# Bits, Bytes and Integers

Introduction to Computer Systems

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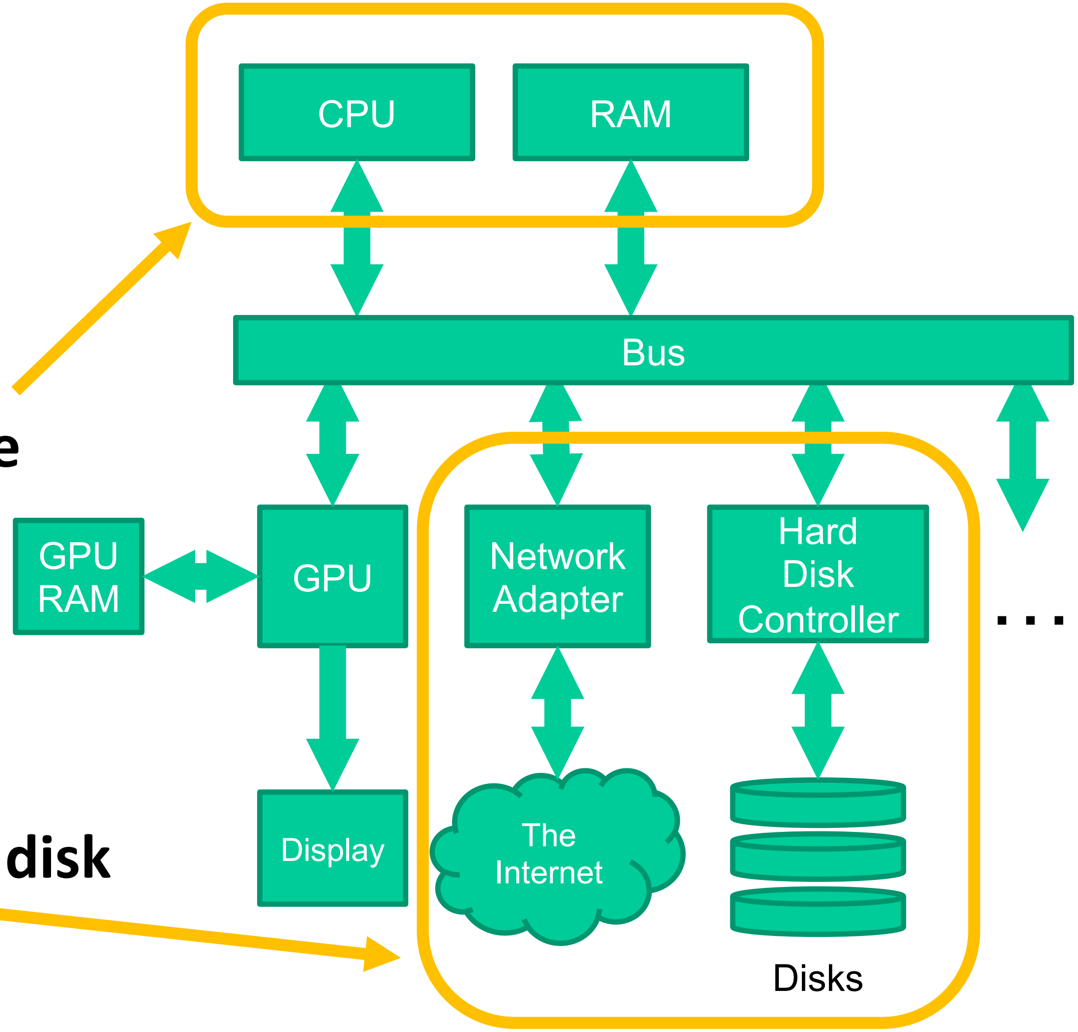
# Roadmap – Inside a Computer




For the first half of the course we'll be concentrating on the CPU and RAM

Second half discusses disk and network I/O

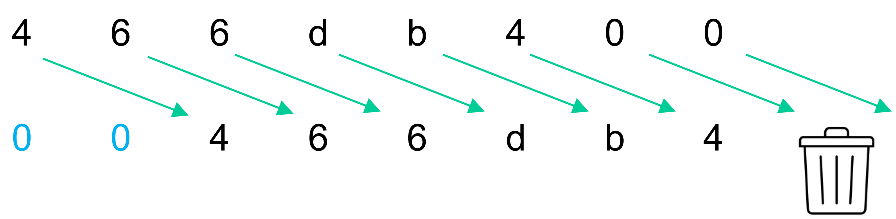
# Course Teaser (Things You May Know Already)

**What value do you get if you arithmetic right-shift the hexadecimal number `0x466db400` by eight bits?**

**Hexadecimal is just like decimal … if you have sixteen fingers.**

**“Eight bits” is two hex digits.**

**“Arithmetic right shift” is division by a power of two.**

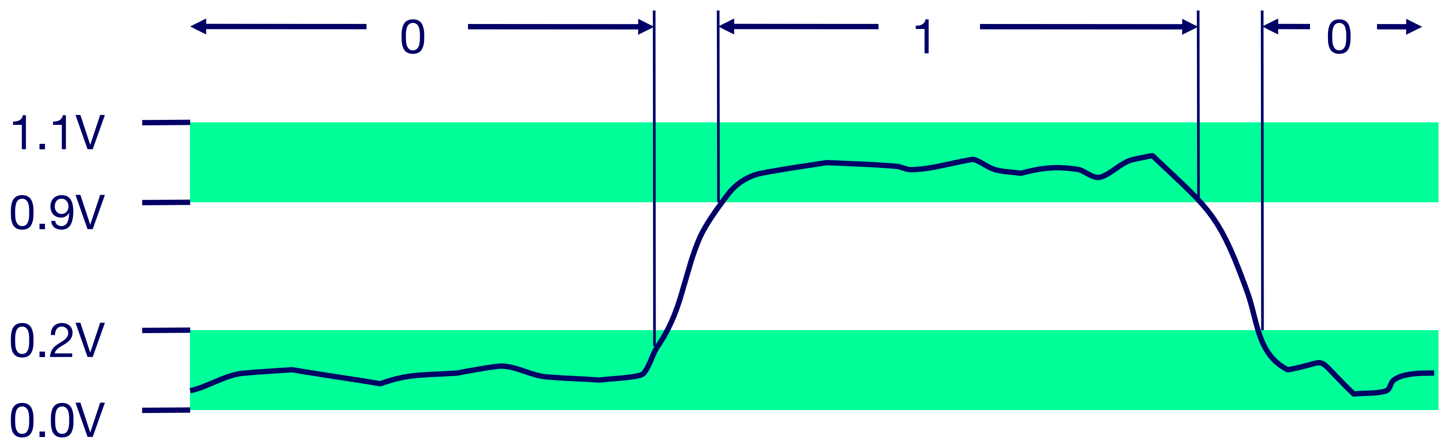


# Today: Bits, Bytes, and Integers

- **Representing information as bits**
- **Bit-level manipulations**
- **Integers**
  - Representation: unsigned and signed
  - Conversion, casting
  - Expanding, truncating
  - Addition, negation, multiplication, shifting
  - Summary
- **Representations in memory, pointers, strings**

# Everything is bits

- **Each bit is 0 or 1**
- **By encoding/interpreting sets of bits in various ways**
  - Computers determine what to do (instructions)
  - … and represent and manipulate numbers, sets, strings, etc…
- **Why bits?  Electronic Implementation**
  - Easy to store with bistable elements (双稳态器件)
  - Reliably transmitted on noisy and inaccurate wires



# For example, can count in binary

## Base 2 Number Representation

Represent $15213_{10}$ as $11101101101101_2$

Represent $1.20_{10}$ as $1.0011001100110011[0011]\ldots_2$

Represent $1.5213 \times 10^4$ as $1.1101101101101_2 \times 2^{13}$

# Encoding Byte Values

**Byte = 8 bits**

- Binary $00000000_2$ to $11111111_2$
- Decimal: $0_{10}$ to $255_{10}$
- Hexadecimal $00_{16}$ to $FF_{16}$
  - Base 16 number representation
  - Use characters '0' to '9' and 'A' to 'F'
  - Write $FA1D37B_{16}$ in C as
    - 0xFA1D37B
    - 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 |

15213: $\underbrace{\texttt{0011}}_{\texttt{3}}\ \underbrace{\texttt{1011}}_{\texttt{B}}\ \underbrace{\texttt{0110}}_{\texttt{6}}\ \underbrace{\texttt{1101}}_{\texttt{D}}$

# Example Data Representations

| C Data Type | Typical 32-bit | Typical 64-bit |
|---|---|---|
| `char` | 1 | 1 |
| `short` | 2 | 2 |
| `int` | 4 | 4 |
| `long` | 4 | 8 |
| `float` | 4 | 4 |
| `double` | 8 | 8 |
| pointer | 4 | 8 |

# Example Data Representations

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| `double` | 8 | 8 |
| pointer | 4 | 8 |
| | "ILP32" | "LP64" |

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# 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=1 and B=1

| & | 0 | 1 |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |

Or

A|B = 1 when either A=1 or B=1 or both

| \| | 0 | 1 |
|---|---|---|
| 0 | 0 | 1 |
| 1 | 1 | 1 |

Not

~A = 1 when A=0

| ~ | 0 | 1 |
|---|---|---|
| | 1 | 0 |

Exclusive-Or (Xor)

A^B = 1 when A=1 or B=1, but not both

| ^ | 0 | 1 |
|---|---|---|
| 0 | 0 | 1 |
| 1 | 1 | 0 |

# General Boolean Algebras

## Operate on Bit Vectors

Operations applied bitwise

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

# Bit-Level Operations in C

## Operations &, |, ~, ^ Available in C

- Apply to any "integral" data type
  - `long, int, short, char, unsigned`
- View arguments as bit vectors
- Arguments applied bit-wise

| 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 |
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# Contrast: Logic Operations in C

## Contrast to Bit-Level Operators

**Logic Operations: &&, ||, !**

- 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)

Watch out for && vs. & (and || vs. |)…
Super common C programming pitfall!

