# Bits, Bytes and Integers

Introduction to Computer Systems
1st and 2nd Lectures, Feb. 22 and Mar. 1, 2019

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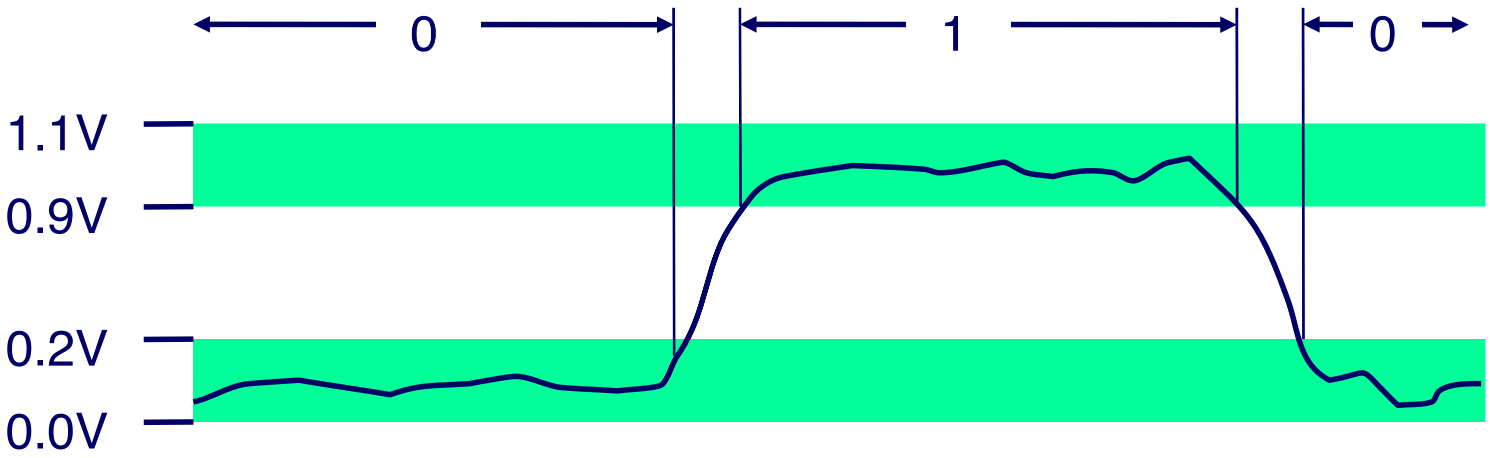
# Today: Bits, Bytes, and Integers

- **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 bi-stable elements
  - 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 $1.0011001100110011[0011]..._2$
  - 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 |

# 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 |
| `long double` | − | − | 10/16 |
| pointer | 4 | 8 | 8 |

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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**

| \| | 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 either 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
```

- **All of the Properties of Boolean Algebra Apply**

# Example: 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 &, |, ~, ^ 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 → 0xD6
    - ~$00101001_2$ → $11010110_2$
  - ~0x00 → 0xFF
    - ~$00000000_2$ → $11111111_2$
  - 0x69 & 0x55 → 0x41
    - $01101001_2$ & $01010101_2$ → $01000001_2$
  - 0x69 | 0x55 → 0x7D
    - $01101001_2$ | $01010101_2$ → $01111101_2$

# 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)

# Contrast: Logic Operations in C

- **Contrast to Logical Operators**
  - `&&, ||, !`
    - View 0 as "Fal
    - Anything nonze
    - Alway
    - Early
- **Example**
  - `!0x41`
  - `!0x00`
  - `!!0x41`

  - `0x69 && 0x55` → `0x01`
  - `0x69 || 0x55` → `0x01`
  - `p && *p` (avoids null pointer access)

**Watch out for && vs. & (and || vs. |)… one of the more common opposites in C programming**

# 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** | 00010*000* |
| **Log. >> 2** | *00*011000 |
| **Arith. >> 2** | *00*011000 |

| | |
|---|---|
| **Argument x** | 10100010 |
| **<< 3** | 00010*000* |
| **Log. >> 2** | *00*101000 |
| **Arith. >> 2** | *11*101000 |

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# Encoding Integers

**Unsigned**

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

**Two's Complement**

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

**Sign Bit**

```
short int x =  15213;
short int y = -15213;
```

- **C `short` 2 bytes long**

| | Decimal | Hex | Binary |
|---|---|---|---|
| `x` | 15213 | `3B 6D` | `00111011 01101101` |
| `y` | -15213 | `C4 93` | `11000100 10010011` |

- **Sign Bit**
  - For 2's complement, most significant bit indicates sign
    - 0 for nonnegative
    - 1 for negative

