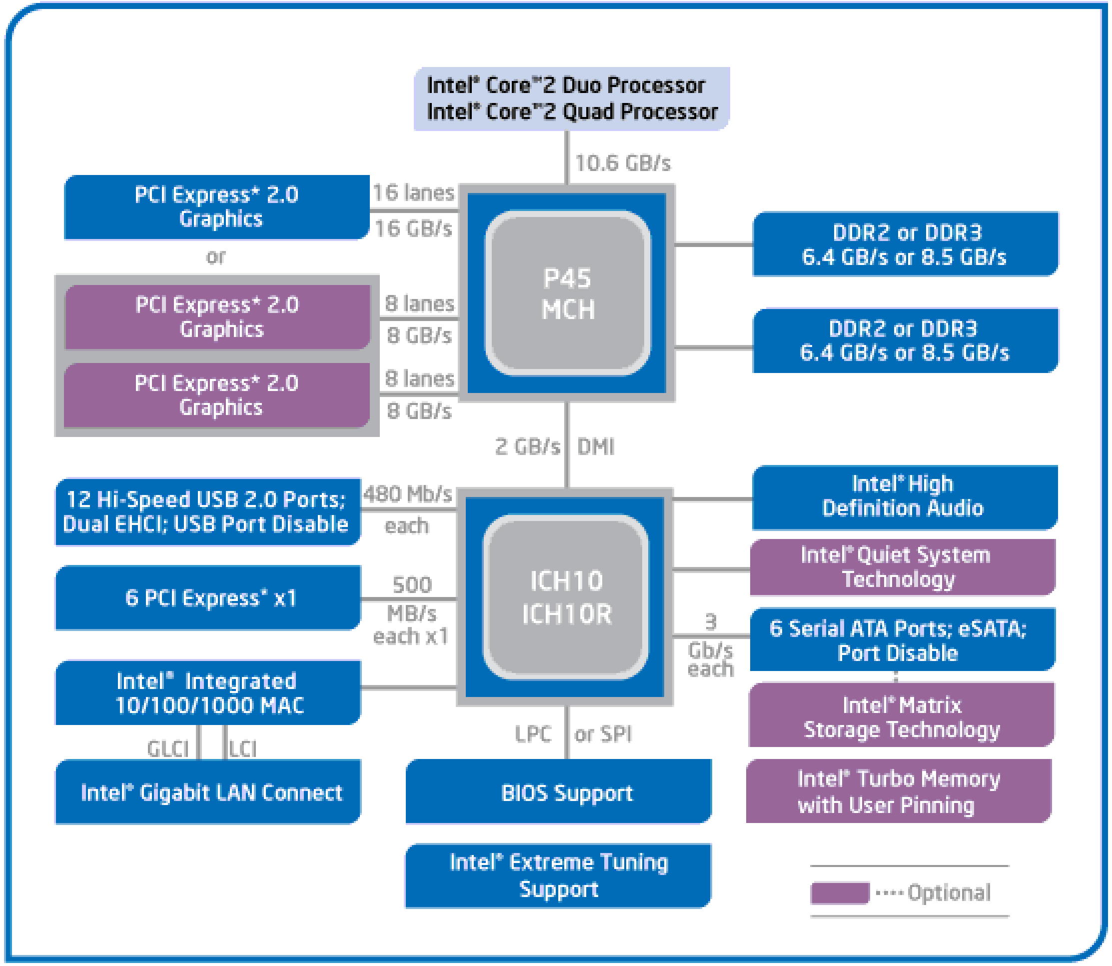
Today's topics

- **Memory and its bits, bytes, and integers**
- **Representing information as bits**
- **Bit-level manipulations**
  - Boolean algebra
  - Boolean algebra in C