# Shift Operations

**Left Shift: `x << y`**

Shift bit-vector **`x`** left **`y`** positions

- Throw away extra bits on left

Fill with 0's on right

**Right Shift: `x >> y`**

Shift bit-vector **`x`** right **`y`** positions

Throw away extra bits on right

Logical shift

Fill with 0's on left

Arithmetic shift

Replicate most significant bit on left

**Undefined Behavior**

Shift amount < 0 or ≥ word size

| | |
|---|---|
| Argument **`x`** | `01100010` |
| `<< 3` | `00010000` |
| Log. `>> 2` | `00011000` |
| Arith. `>> 2` | `00011000` |

| | |
|---|---|
| Argument **`x`** | `10100010` |
| `<< 3` | `00010000` |
| Log. `>> 2` | `00101000` |
| Arith. `>> 2` | `11101000` |

# Today: Bits, Bytes, and Integers

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# Question?

```
int foo = -1;
unsigned bar = 1;

(foo < bar) == true ?
```

# Encoding "Integers"

**Unsigned**

**Signed (twos complement)**

Given a bit vector $x$, $w$ bits long…

$$\mathrm{B2U}(x) = \sum_{i=0}^{w-1} x_i \cdot 2^i$$

$$\mathrm{B2T}(x) = -x_{w-1} \cdot 2^{w-1} + \sum_{i=0}^{w-2} x_i \cdot 2^i$$

**Sign Bit**

## Examples (w = 5)

| ±16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|
| 0 | 1 | 0 | 1 | 0 |

$0 + 8 + 0 + 2 + 0 = 10$

| 16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 0 |
| -16 | 8 | 4 | 2 | 1 |