# Two-complement Encoding Example (Cont.)

```
x =      15213: 00111011 01101101
y =     -15213: 11000100 10010011
```

| Weight | 15213 | | -15213 | |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 |
| 2 | 0 | 0 | 1 | 2 |
| 4 | 1 | 4 | 0 | 0 |
| 8 | 1 | 8 | 0 | 0 |
| 16 | 0 | 0 | 1 | 16 |
| 32 | 1 | 32 | 0 | 0 |
| 64 | 1 | 64 | 0 | 0 |
| 128 | 0 | 0 | 1 | 128 |
| 256 | 1 | 256 | 0 | 0 |
| 512 | 1 | 512 | 0 | 0 |
| 1024 | 0 | 0 | 1 | 1024 |
| 2048 | 1 | 2048 | 0 | 0 |
| 4096 | 1 | 4096 | 0 | 0 |
| 8192 | 1 | 8192 | 0 | 0 |
| 16384 | 0 | 0 | 1 | 16384 |
| -32768 | 0 | 0 | 1 | -32768 |
| **Sum** | | **15213** | | **-15213** |

# Numeric Ranges

- **Unsigned Values**
  - *UMin* = 0

    000…0
  - *UMax* = $2^w - 1$

    111…1

- **Two's Complement Values**
  - *TMin* = $-2^{w-1}$

    100…0
  - *TMax* = $2^{w-1} - 1$

    011…1

- **Other Values**
  - Minus 1

    111…1

**Values for *W* = 16**

| | Decimal | Hex | Binary |
|---|---|---|---|
| UMax | 65535 | FF FF | 11111111 11111111 |
| TMax | 32767 | 7F FF | 01111111 11111111 |
| TMin | -32768 | 80 00 | 10000000 00000000 |