Hardware: Logical View

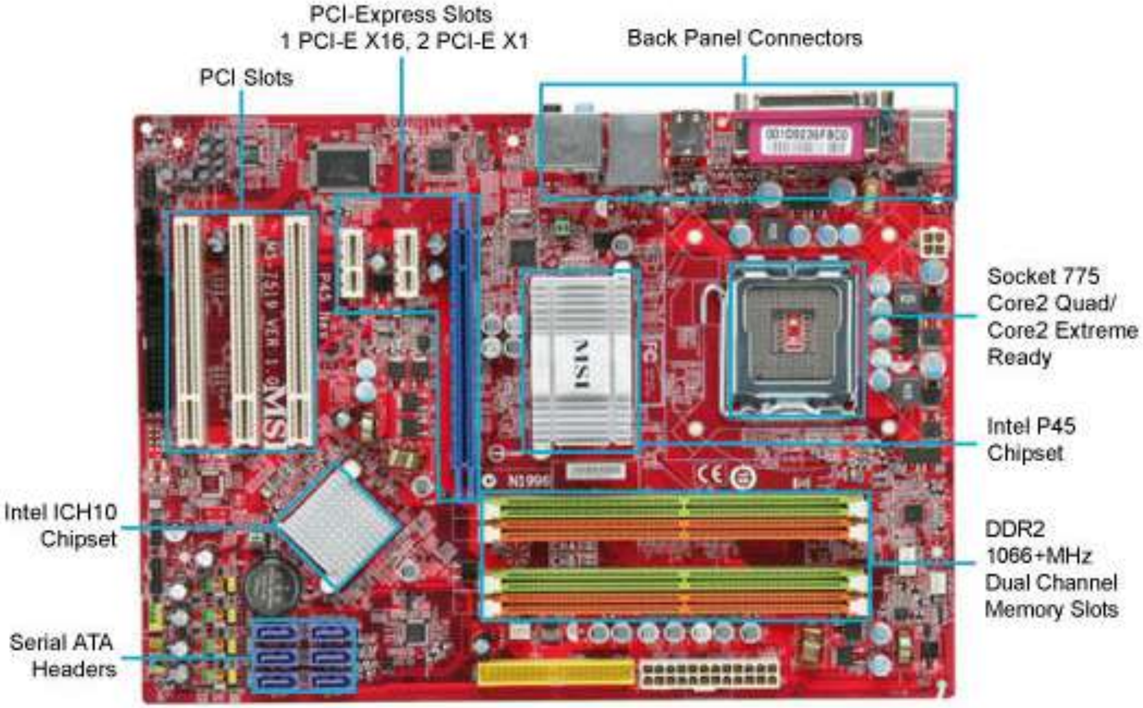


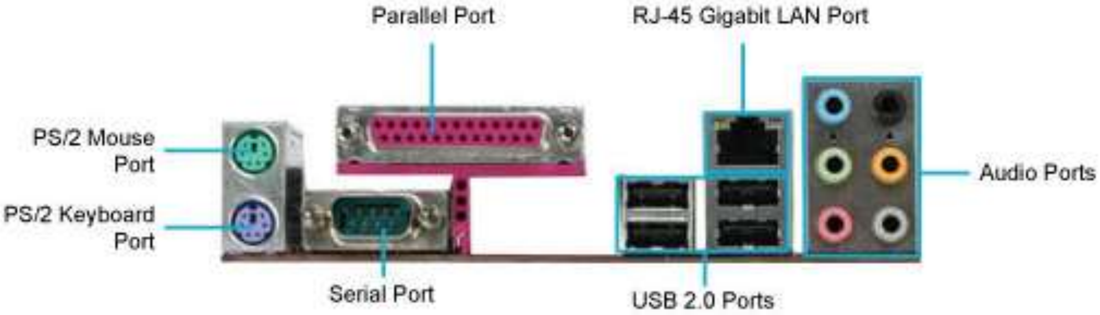
Hardware: Semi-Logical View



Intel® P45 Express Chipset Block Diagram

Hardware: Physical View

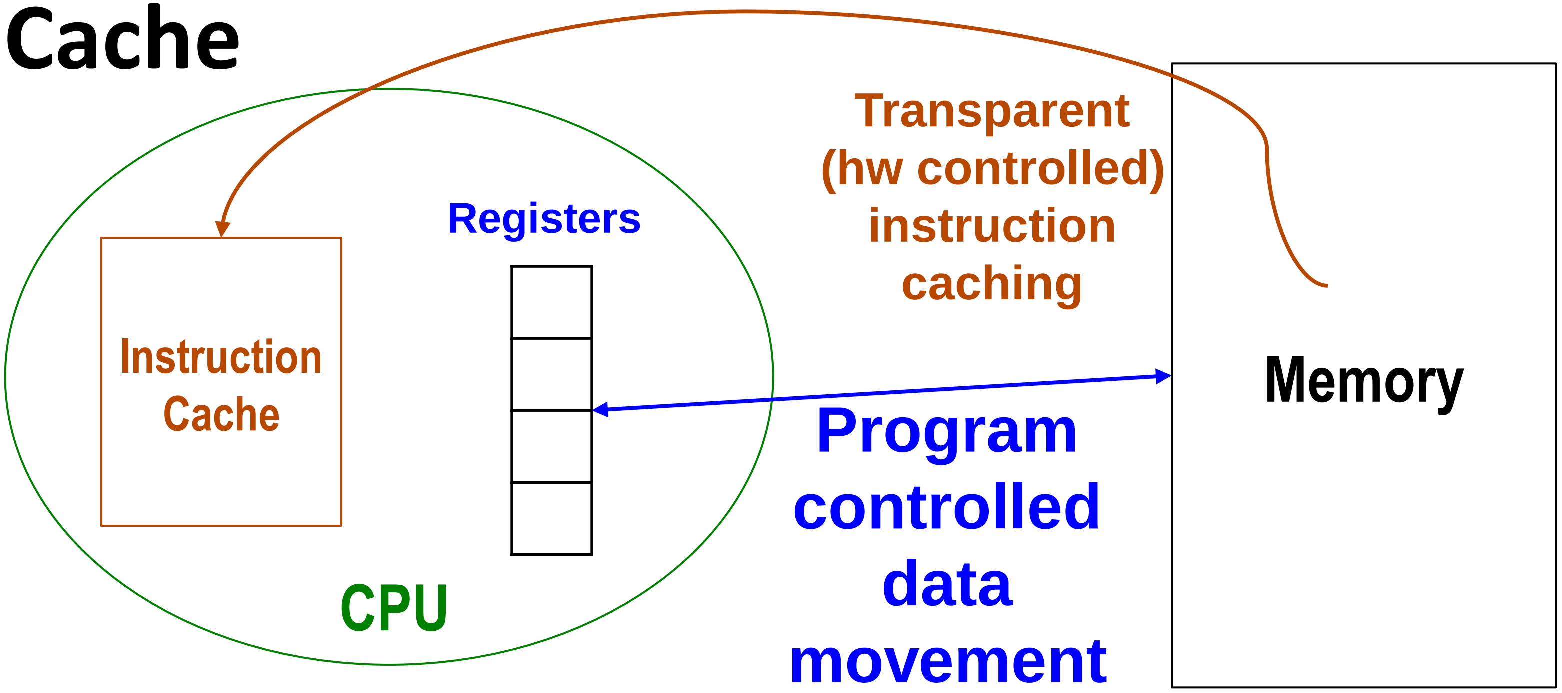




Performance: It's Not Just CPU Speed

- Data and instructions reside in memory
  - To execute an ***instruction***, it must be fetched onto the CPU
  - Then, the ***data*** the instruction operates on must be fetched onto 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" on the CPU chip
    - *The next slide is just an introduction. We'll see a more full explanation later in the course.*

CPU “Memory”: Registers and Instruction Cache

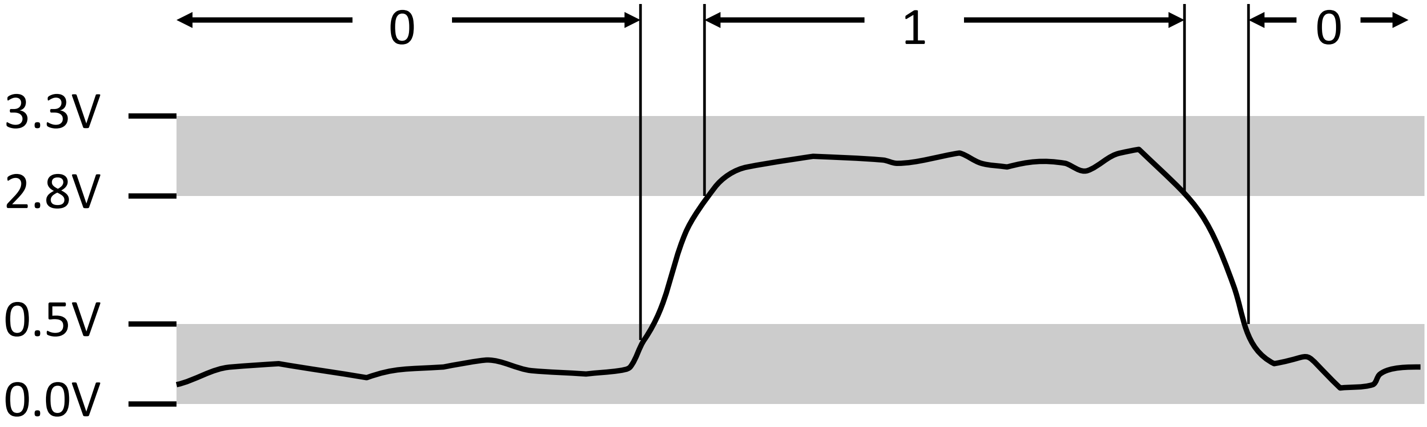


- **There are a fixed number of <u>registers</u> on the CPU**
  - Registers hold data
- **There is an <u>I-cache</u> on the CPU holding recently fetched instructions**
  - If you execute a loop that fits in the cache, the CPU goes to memory for those instructions only once, then executes out of its cache

- Introduction to 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



Encoding Byte Values

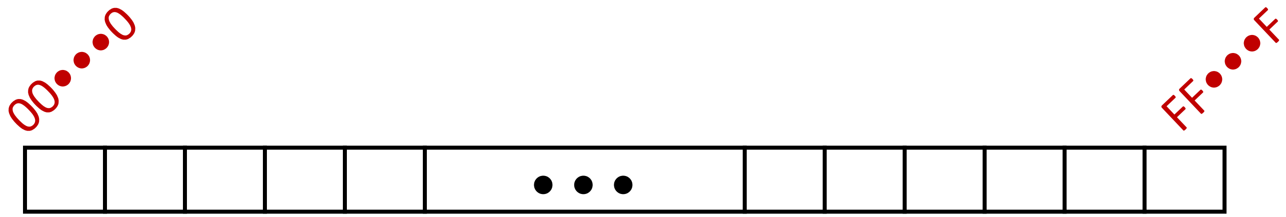
- **Binary** **00000000_2 -- 11111111_2**
  - Byte = 8 bits (binary digits)
- **Decimal** **0_{10} -- 255_{10}**
- **Hexadecimal** **00_{16} -- FF_{16}**
  - Byte = 2 hexadecimal (hex) or base 16 digits
  - Base-16 number representation
  - Use characters ‘0’ to ‘9’ and ‘A’ to ‘F’
  - Write $\mathrm{FA1D37B}_{16}$ 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