$16 + 8 + 0 + 2 + 0 = 26$

$-16 + 8 + 0 + 2 + 0 = -10$

# Negation: Complement & Increment

## Negate through complement and increase

`~x + 1 == -x`

## Why?

```
-x + x       == 0  (by definition)
~x + x       == 1111…111 == -1
~x + x + 1   == 0
(~x+1) + x   == 0
 ~x+1        == -x
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| x | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| + ~x | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| −1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

## Example: x = 15213

| | Decimal | Hex | Binary |
|---|---|---|---|
| `x` | 15213 | 3B 6D | 00111011 01101101 |
| `~x` | -15214 | C4 92 | 11000100 10010010 |
| `~x+1` | -15213 | C4 93 | 11000100 10010011 |
| `y` | -15213 | C4 93 | 11000100 10010011 |

# Complement & Increment Examples

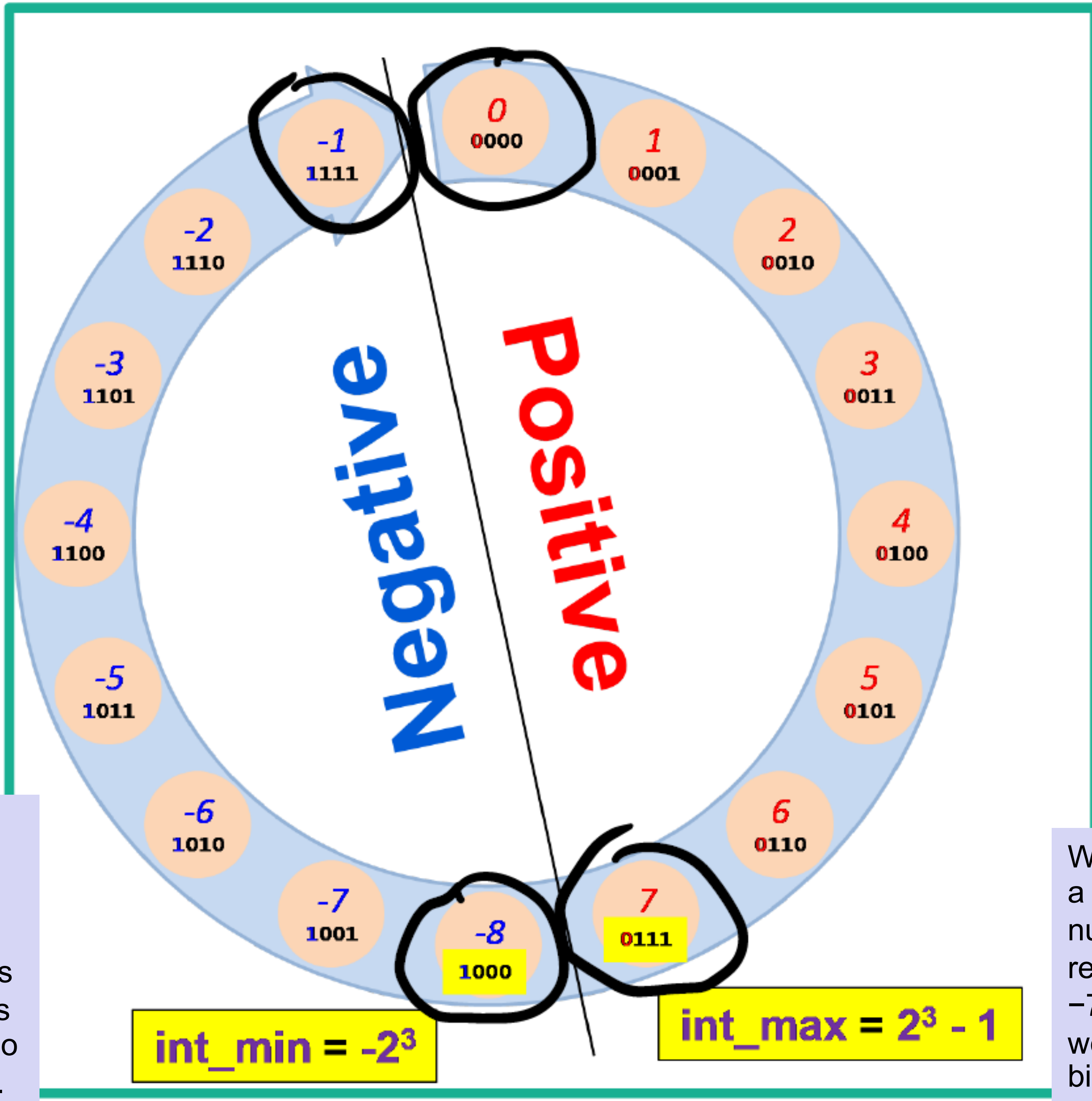
$x = 0$

| | Decimal | Hex | Binary |
|---|---|---|---|
| 0 | **0** | 00 00 | 00000000 00000000 |
| ~0 | **-1** | FF FF | 11111111 11111111 |
| ~0+1 | **0** | 00 00 | 00000000 00000000 |

$x = T_{\min}$

| | Decimal | Hex | Binary |
|---|---|---|---|
| x | **-32768** | 80 00 | 10000000 00000000 |
| ~x | **32767** | 7F FF | 01111111 11111111 |
| ~x+1 | **-32768** | 80 00 | 10000000 00000000 |

Oops!
It's still
negative!




Eight negative values:
−1, − 2, …, − 8

Eight *non*-negative values:
0, 1, …, 7

Mathematicians would prefer it if a 4-bit signed number could represent values −8…8, but that's $2^4 + 1$ values, so they won't all fit.

What if we made a 4-bit signed number only represent values −7…7? Then we wouldn't be using bit pattern `1000`…

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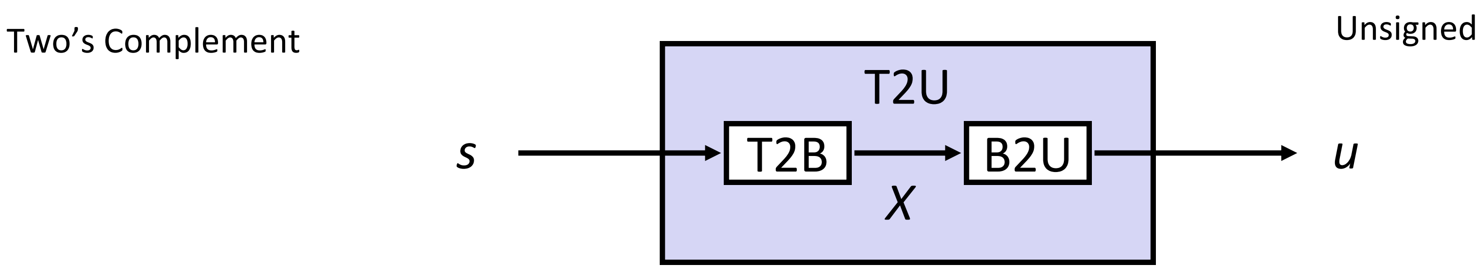
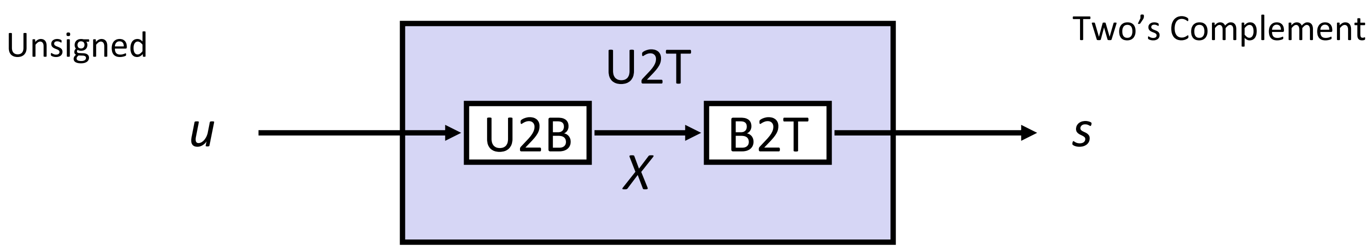
# Mapping Between Signed & Unsigned



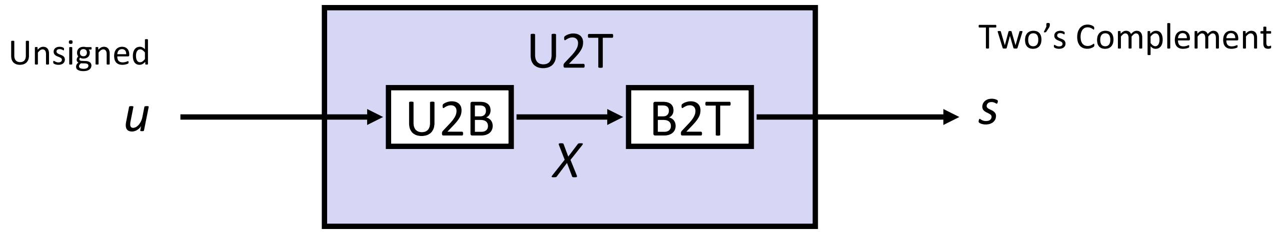

Maintain Same Bit Pattern



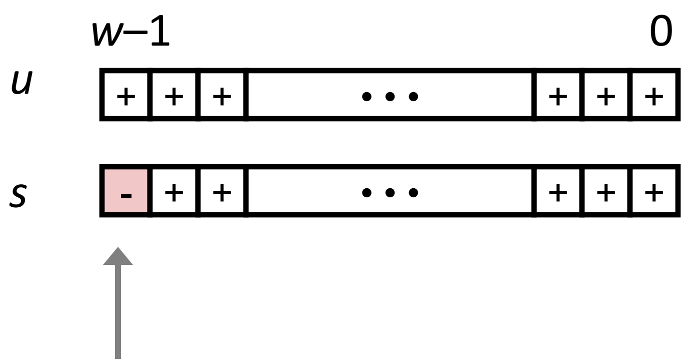

Maintain Same Bit Pattern

**Mappings between unsigned and two's complement numbers:**
**Keep bit representations and reinterpret**

# Relation between Signed & Unsigned




Maintain Same Bit Pattern




Large positive weight
*becomes*
Large negative weight

# Mapping Signed ↔ Unsigned

| Bits | Signed | Unsigned |
|---|---|---|
| 0000 | 0 | 0 |
| 0001 | 1 | 1 |
| 0010 | 2 | 2 |
| 0011 | 3 | 3 |
| 0100 | 4 | 4 |
| 0101 | 5 | 5 |
| 0110 | 6 | 6 |
| 0111 | 7 | 7 |
| 1000 | -8 | 8 |
| 1001 | -7 | 9 |
| 1010 | -6 | 10 |
| 1011 | -5 | 11 |
| 1100 | -4 | 12 |
| 1101 | -3 | 13 |
| 1110 | -2 | 14 |
| 1111 | -1 | 15 |

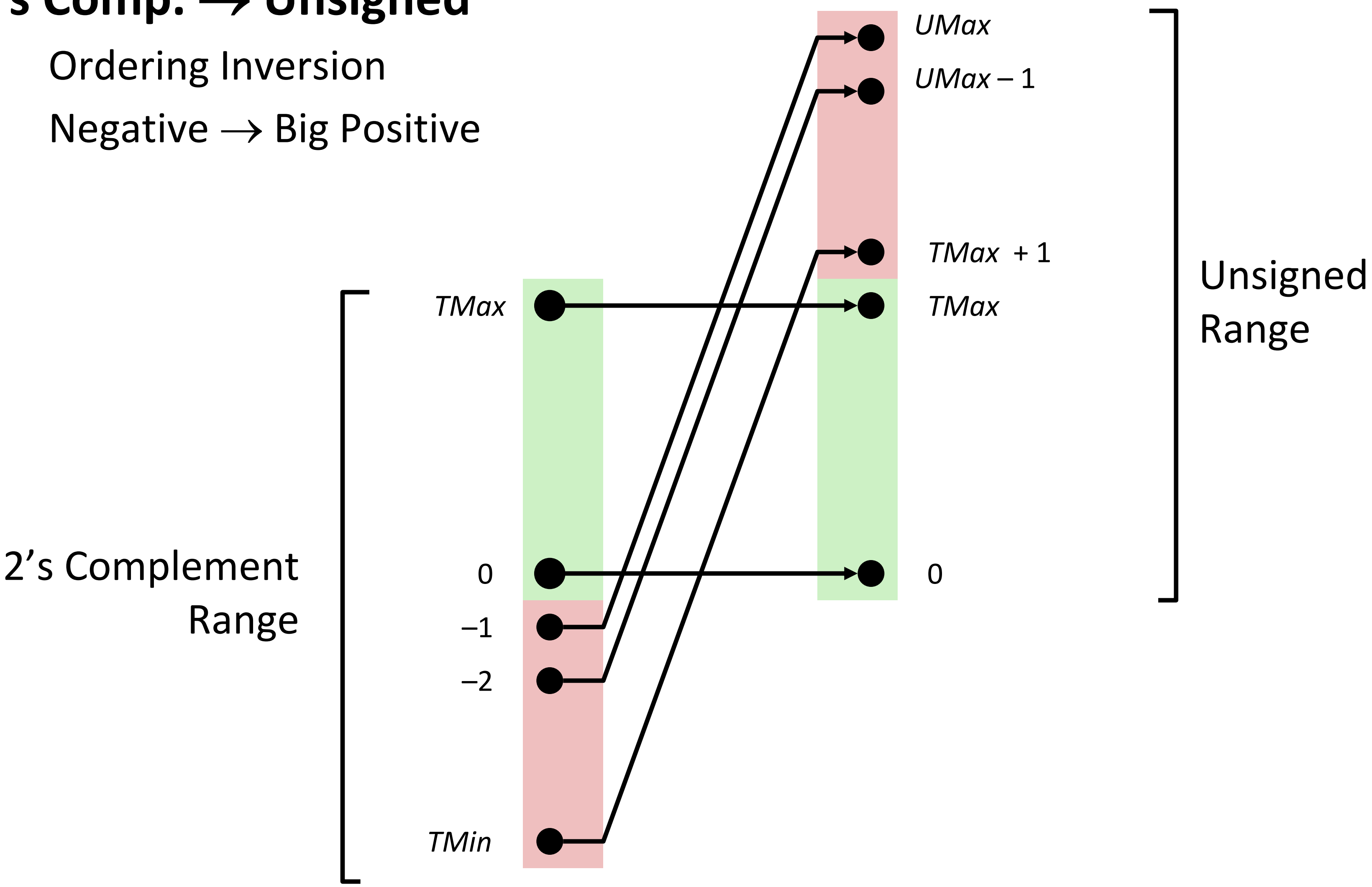
=

$\pm 16$

# Conversion Visualized

**2’s Comp. → Unsigned**

- Ordering Inversion
- Negative → Big Positive



# Signed vs. Unsigned in C

## Constants

- By default are considered to be signed integers
- Unsigned if have "U" as suffix