| -1 | -1 | FF FF | 11111111 11111111 |
| 0 | 0 | 00 00 | 00000000 00000000 |

# Values for Different Word Sizes

| | W | | | |
|---|---|---|---|---|
| | **8** | **16** | **32** | **64** |
| **UMax** | 255 | 65,535 | 4,294,967,295 | 18,446,744,073,709,551,615 |
| **TMax** | 127 | 32,767 | 2,147,483,647 | 9,223,372,036,854,775,807 |
| **TMin** | -128 | -32,768 | -2,147,483,648 | -9,223,372,036,854,775,808 |

- **Observations**
  - $|TMin| = TMax + 1$
    - Asymmetric range
  - $UMax = 2 * TMax + 1$

- **C Programming**
  - #include <limits.h>
  - Declares constants, e.g.,
    - ULONG_MAX
    - LONG_MAX
    - LONG_MIN
  - Values platform specific

# Unsigned & Signed Numeric Values

| $X$ | B2U($X$) | B2T($X$) |
|---|---|---|
| 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 | 9 | –7 |
| 1010 | 10 | –6 |
| 1011 | 11 | –5 |
| 1100 | 12 | –4 |
| 1101 | 13 | –3 |
| 1110 | 14 | –2 |
| 1111 | 15 | –1 |

- **Equivalence**
  - Same encodings for nonnegative values
- **Uniqueness**
  - Every bit pattern represents unique integer value
  - Each representable integer has unique bit encoding