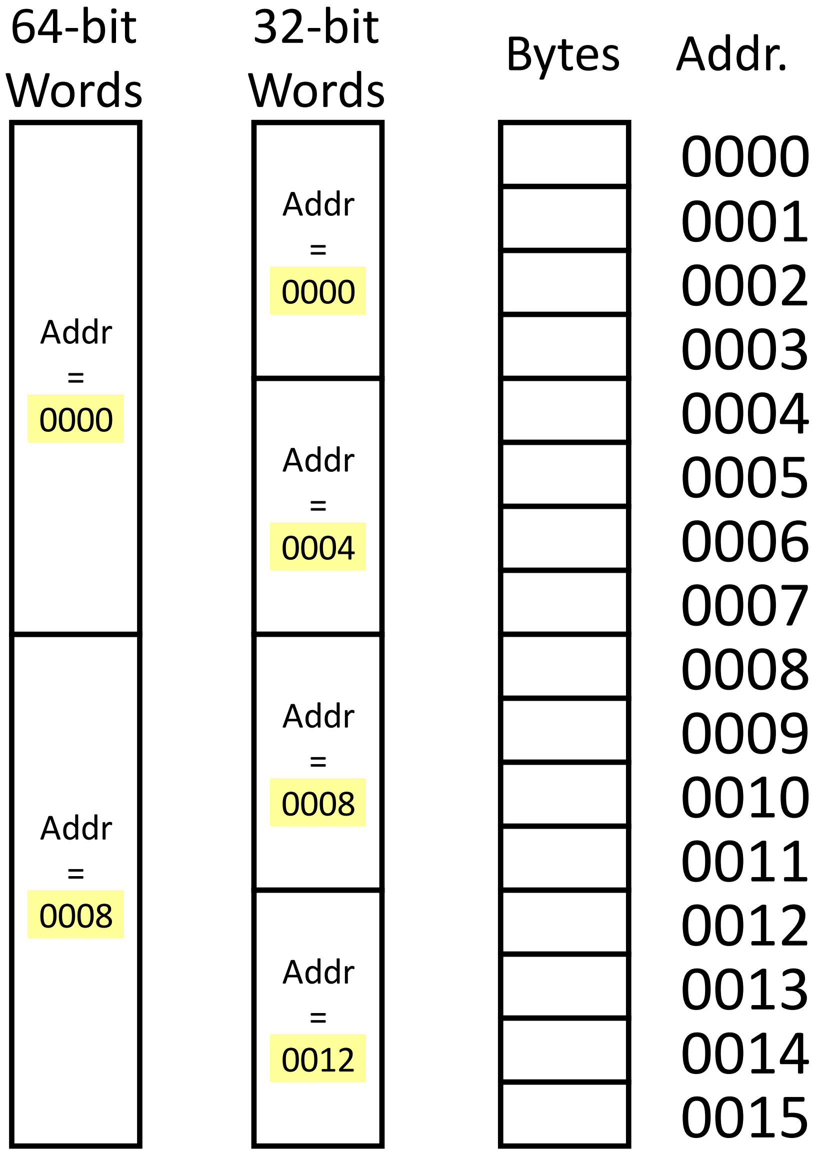
- **Programs refer to addresses**
  - Conceptually, a very large array of bytes
  - System provides an address space private to each “process”
    - Process = program being executed + its data + its “state”
    - Program can clobber its own data, but not that of others
    - Clobbering code or “state” 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
  - Most current machines use 32 bits (4 bytes) words
    - Limits addresses to 4GB
    - Becoming too small for memory-intensive applications
  - High-end systems use 64 bits (8 bytes) words
    - Potential address space ≈ 1.8 X 10^{19} bytes
    - x86-64 machines support 48-bit addresses: 256 Terabytes
    - Can’t be real physical addresses -> virtual addresses
  - Machines support multiple data formats
    - Fractions or multiples of word size
    - Always integral number of bytes

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?



64-bit Words

Addr = 0000

Addr = 0008

32-bit Words

Addr = 0000

Addr = 0004

Addr = 0008

Addr = 0012

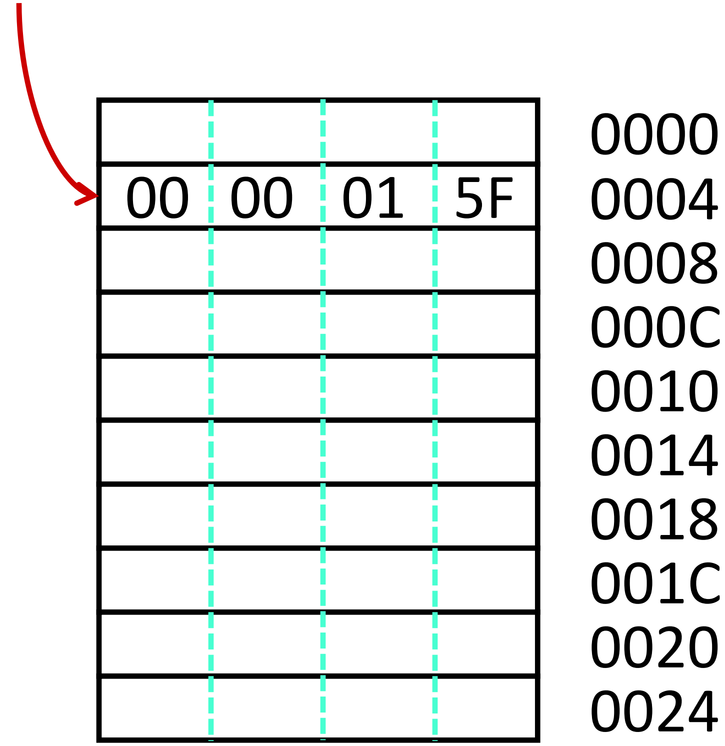
Bytes

Addr.