```
0U, 4294967259U
```

## Casting

- Explicit casting between signed & unsigned same as U2T and T2U

```
int tx, ty;
unsigned ux, uy;
tx = (int) ux;
uy = (unsigned) ty;
```

- Implicit casting also occurs via assignments and procedure calls

```
tx = ux;                int fun(unsigned u);
uy = ty;                uy = fun(tx);
```

# Casting Surprises

## Expression Evaluation

If there is a mix of unsigned and signed in single expression, ***signed values implicitly cast to unsigned***

Including comparison operations **<, >, ==, <=, >=**

Examples:

| **Constant 1** | **Constant 2** | **Relation** | **Evaluation** |
|---|---|---|---|
| `0` | `0U` | `==` | Unsigned |
| `-1` | `0` | `<` | Signed |
| `-1` | `0U` | `>` | Unsigned |
| `INT_MAX` | `INT_MIN` | `>` | Signed |
| `(unsigned)INT_MAX` | `INT_MIN` | `<` | Unsigned |
| `-1` | `-2` | `>` | Signed |
| `(unsigned)-1` | `-2` | `>` | Unsigned |
| `INT_MAX` | `((unsigned)INT_MAX) + 1` | `<` | Unsigned |
| `INT_MAX` | `(int)(((unsigned)INT_MAX) + 1)` | `>` | Signed |

# Question?

example02.c

```
int foo = -1;
unsigned bar = 1;

foo < bar == true ?
```

# Summary
# Casting Signed ↔ Unsigned: Basic Rules

- **Bit pattern is maintained**
- **But reinterpreted**
- **Can have unexpected effects: adding or subtracting $2^w$**

**Expression containing signed and unsigned int**

- `int` is cast to `unsigned`!!

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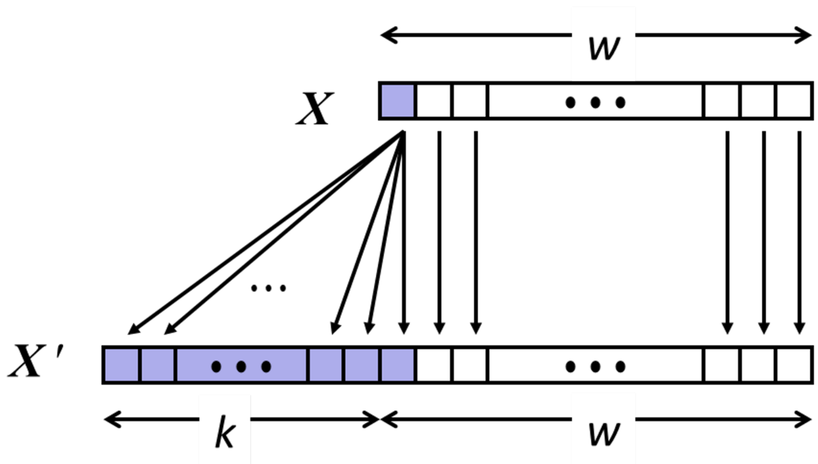
# Question?

example03.c

```
int x = 0x8000;
short sx = (short) x;
int y = sx;
```

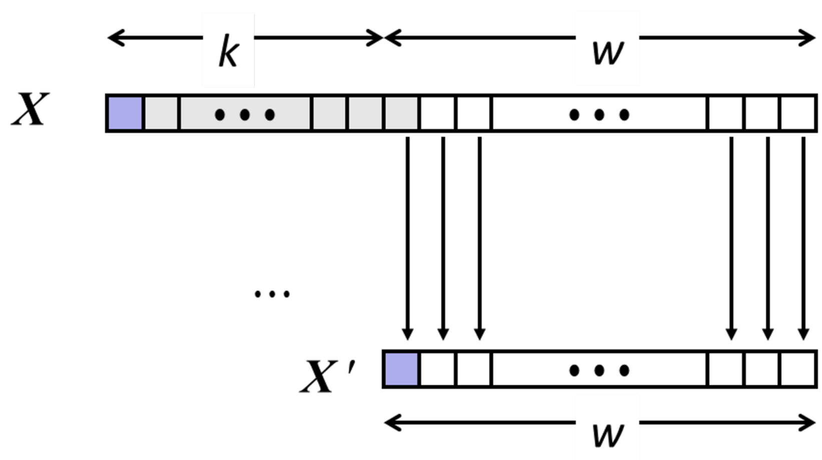
# Sign Extension and Truncation

## Sign Extension




Make *k* copies of sign bit

## Truncation




Chop off *k* highest bits

# Sign Extension: Simple Example

Positive number

| | -16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|
| 10 = | 0 | 1 | 0 | 1 | 0 |

| | -32 | 16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|---|
| 10 = | 0 | 0 | 1 | 0 | 1 | 0 |

Negative number

| | -16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|
| -10 = | 1 | 0 | 1 | 1 | 0 |

| | -32 | 16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|---|
| -10 = | 1 | 1 | 0 | 1 | 1 | 0 |

# Truncation: Simple Example

No sign change

| | -16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|
| 2 = | 0 | 0 | 0 | 1 | 0 |

| | -8 | 4 | 2 | 1 |
|---|---|---|---|---|
| 2 = | 0 | 0 | 1 | 0 |

| | -16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|
| -6 = | 1 | 1 | 0 | 1 | 0 |

| | -8 | 4 | 2 | 1 |
|---|---|---|---|---|
| -6 = | 1 | 0 | 1 | 0 |

Sign change

| | -16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|
| 10 = | 0 | 1 | 0 | 1 | 0 |

| | -8 | 4 | 2 | 1 |
|---|---|---|---|---|
| -6 = | 1 | 0 | 1 | 0 |

| | -16 | 8 | 4 | 2 | 1 |
|---|---|---|---|---|---|
| -10 = | 1 | 0 | 1 | 1 | 0 |

| | -8 | 4 | 2 | 1 |
|---|---|---|---|---|
| 6 = | 0 | 1 | 1 | 0 |

# Question?

example03.c

```
int x = 0x8000;
short sx = (short) x;
int y = sx;
```

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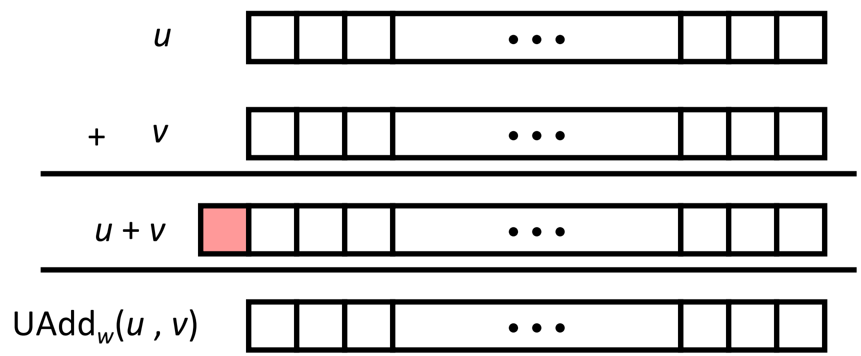
# Unsigned Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits




**Standard Addition Function**

Ignores carry output

```
unsigned char     1110 1001       E9       233
              +   1101 0101     + D5     + 213
                  _________     ____     _____

                  _________     ____     _____
```

| 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 |
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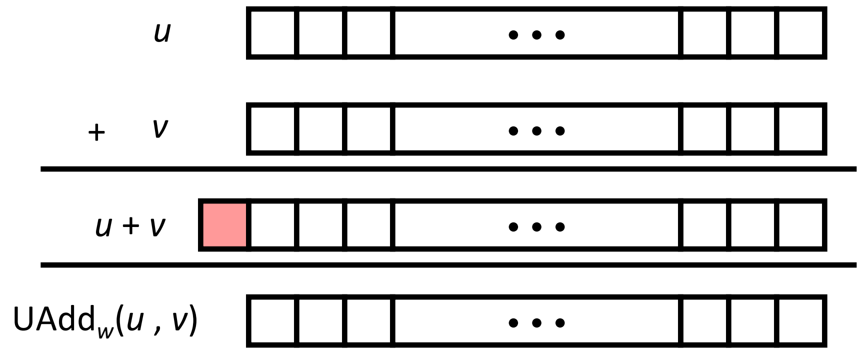


**Standard Addition Function**

Ignores carry output