- **$\Rightarrow$ Can Invert Mappings**
  - U2B($x$) = B2U$^{-1}$($x$)
    - Bit pattern for unsigned integer
  - T2B($x$) = B2T$^{-1}$($x$)
    - Bit pattern for two's comp integer

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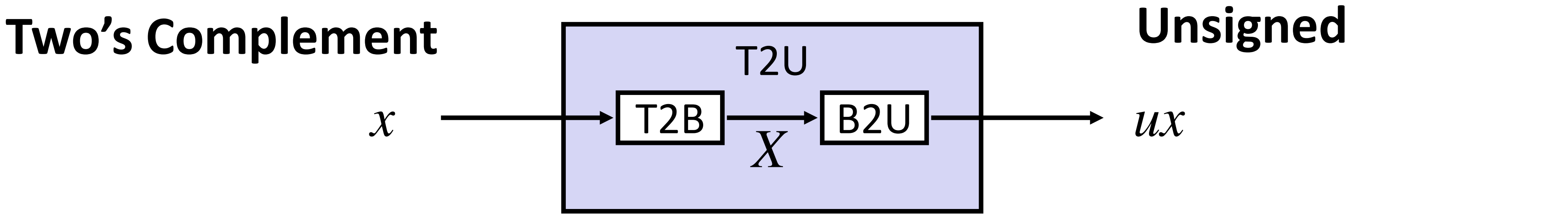
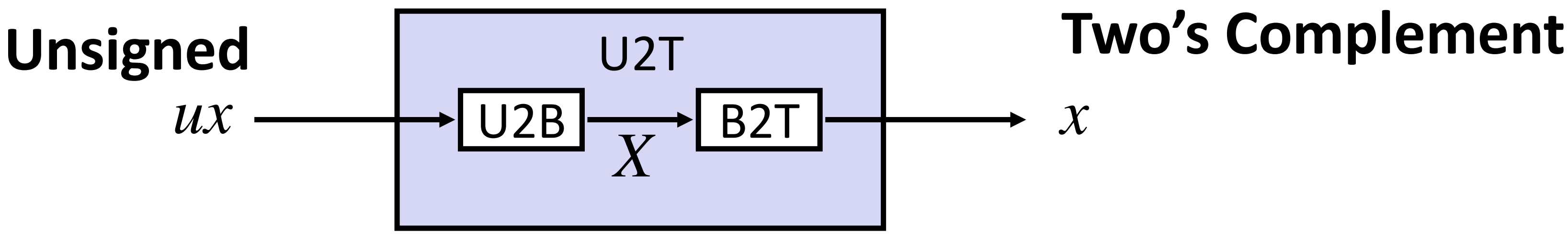
# Mapping Between Signed & Unsigned




Maintain Same Bit Pattern




Maintain Same Bit Pattern

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

# 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 |

→ T2U →

← U2T ←

# Mapping Signed ↔ Unsigned

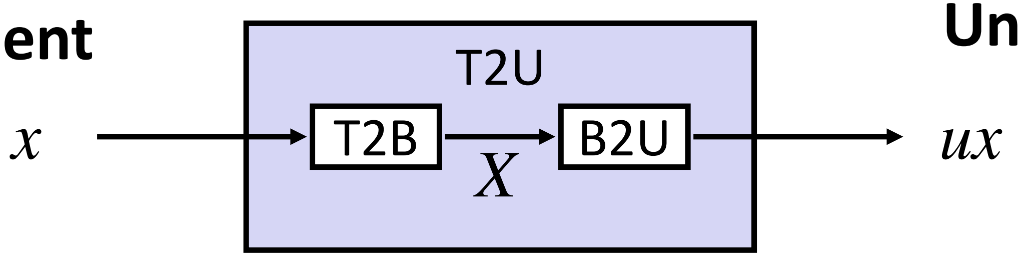
| Bits | Signed | Unsigned |
|---|---|---|
| 0000 | 0 | 0 |
| 0001 | 1 | 1 |
| 0010 | 2 | 2 |
| 0011 | 3 | 3 |
| 0100 | 4 | 4 |
| 0101 | 5 | 5 |
| 0110 | 6 | 6 |
| 0111 | 7 | 7 |
| 1000 | -8 | 8 |
| 1001 | -7 | 9 |
| 1010 | -6 | 10 |
| 1011 | -5 | 11 |
| 1100 | -4 | 12 |
| 1101 | -3 | 13 |
| 1110 | -2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

=

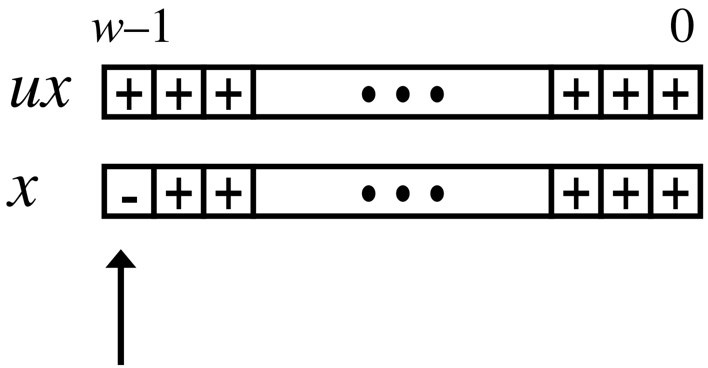
+/- 16