0000
0001
0002
0003
0004
0005
0006
0007
0008
0009
0010
0011
0012
0013
0014
0015

Addresses and Pointers

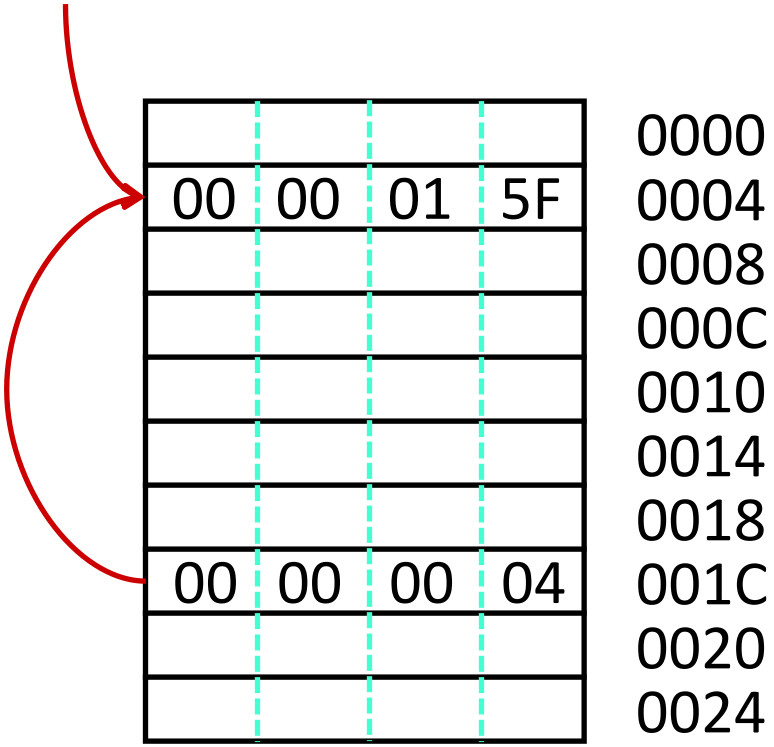
- **Address is a *location* in memory**
- **Pointer is a data object that *contains an address***
- **Address 0004 stores the value 351 (or $15F_{16}$)**



				0000
00	00	01	5F	0004
				0008
				000C
				0010
				0014
				0018
				001C
				0020
				0024

Addresses and Pointers

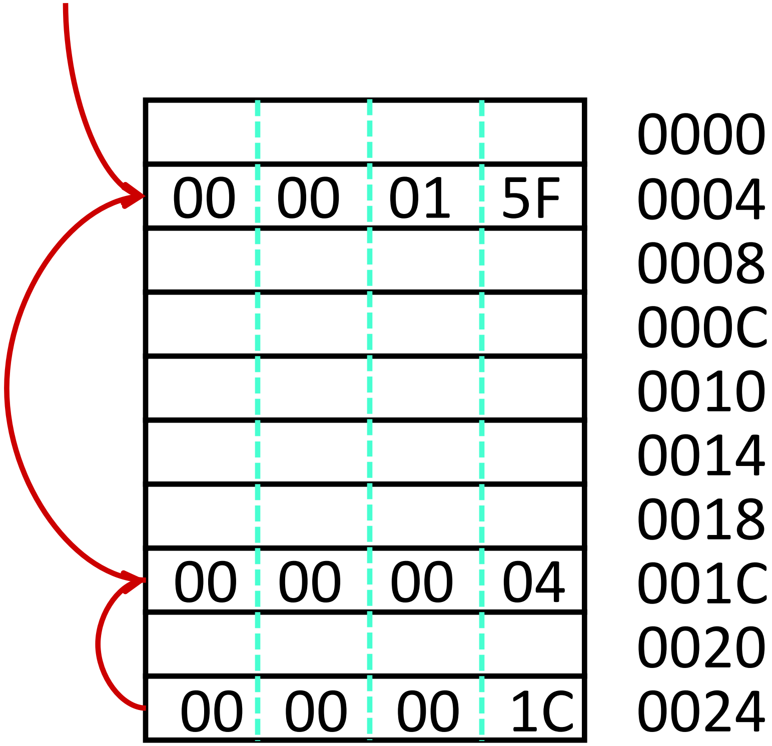
- Address is a *location* in memory
- Pointer is a data object that *contains an address*
- Address 0004 stores the value 351 (or $15F_{16}$)
- Pointer to address 0004 stored at address 001C



				0000
00	00	01	5F	0004
				0008
				000C
				0010
				0014
				0018
00	00	00	04	001C
				0020
				0024

Addresses and Pointers

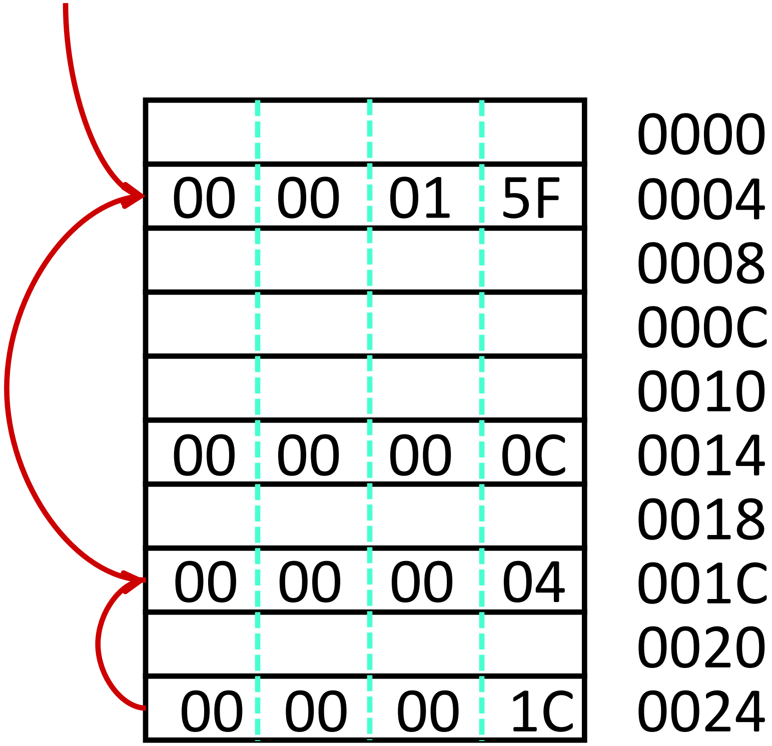
- Address is a *location* in memory
- Pointer is a data object that *contains an address*
- Address 0004 stores the value 351 (or $15F_{16}$)
- Pointer to address 0004 stored at address 001C
- Pointer to a pointer in 0024



				0000
00	00	01	5F	0004
				0008
				000C
				0010
				0014
				0018
00	00	00	04	001C
				0020
00	00	00	1C	0024

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



				0000
00	00	01	5F	0004
				0008
				000C
				0010
00	00	00	0C	0014
				0018
00	00	00	04	001C
				0020
00	00	00	1C	0024

Data Representations

- **Sizes of objects (in bytes)**

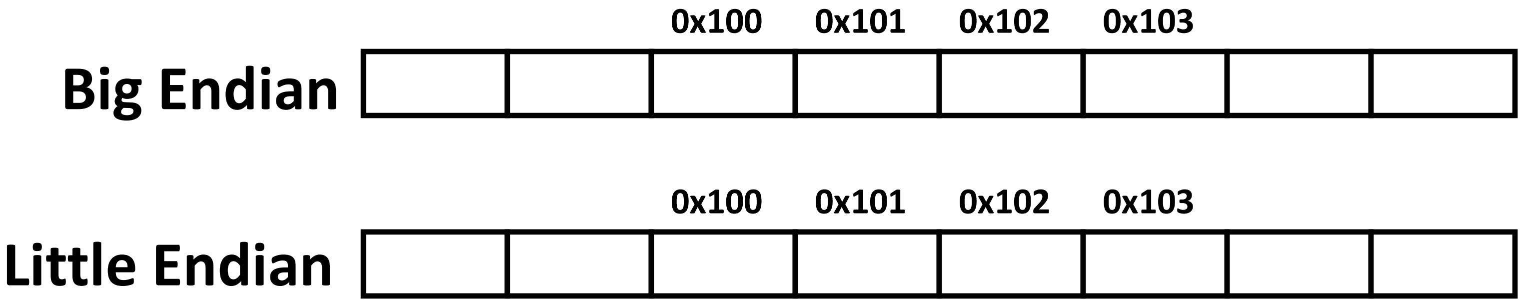
Java Data Type	C Data Type	Typical 32-bit	x86-64
boolean	*bool*	1	1
byte	char	1	1
char		2	2
short	short int	2	2
int	int	4	4
float	float	4	4
	long int	4	8
double	double	8	8
long	long long	8	8
	long double	8	16
(reference)	pointer *	4	8