```
unsigned char      1110 1001        E9        233
                 +   1101 0101      + D5      + 213
                   1 1011 1110       1BE        446
                     1011 1110        BE        190
```

| Hex | Decimal | Binary |
|---|---|---|
| 0 | 0 | 0000 |
| 1 | 1 | 0001 |
| 2 | 2 | 0010 |
| 3 | 3 | 0011 |
| 4 | 4 | 0100 |
| 5 | 5 | 0101 |
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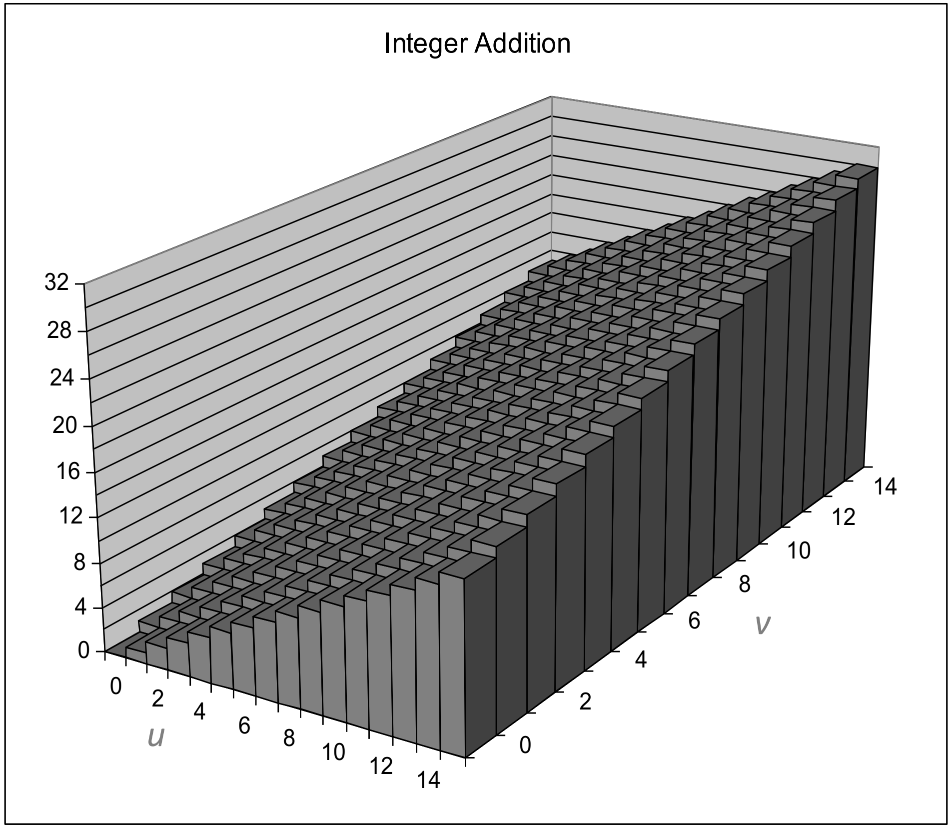
# Visualizing (Mathematical) Integer Addition

## Integer Addition

- 4-bit integers *u*, *v*
- Compute true sum $\text{Add}_4(u , v)$
- Values increase linearly with *u* and *v*
- Forms planar surface

$\text{Add}_4(u , v)$

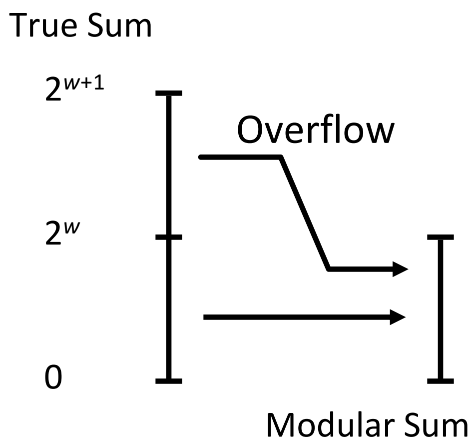


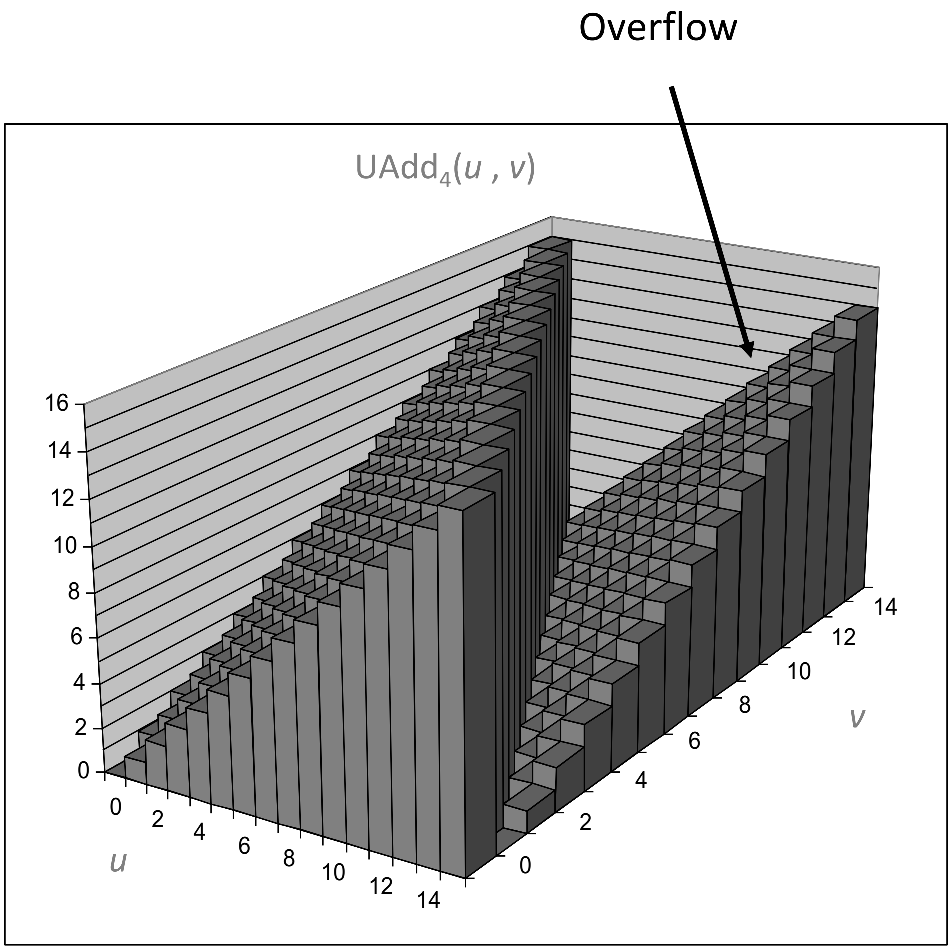
# Visualizing Unsigned Addition

## Wraps Around

If true sum ≥ $2^w$

At most once



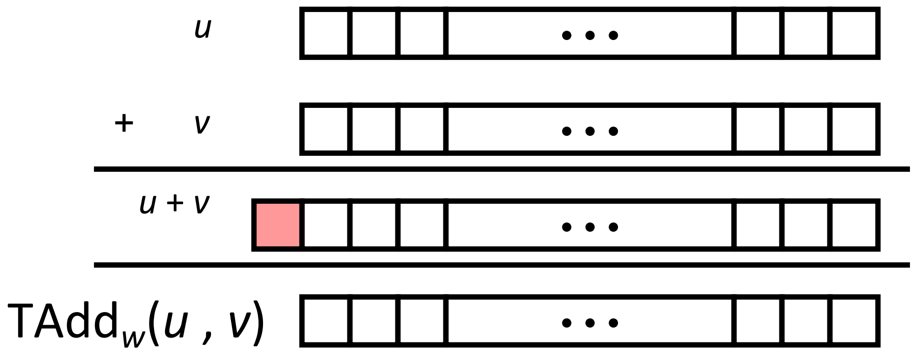



# Two's Complement Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits




## TAdd and UAdd have Identical Bit-Level Behavior

Signed vs. unsigned addition in C:

```
int s, t, u, v;
s = (int) ((unsigned) u + (unsigned) v);
t = u + v
```

Will give `s == t`