# Relation between Signed & Unsigned

**Two's Complement** **Unsigned**




Maintain Same Bit Pattern



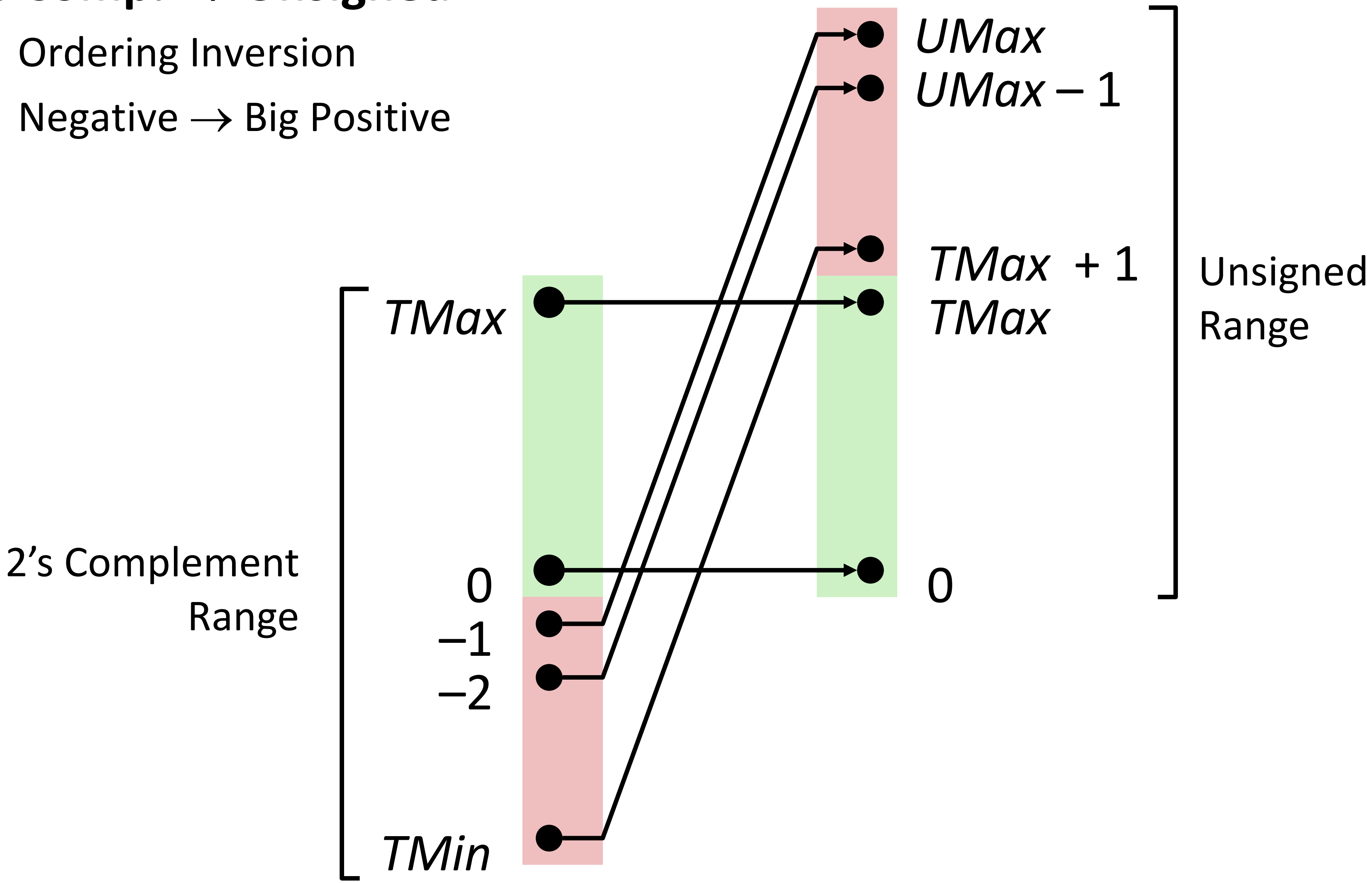

**Large negative weight**

*becomes*

**Large positive weight**

# 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;
    uy = ty;
    ```

# 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 for $W = 32$: **TMIN = -2,147,483,648 , TMAX = 2,147,483,647**

| Constant$_1$ | Constant$_2$ | Relation | Evaluation |
|---|---|---|---|
| 0 | 0U | == | unsigned |
| -1 | 0 | < | signed |
| -1 | 0U | > | unsigned |
| 2147483647 | -2147483647-1 | > | signed |
| 2147483647U | -2147483647-1 | < | unsigned |
| -1 | -2 | > | signed |
| (unsigned)-1 | -2 | > | unsigned |
| 2147483647 | 2147483648U | < | unsigned |
| 2147483647 | (int) 2147483648U | > | signed |

# 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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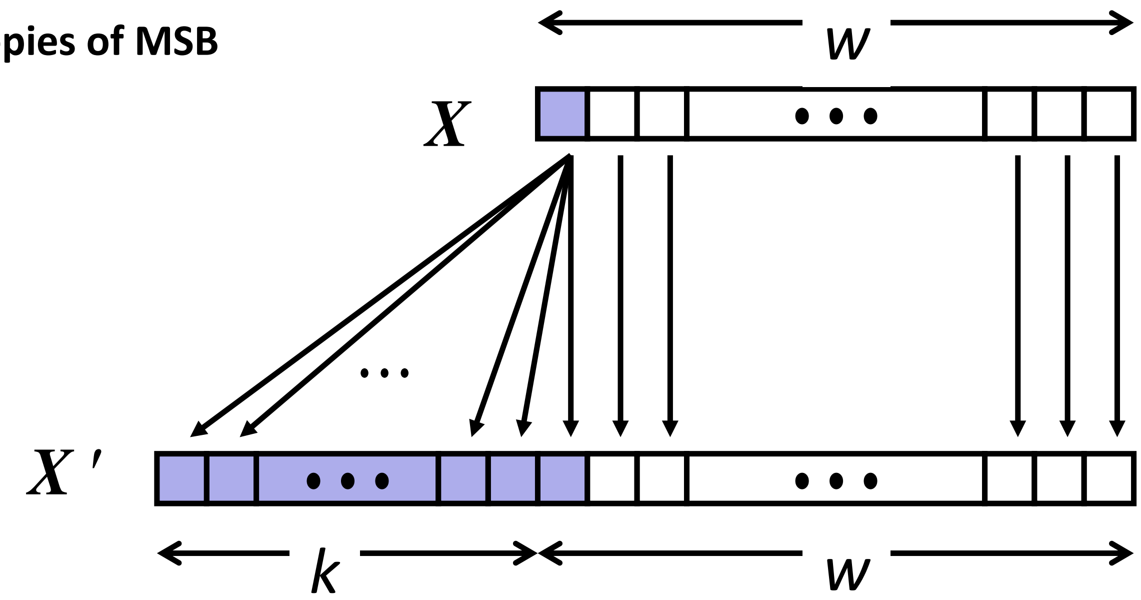
# Sign Extension

- **Task:**
  - Given $w$-bit signed integer $x$
  - Convert it to $w+k$-bit integer with same value
- **Rule:**
  - Make $k$ copies of sign bit:
  - $X' = \underbrace{x_{w-1}, \ldots, x_{w-1}}_{k \text{ copies of MSB}}, x_{w-1}, x_{w-2}, \ldots, x_0$



# Sign Extension Example

```
short int x =  15213;
int       ix = (int) x;
short int y = -15213;
int       iy = (int) y;
```

| | Decimal | Hex | Binary |
|---|---|---|---|
| x | 15213 | 3B 6D | 00111011 01101101 |
| ix | 15213 | 00 00 3B 6D | 00000000 00000000 00111011 01101101 |
| y | -15213 | C4 93 | 11000100 10010011 |
| iy | -15213 | FF FF C4 93 | 11111111 11111111 11000100 10010011 |

- Converting from smaller to larger integer data type
- C automatically performs sign extension

# Summary:
# Expanding, Truncating: Basic Rules

- **Expanding (e.g., short int to int)**
  - Unsigned: zeros added
  - Signed: sign extension
  - Both yield expected result

- **Truncating (e.g., unsigned to unsigned short)**
  - Unsigned/signed: bits are truncated
  - Result reinterpreted
  - Unsigned: mod operation
  - Signed: similar to mod
  - For small numbers yields expected behavior

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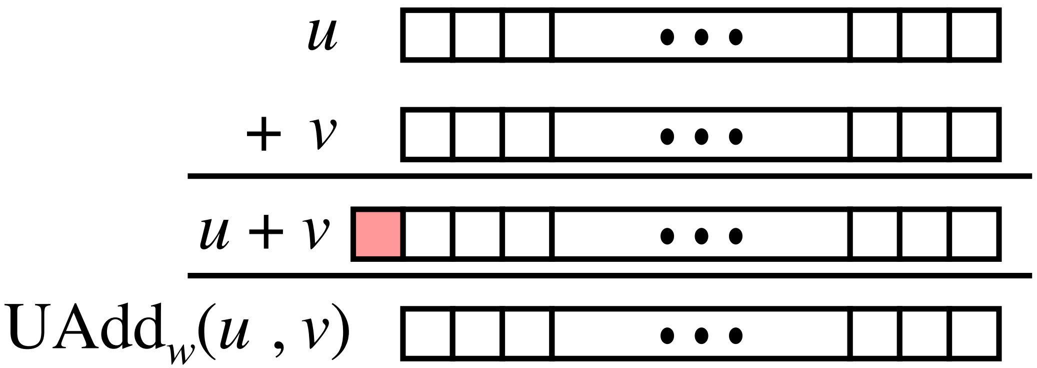