Byte Ordering

- **How should bytes within multi-byte word be ordered in memory?**
  - Peanut butter or chocolate first?
- **Conventions!**
  - Big-endian, Little-endian
  - Based on Guliver stories, tribes cut eggs on different sides (big, little)

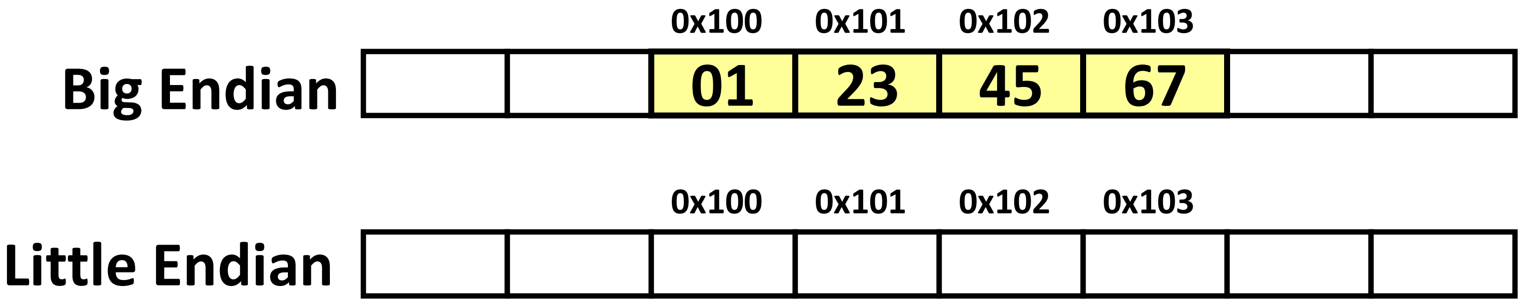
Byte Ordering Example

- **Big-Endian** (PPC, 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`



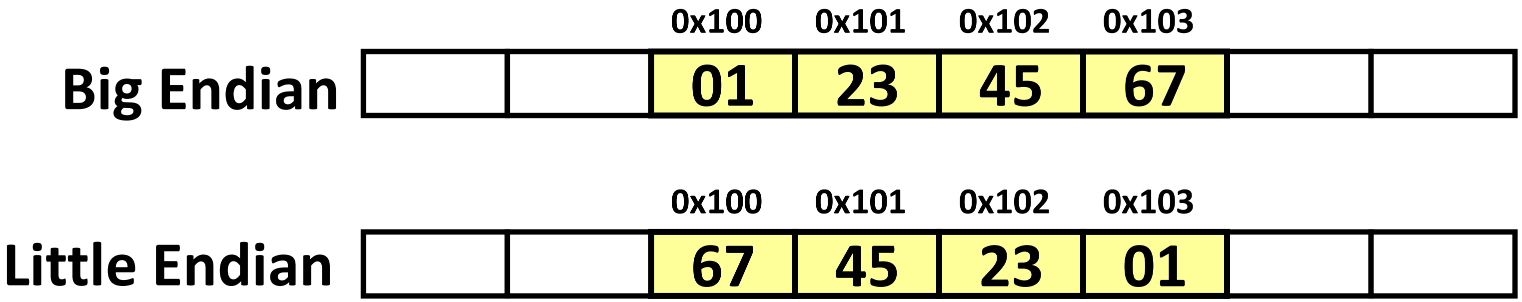
Byte Ordering Example

- **Big-Endian** (PPC, 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`



Byte Ordering Example

- **Big-Endian** (PPC, 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		
Little Endian			67	45	23	01		

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

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

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'
**= 'value at address'*
or 'de-reference'

**(&x) is equivalent to x*

- **Pointer declarations use ***
  - int * ptr; int x, y;   ptr = &x;
  - Declares a variable ptr that is a pointer to a data item that is an integer
  - Declares integer values named x and y
  - Assigns ptr to point to the address where x is stored
- **We can do arithmetic on pointers**
  - ptr = ptr + 1;   *// really adds 4 (because an integer 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, may not – dangerous!)
- **To use the value pointed to by a pointer we use de-reference**
  - y = *ptr + 1; is the same as y = x + 1;
  - But, if ptr = &y then y = *ptr + 1; is the same as y = y + 1;
  - *ptr is the value stored at the location to which the pointer ptr is pointing

Arrays

- **Arrays represent adjacent locations in memory storing the same type of data object**
  - E.g., int big_array[128];
    allocated 512 adjacent locations in memory starting at 0x00ff0000
- **Pointers to arrays point to a certain type of object**
  - E.g., int * array_ptr;
    array_ptr = big_array;
    array_ptr = &big_array[0];
    array_ptr = &big_array[3];
    array_ptr = &big_array[0] + 3;
    array_ptr = big_array + 3;
    *array_ptr = *array_ptr + 1;
    array_ptr = &big_array[130];
  - In general: &big_array[i] is the same as (big_array + i)
    - *which implicitly computes: &bigarray[0] + i*sizeof(bigarray[0]);*

Arrays

- **Arrays represent adjacent locations in memory storing the same type of data object**
  - E.g., int big_array[128];
    allocated 512 adjacent locations in memory starting at 0x00ff0000
- **Pointers to arrays point to a certain type of object**
  - E.g., 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]);*

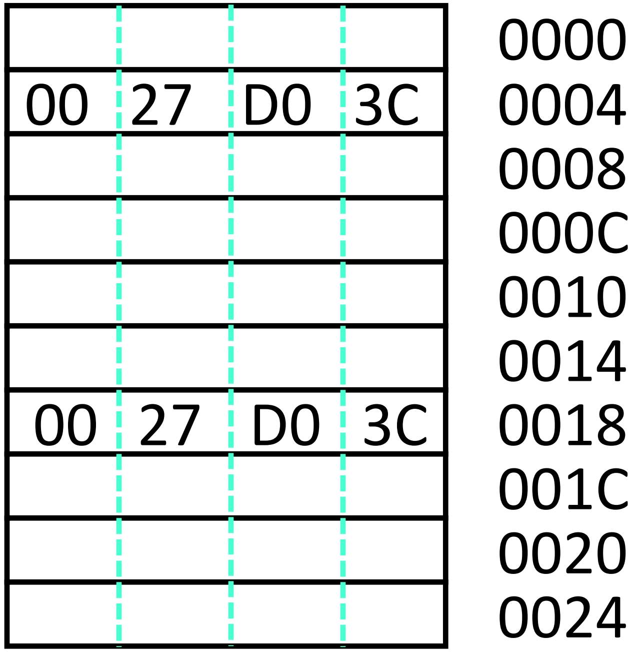
General rules for C (assignments)