```
    1110 1001      E9      -23
+   1101 0101    + D5    + -43
  1 1011 1110     1BE      -66
    1011 1110      BE      -66
```

# Visualizing 2's Complement Addition

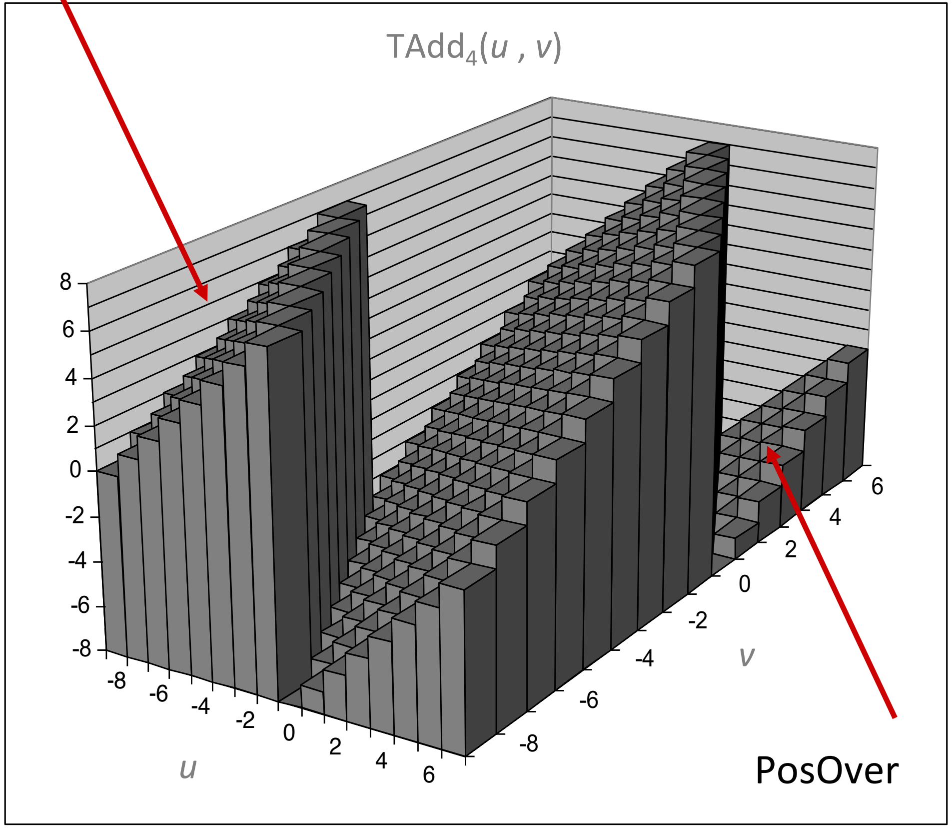
**Values**

- 4-bit two's comp.
- Range from -8 to +7

**Wraps Around**

- If sum $\geq 2^{w-1}$
  - Becomes negative
  - At most once
- If sum $< -2^{w-1}$
  - Becomes positive
  - At most once

NegOver

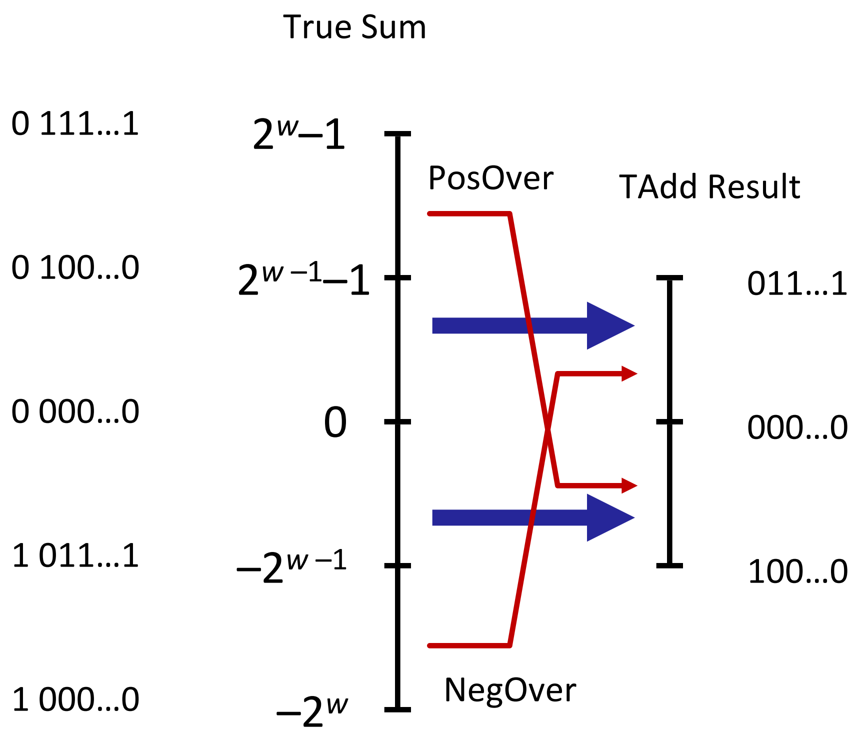



PosOver

# TAdd Overflow

## Functionality

- True sum requires $w$+1 bits
- Drop off MSB
- Treat remaining bits as 2's comp. integer



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# Shifting

**Left Shift: `x << y`**

- Shift bit-vector x left y positions
  - Throw away extra bits on left
  - Fill with 0's on right
  - Equivalent to multiplying by $2^y$

**Right Shift: `x >> y`**

- Shift bit-vector x right y positions
  - Throw away extra bits on right
- Two kinds:
  - "Logical": Fill with 0's on left
  - "Arithmetic": Replicate most significant bit on left
- *Almost* equivalent to dividing by $2^y$

**Undefined Behavior (in C)**

- Shift amount < 0 or ≥ word size

| Argument x | 01100010 |
|---|---|
| << 3 | 00010000 |
| Logical >> 2 | 00011000 |
| Arithmetic >> 2 | 00011000 |

| Argument x | 10100010 |
|---|---|
| << 3 | 00010000 |
| Logical >> 2 | 00101000 |
| Arithmetic >> 2 | 11101000 |

# Multiplication

**Goal: Computing Product of *w*-bit numbers *x*, *y***

Either signed or unsigned

**But, exact results can be bigger than *w* bits**

Unsigned: up to $2w$ bits

Result range: $0 \le x * y \le (2^w - 1)^2 = 2^{2w} - 2^{w+1} + 1$

Two's complement min (negative): Up to $2w$-1 bits

Result range: $x * y \ge (-2^{w-1})*(2^{w-1}-1) = -2^{2w-2} + 2^{w-1}$

Two's complement max (positive): Up to $2w$ bits, but only for $(TMin_w)^2$

Result range: $x * y \le (-2^{w-1})^2 = 2^{2w-2}$

**So, maintaining exact results…**

would need to keep expanding word size with each product computed

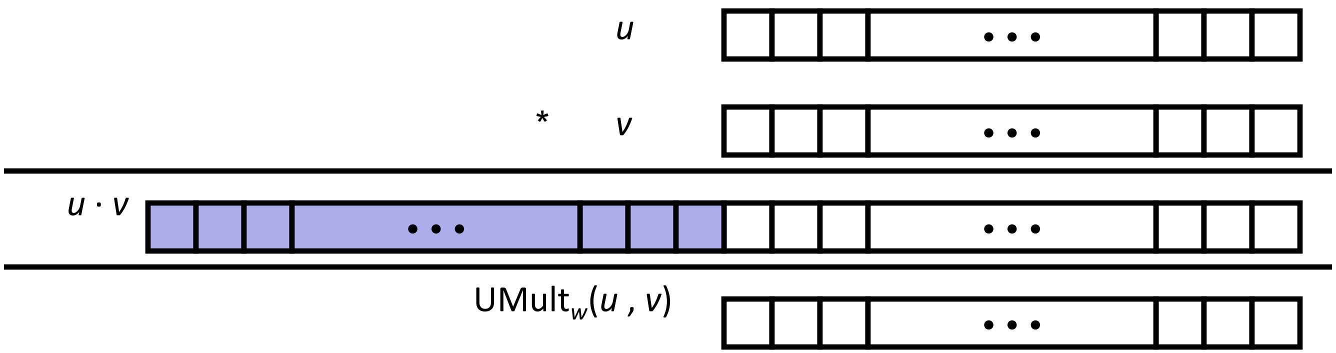
is done in software, if needed

# Unsigned Multiplication in C

Operands: $w$ bits

True Product: $2*w$ bits

Discard $w$ bits: $w$ bits

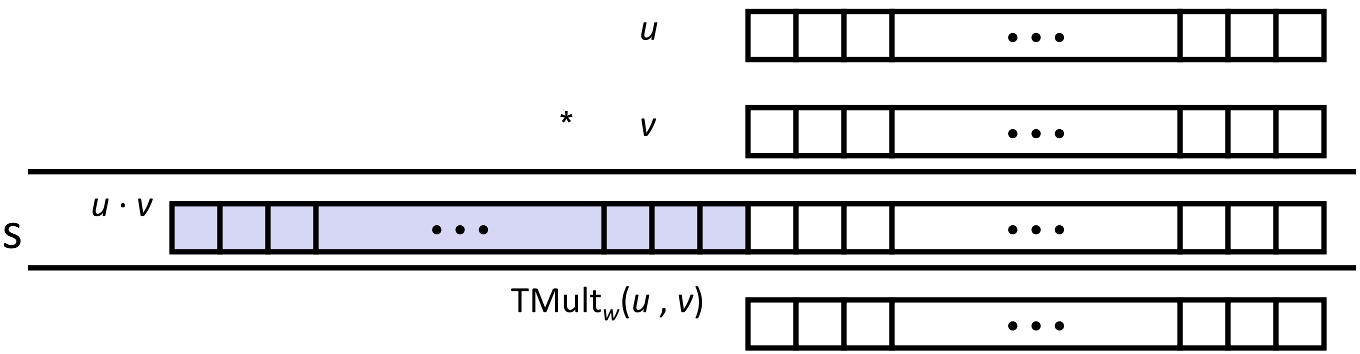



## Standard Multiplication Function

Ignores high order $w$ bits