# Unsigned Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



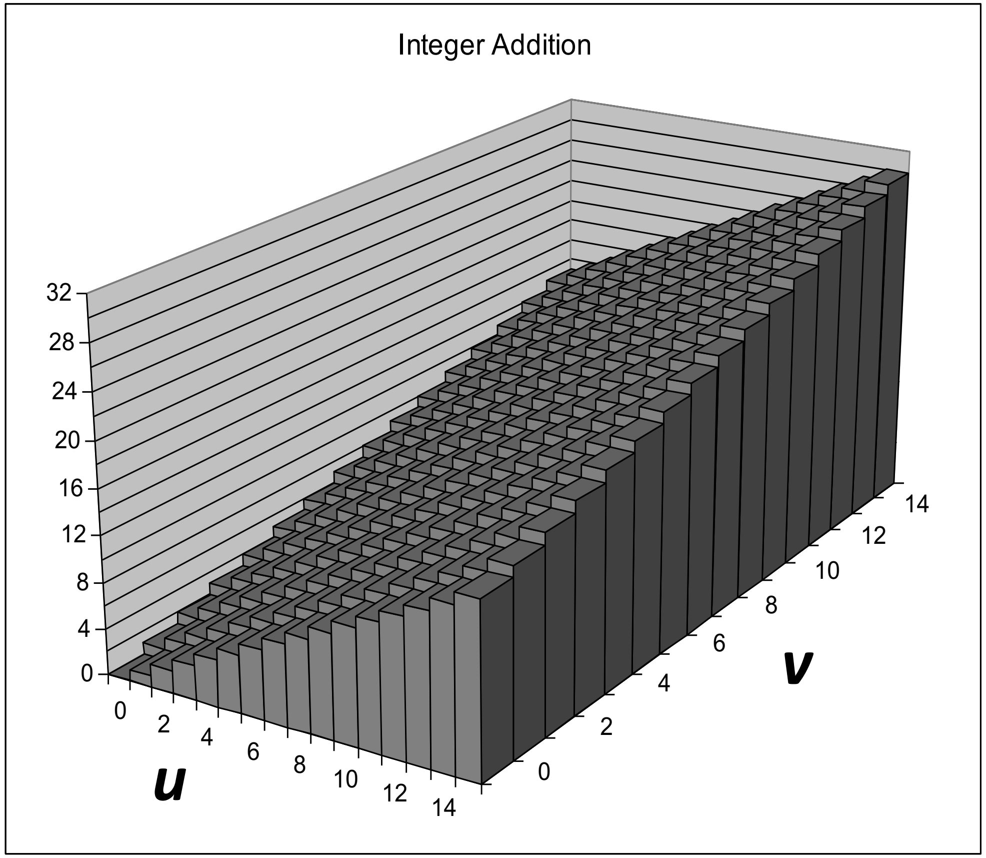

- **Standard Addition Function**
  - Ignores carry output
- **Implements Modular Arithmetic**

$$s \quad = \quad \mathrm{UAdd}_w(u\ ,\ v) \quad = \quad u + v \mod 2^w$$

# Visualizing (Mathematical) Integer Addition

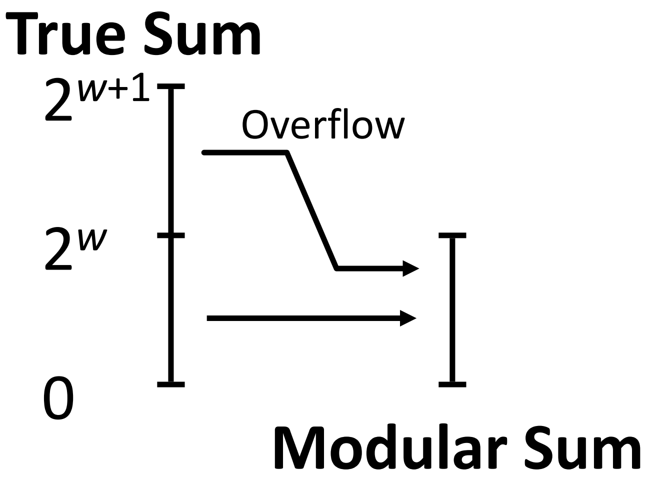
- **Integer Addition**
  - 4-bit integers *u*, *v*
  - Compute true sum $\text{Add}_4(u, v)$
  - Values increase linearly with *u* and *v*
  - Forms planar surface

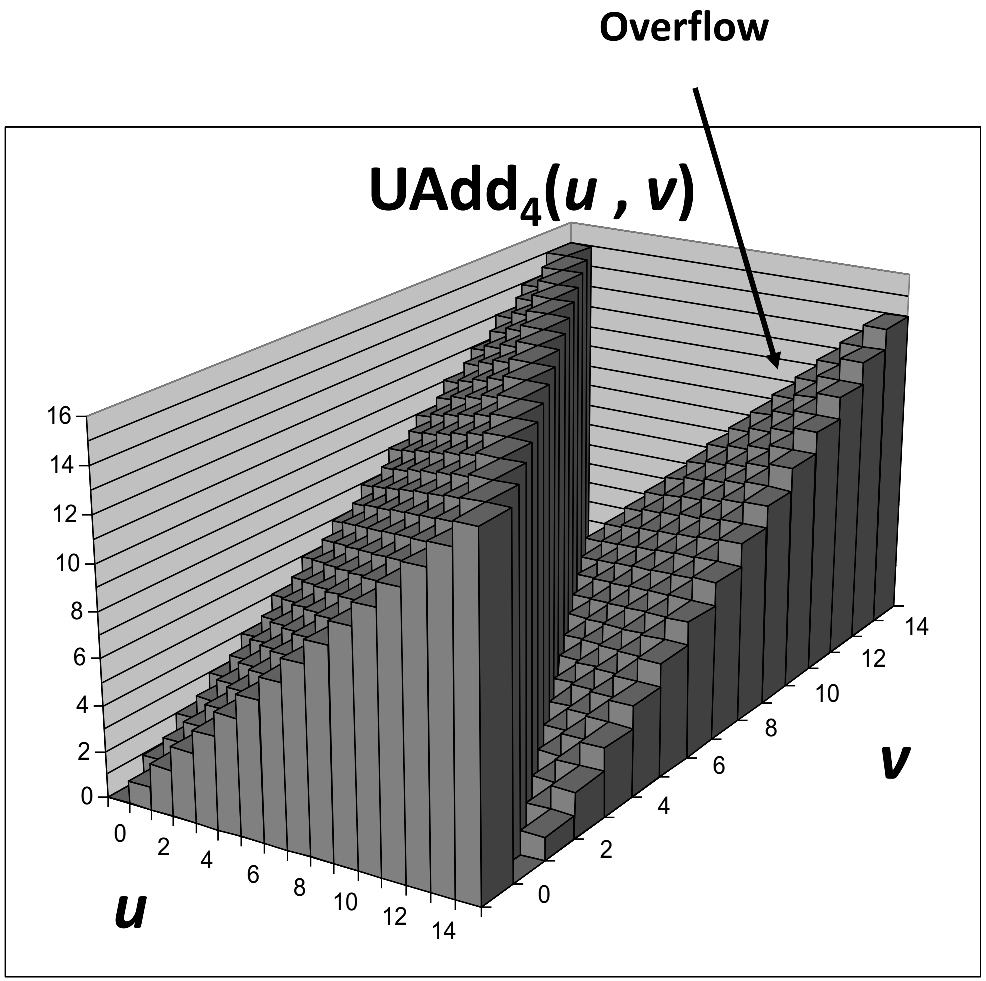
**$\text{Add}_4(u, v)$**



# Visualizing Unsigned Addition

- **Wraps Around**
  - If true sum ≥ $2^w$
  - At most once



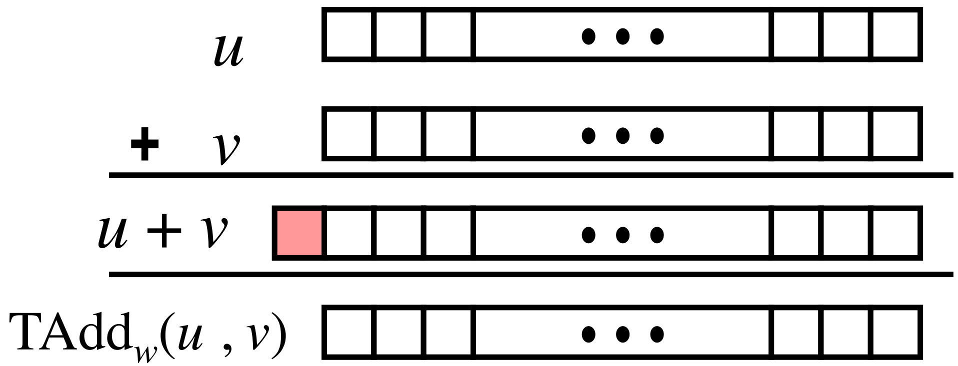



# Two's Complement Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



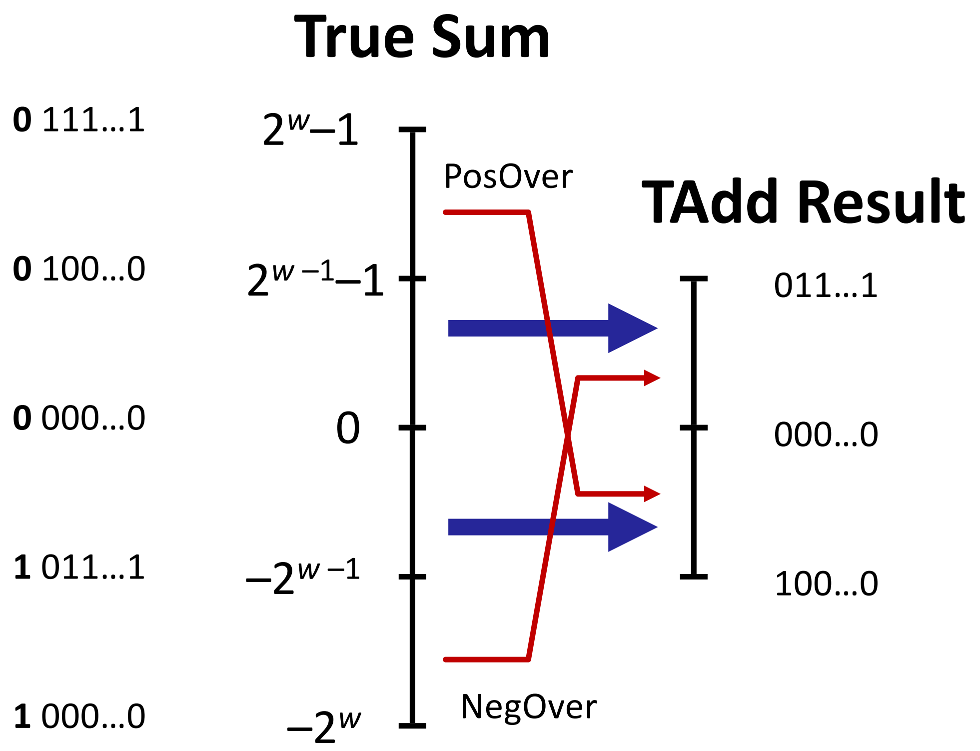

- **TAdd and UAdd have Identical Bit-Level Behavior**
  - Signed vs. unsigned addition in C:

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

  - Will give `s == t`

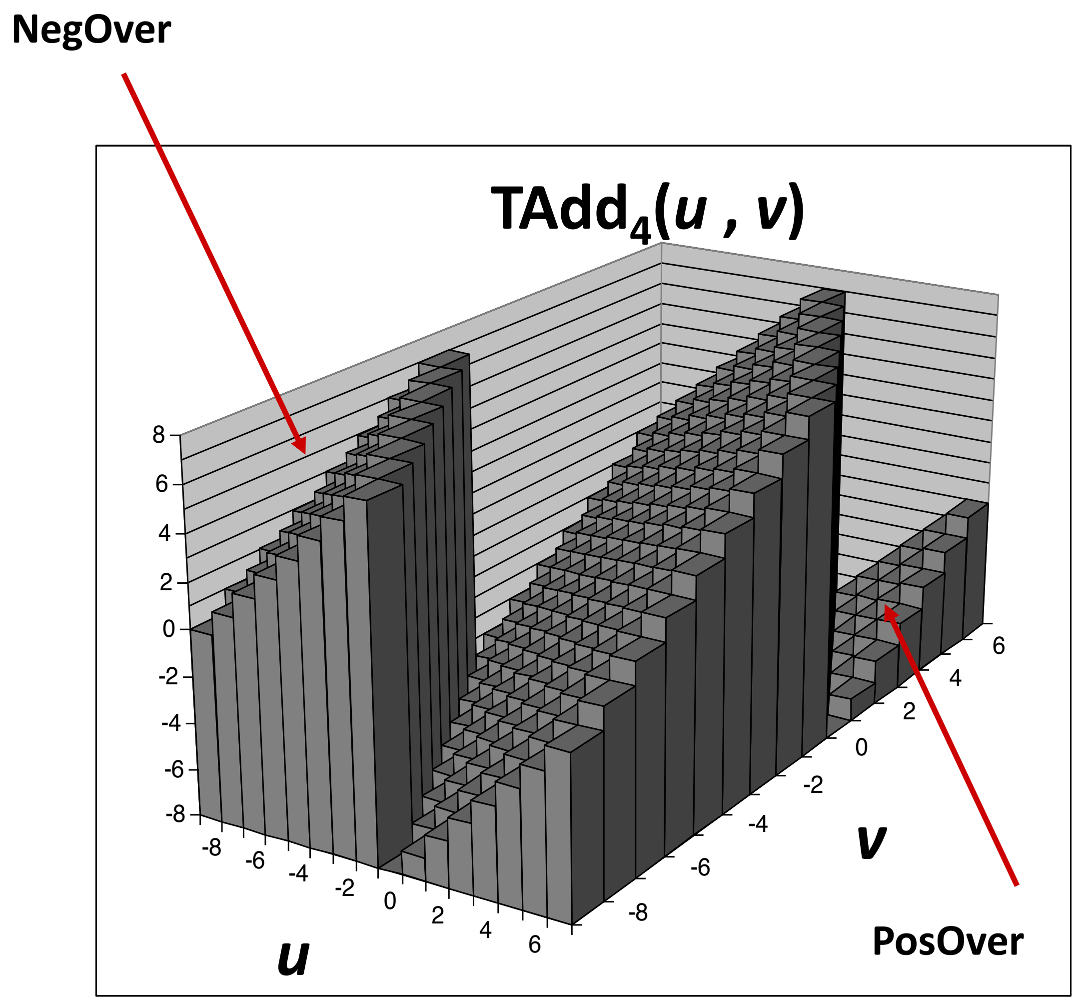