- **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**
  - int x, y;
    x = y; // get value at y and put it in x

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

General rules for C (assignments)

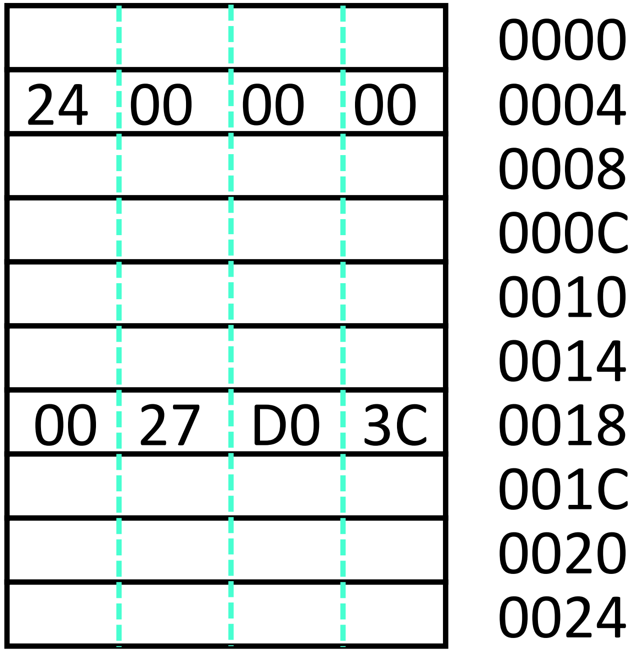
- **Left-hand-side = right-hand-side**
  - LHS must evaluate to a memory LOCATION
  - RHS must evaluate to a VALUE (could be an address)
- **E.g., x at location 0x04, y at 0x18**
  - int x, y;
    x = y; // get value at y and put it in x



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

General rules for C (assignments)

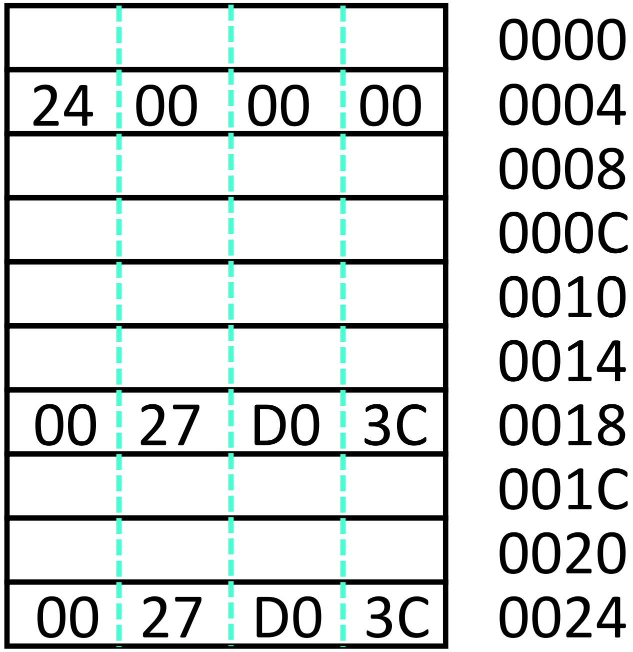
- **Left-hand-side = right-hand-side**
  - LHS must evaluate to a memory LOCATION
  - RHS must evaluate to a VALUE (could be an address)
- **E.g., x at location 0x04, y at 0x18**
  - int x, y;
    x = y; // get value at y and put it in x
  - int * x; int y;
    x = &y + 12; // get address of y add 12



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

General rules for C (assignments)

- **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**
  - int x, y;
    x = y; // get value at y and put it in x
  - int * x; int y;
    x = &y + 3; // get address of y add 12
  - int * x; int y;
    *x = y; // value of y to location x points



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

Examining Data Representations

- **Code to print byte representation of data**
  - Casting pointer to `unsigned char *` creates byte array

```
typedef unsigned char * pointer;

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

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

Some printf directives:

%p: Print pointer

%x: Print hexadecimal

“\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
```