```
               1110 1001       E9        233
*              1101 0101    *  D5    *   213
 1100 0001 1101 1101         C1DD      49629
               1101 1101       DD        221
```

# Signed Multiplication in C




Operands: *w* bits

True Product: 2**w* bits

Discard *w* bits: *w* bits

## Standard Multiplication Function

Ignores high order *w* bits

Some of which are different for signed vs. unsigned multiplication

Lower bits are the same

```
            1110 1001       E9          -23
*           1101 0101   *   D5   *      -43
 0000 0011  1101 1101     03DD          989
            1101 1101       DD          -35
```

# Power-of-2 Multiply with Shift

## Operation

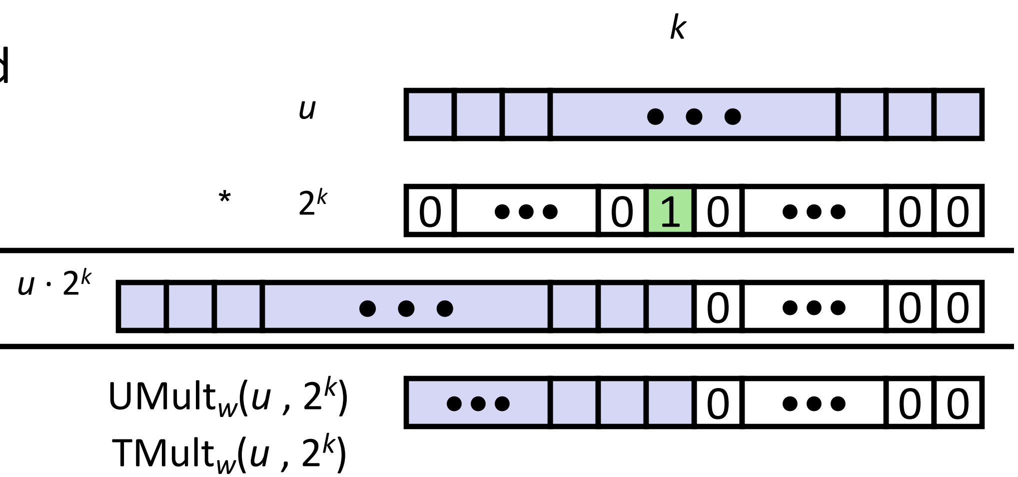
**u << k** gives **u * $2^k$**

Both signed and unsigned

Operands: $w$ bits

True Product: $w+k$ bits

Discard $k$ bits: $w$ bits




## Examples

`u << 3 == u * 8`

`(u << 5) - (u << 3) == u * 24`

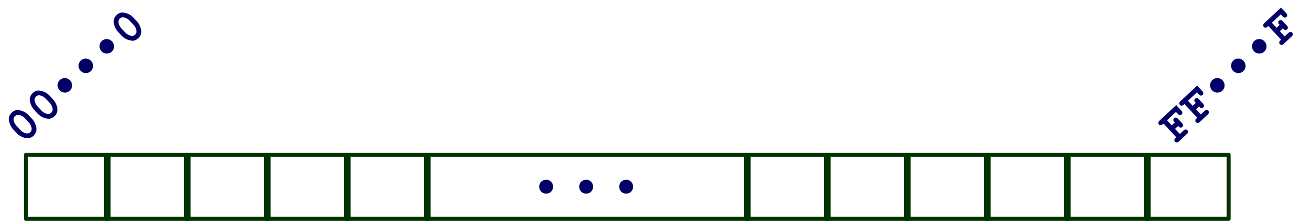
Most machines shift and add faster than multiply

Compiler generates this code automatically

# Today: Bits, Bytes, and Integers

- Representing information as bits
- Bit-level manipulations
- Integers
  - Representation: unsigned and signed
  - Conversion, casting
  - Expanding, truncating
  - Addition, negation, multiplication, shifting
  - Summary
- **Byte order in memory, pointers, strings**

# Byte-Oriented Memory Organization




## Programs refer to data by address

- Imagine all of RAM as an enormous array of bytes
- An address is an index into that array
  - A pointer variable stores an address

## System provides a private *address space* to each "process"

- A process is an instance of a program, being executed
- An address space is one of those enormous arrays of bytes
- Each program can see only its own code and data within its enormous array
- We'll come back to this later ("virtual memory" classes)

# Machine Words

**Any given computer has a “Word Size”**

Nominal size of integer-valued data

and of addresses

Historically, most machines used 32 bits (4 bytes) as word size

Limits addresses to 4GB ($2^{32}$ bytes)

Recently, machines have 64-bit word size

Potentially, could have 16 EB (exabytes) of addressable memory

That’s $18.4 \times 10^{18}$ bytes

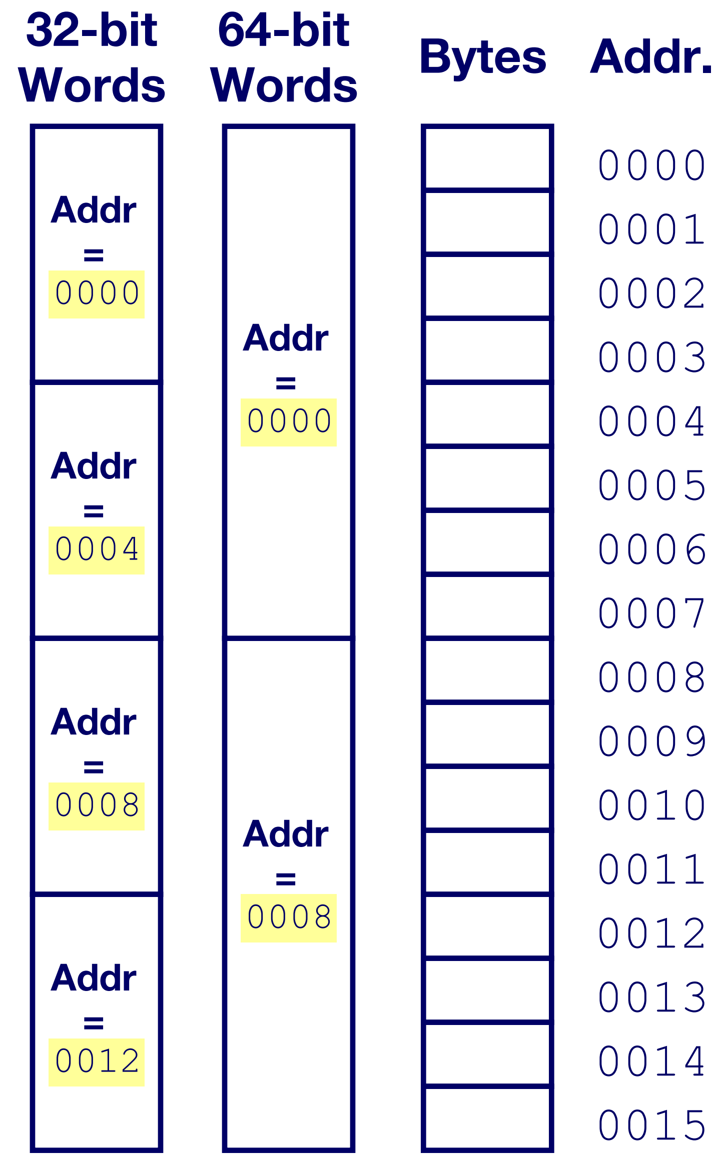
Machines still support multiple data formats

Fractions or multiples of word size

Always integral number of bytes

# Addresses *Always* Specify Byte Locations

- Address of a word is address of the first byte in the word
- Addresses of successive words differ by 4 (32-bit) or 8 (64-bit)



# Example Data Representations

| C Data Type | Typical 32-bit | Typical 64-bit | x86-64 |
|---|---|---|---|
| `char` | 1 | 1 | 1 |
| `short` | 2 | 2 | 2 |
| `int` | 4 | 4 | 4 |
| `long` | 4 | 8 | 8 |
| `float` | 4 | 4 | 4 |
| `double` | 8 | 8 | 8 |
| pointer | 4 | 8 | 8 |

# Question?

example04.c