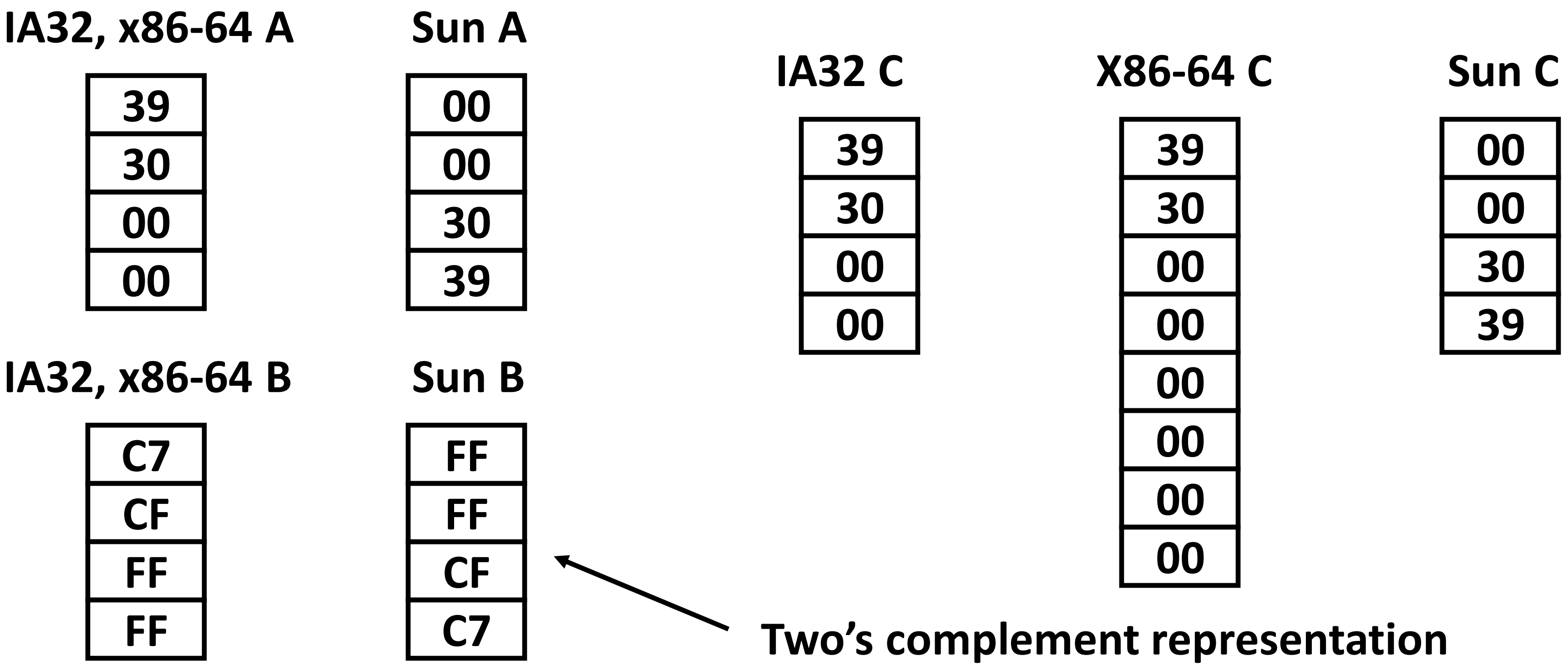
Representing Integers

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

Decimal: 12345

Binary: 0011 0000 0011 1001

Hex: 3 0 3 9



IA32, x86-64 A

39
30
00
00

Sun A

00
00
30
39

IA32, x86-64 B

C7
CF
FF
FF

Sun B

FF
FF
CF
C7

IA32 C

39
30
00
00

X86-64 C

39
30
00
00
00
00
00
00

Sun C

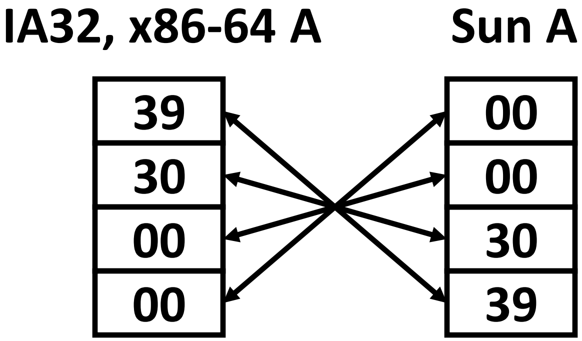
00
00
30
39

Two's complement representation for negative integers (covered later)

Representing Integers

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

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



IA32, x86-64 B

C7
CF
FF
FF

Sun B

FF
FF
CF
C7

IA32 C

39
30
00
00

X86-64 C

39
30
00
00
00
00
00
00

Sun C

00
00
30
39

Two's complement representation for negative integers (covered later)

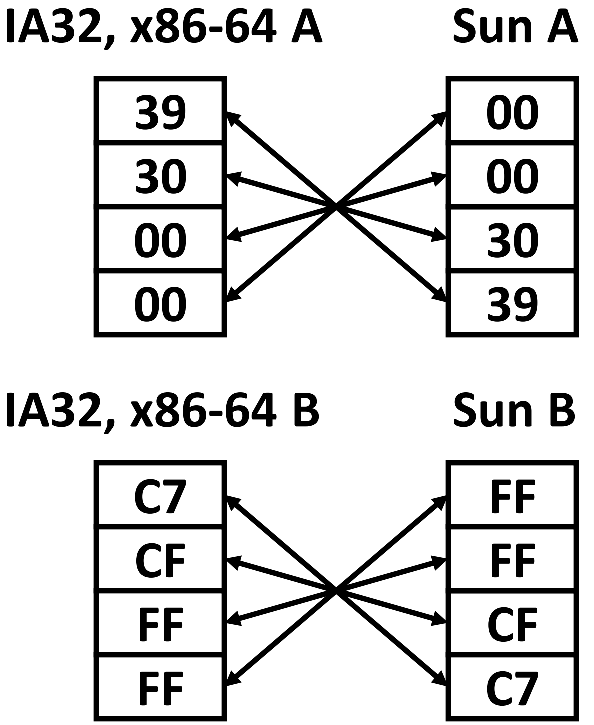
Representing Integers

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

Decimal: 12345

Binary: 0011 0000 0011 1001

Hex: 3 0 3 9



IA32, x86-64 A

39
30
00
00

Sun A

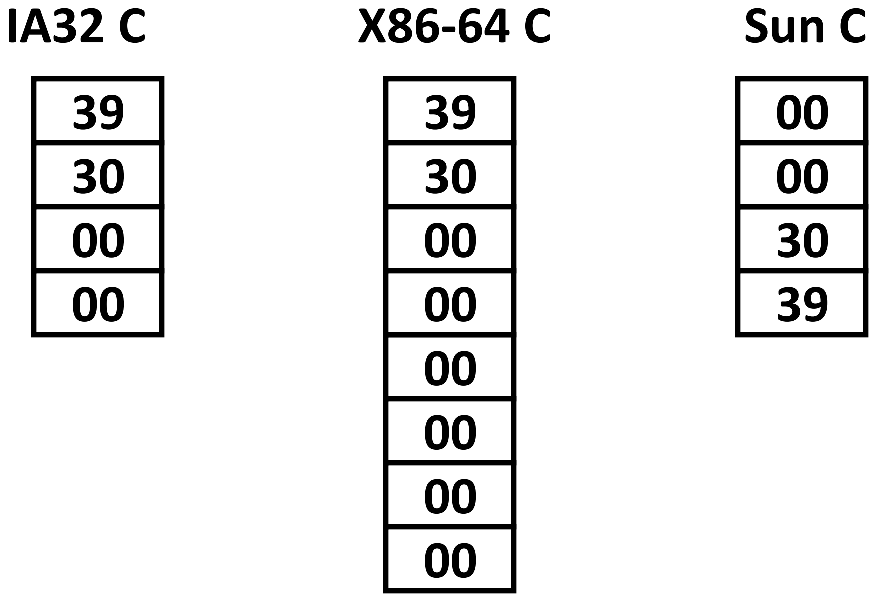
00
00
30
39

IA32, x86-64 B

C7
CF
FF
FF

Sun B

FF
FF
CF
C7



IA32 C

39
30
00
00

X86-64 C

39
30
00
00
00
00
00
00

Sun C

00
00
30
39

Two’s complement representation for negative integers (covered later)

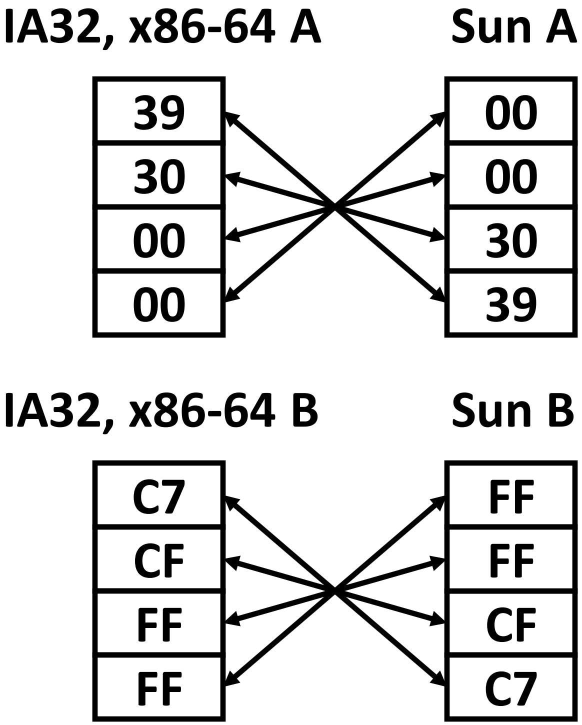
Representing Integers

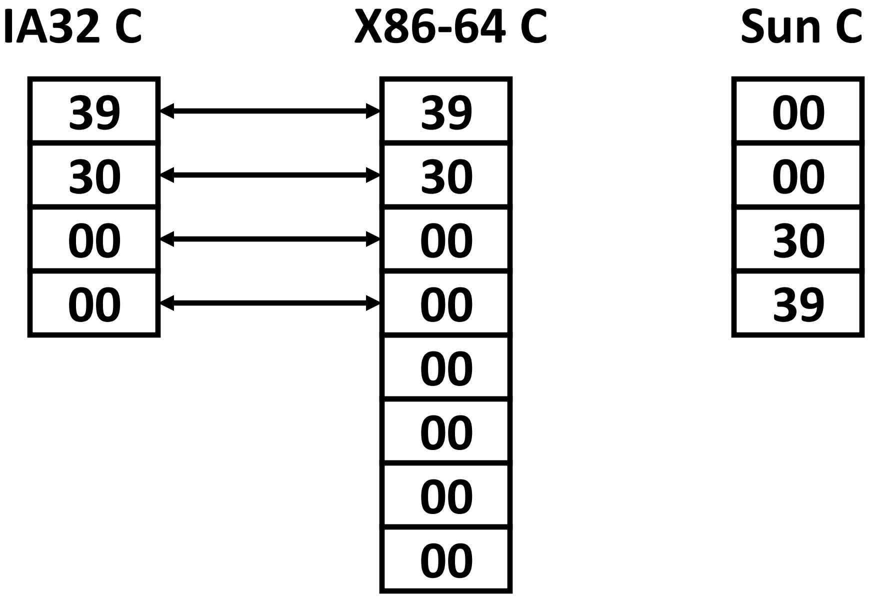
- `int A = 12345;`
- `int B = -12345;`
- `long int C = 12345;`