```
struct foo {
    char mem1[3];  // 3 bytes
    int mem2;      // 4 bytes
    char mem3;     // 1 byte
};
sizeof(struct foo) = ?
```

# Byte Ordering

- **So, how are the bytes within a multi-byte word ordered in memory?**
- **Conventions**
  - Big Endian: Sun, PPC Mac, *network packet headers*
    - Least significant byte has highest address
  - Little Endian: *x86*, ARM processors running Android, iOS, and Windows
    - Least significant byte has lowest address

# Byte Ordering Example

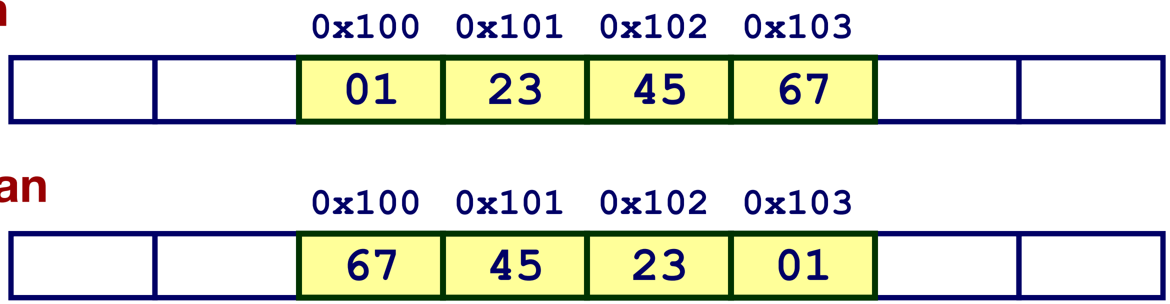
## Example

Variable x has 4-byte value of 0x01234567

Address given by &x is 0x100

**Big Endian**

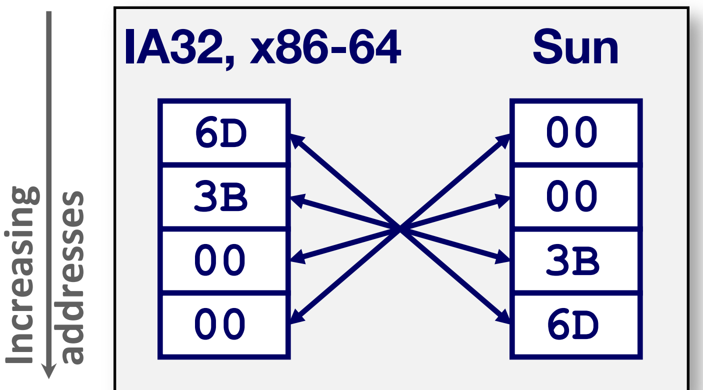
**Little Endian**



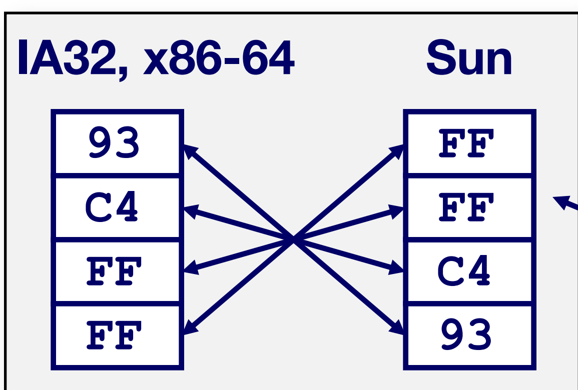
# Representing Integers

| | | | | |
|---|---|---|---|---|
| **Decimal:** | 15213 | | | |
| **Binary:** | 0011 | 1011 | 0110 | 1101 |
| **Hex:** | 3 | B | 6 | D |

`int A = 15213;`

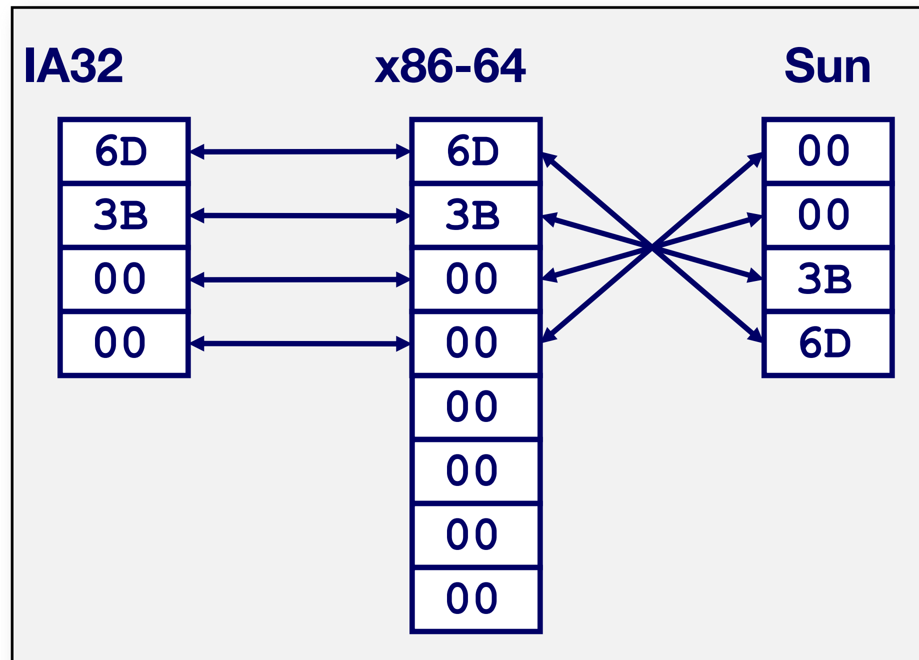



`int B = -15213;`




**Two's complement representation**

`long int C = 15213;`



# Examining Data Representations

## Code to Print Byte Representation of Data

Casting pointer to unsigned char * allows treatment as a byte array

```
typedef unsigned char *pointer;

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

**Printf directives:**

%p**:** Print pointer

%x**:** Print Hexadecimal

# show_bytes Execution Example

```
int a = 15213;
printf("int a = 15213;\n");
show_bytes((pointer) &a, sizeof(int));
```

**Result (Linux x86-64):**

```
int a = 15213;
0x7fffb7f71dbc    6d
0x7fffb7f71dbd    3b
0x7fffb7f71dbe    00
0x7fffb7f71dbf    00
```

# Representing Pointers

```
int B = -15213;
int *P = &B;
```

| Sun | IA32 | x86-64 |
|---|---|---|
| EF | AC | 3C |
| FF | 28 | 1B |
| FB | F5 | FE |
| 2C | FF | 82 |
| | | FD |
| | | 7F |
| | | 00 |
| | | 00 |

- Different compilers & machines assign different locations to objects
- Even get different results each time run program

# Representing Strings

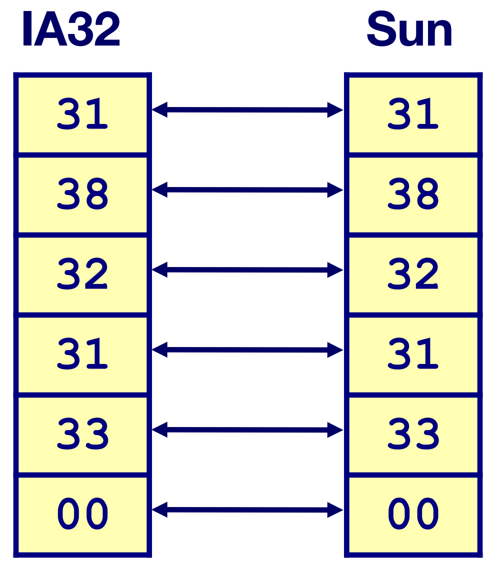
```
char S[6] = "18213";
```

## Strings in C

- Represented by array of characters
- Each character encoded in ASCII format
  - Standard 7-bit encoding of character set
  - Character “0” has code 0x30
    - Digit *i* has code 0x30+*i*
- String should be null-terminated
  - Final character = 0

## Compatibility

- Byte ordering not an issue



# Representing x86 machine code

## x86 machine code is a sequence of *bytes*

Grouped into variable-length instructions, which look like strings…

But they contain embedded little-endian numbers…

## Example Fragment

| Address | Instruction Code | Assembly Rendition |
|---|---|---|
| `8048365:` | `5b` | `pop %ebx` |
| `8048366:` | `81 c3 ab 12 00 00` | `add $0x12ab,%ebx` |
| `804836c:` | `83 bb 28 00 00 00 00` | `cmpl $0x0,0x28(%ebx)` |

## Deciphering Numbers

| | |
|---|---|
| Value: | `0x12ab` |
| Pad to 32 bits: | `0x000012ab` |
| Split into bytes: | `00 00 12 ab` |
| Reverse: | `ab 12 00 00` |