Decimal: 12345

Binary: 0011 0000 0011 1001

Hex: 3 0 3 9





Two’s complement representation for negative integers (covered later)

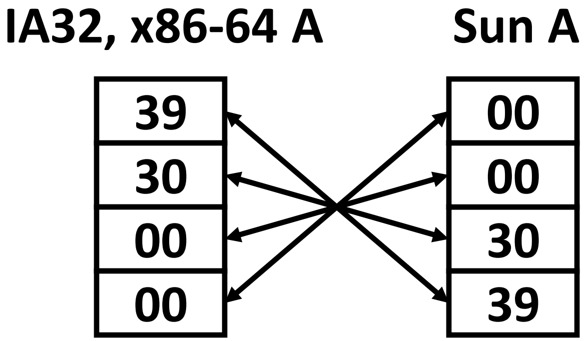
Representing Integers

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

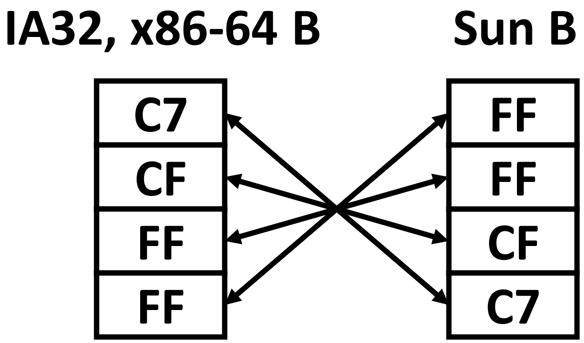
Decimal: 12345

Binary: 0011 0000 0011 1001

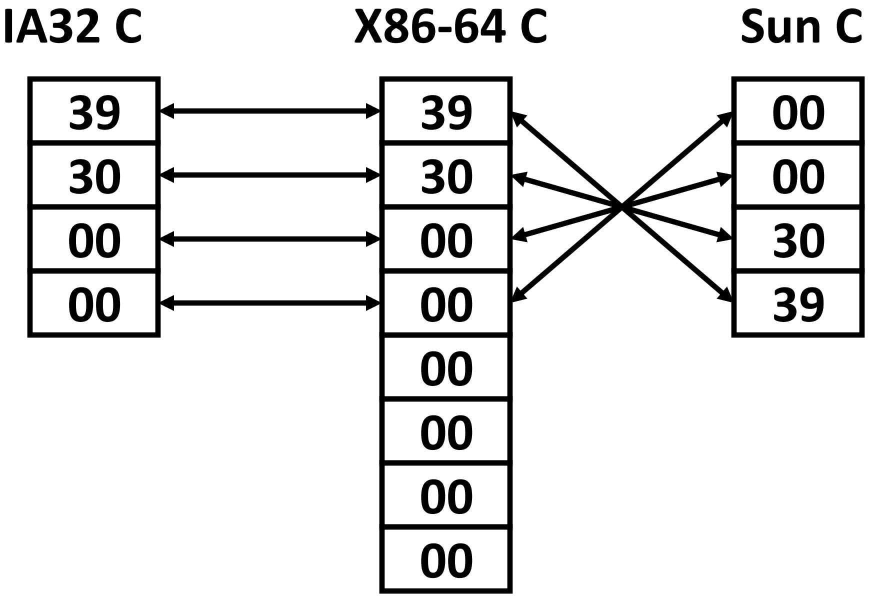
Hex: 3 0 3 9



IA32, x86-64 A	Sun A
39	00
30	00
00	30
00	39



IA32, x86-64 B	Sun B
C7	FF
CF	FF
FF	CF
FF	C7



IA32 C	X86-64 C	Sun C
39	39	00
30	30	00
00	00	30
00	00	39
	00	
	00	
	00	
	00	

Two's complement representation for negative integers (covered later)

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

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.**

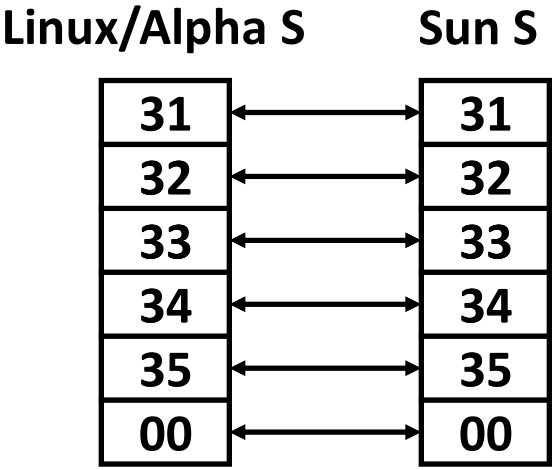
72	97	114	114	121	32	80	111	116	116	101	114	0
H	a	r	r	y		P	o	t	t	e	r	\0

- **Why do we put a a 0, or null, at the end of the string?**

- **Computing string length?**

Compatibility

char S[6] = "12345";



Linux/Alpha S	Sun S
31	31
32	32
33	33
34	34
35	35
00	00

- **Byte ordering not an issue**
- **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)

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

General Boolean Algebras

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

01101001	**01101001**	**01101001**	
& 01010101	**| 01010101**	**^ 01010101**	**~ 01010101**

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

01010101
^ 01010101

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

Representing & Manipulating Sets

- **Representation**
  - Width *w* bit vector represents subsets of {0, …, *w*–1}
  - $a_j = 1$ if $j \in A$

`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

- **Operations &, |, ^, ~ are available in C**
  - Apply to any “integral” data type
    - `long, int, short, char, unsigned`
  - View arguments as bit vectors
  - Arguments applied bit-wise
- **Examples (char data type)**
  - `~0x41 --> 0xBE`

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

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

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

    $01101001_2 \; | \; 01010101_2 \; \text{-->} \; 01111101_2$

Contrast: Logic Operations in C

- **Contrast to logical operators**
  - `&&, ||, !`
    - View 0 as “False”
    - Anything nonzero as “True”
    - Always return 0 or 1
    - Early termination
- **Examples (char data type)**
  - `!0x41   -->   0x00`
  - `!0x00   -->   0x01`
  - `!!0x41  -->   0x01`

  - `0x69 && 0x55   -->   0x01`
  - `0x69 || 0x55   -->   0x01`
  - `p && *p++`   (avoids null pointer access, null pointer = 0x00000000)