# TAdd Overflow

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



# 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



# Multiplication

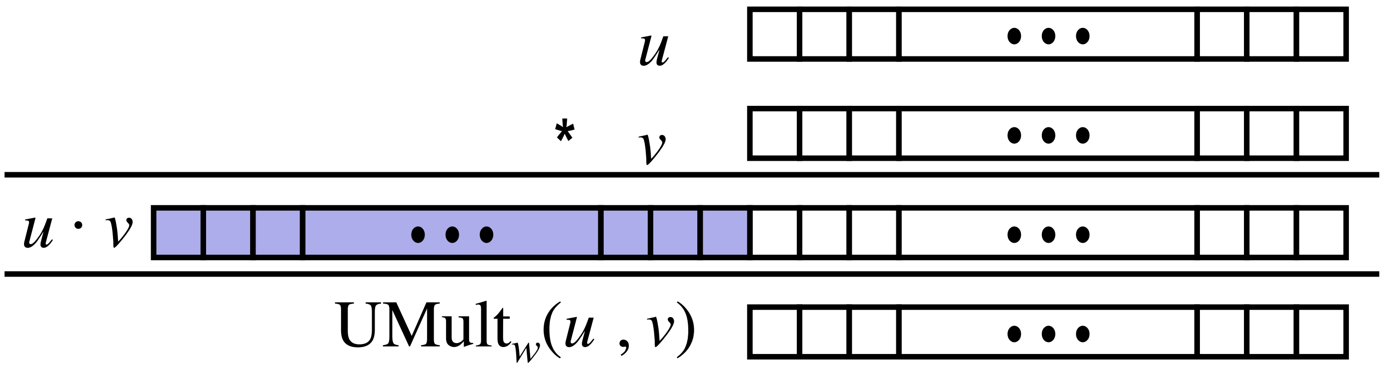
- **Goal: Computing Product of *w*-bit numbers *x*, *y***
  - Either signed or unsigned
- **But, exact results can be bigger than *w* bits**
  - Unsigned: up to 2*w* bits
    - Result range: $0 \le x * y \le (2^{w} - 1)^{2} = 2^{2w} - 2^{w+1} + 1$
  - Two's complement min (negative): Up to 2*w*-1 bits
    - 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 2*w* 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
    - e.g., by "arbitrary precision" arithmetic packages

# 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
- **Implements Modular Arithmetic**

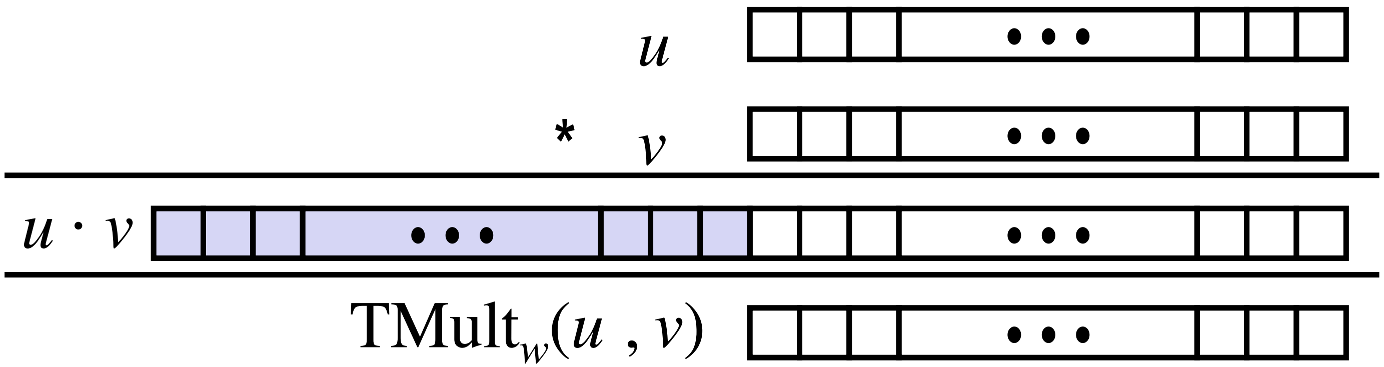
$\text{UMult}_w(u, v) = u \cdot v \bmod 2^w$

# 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

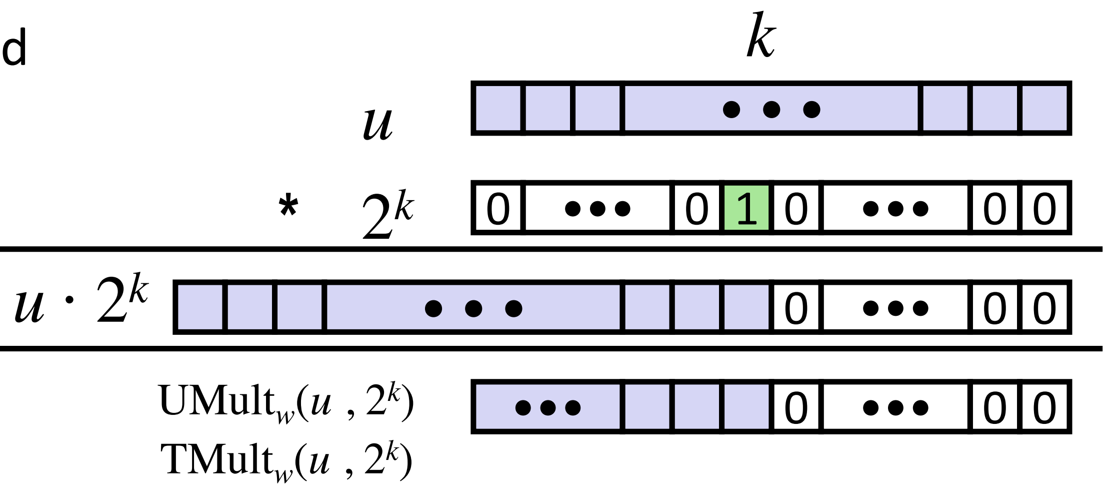
# Power-of-2 Multiply with Shift

- **Operation**
  - `u << k` gives `u * 2`$^k$
  - Both signed and unsigned

Operands: $w$ bits

True Product: $w+k$ bits

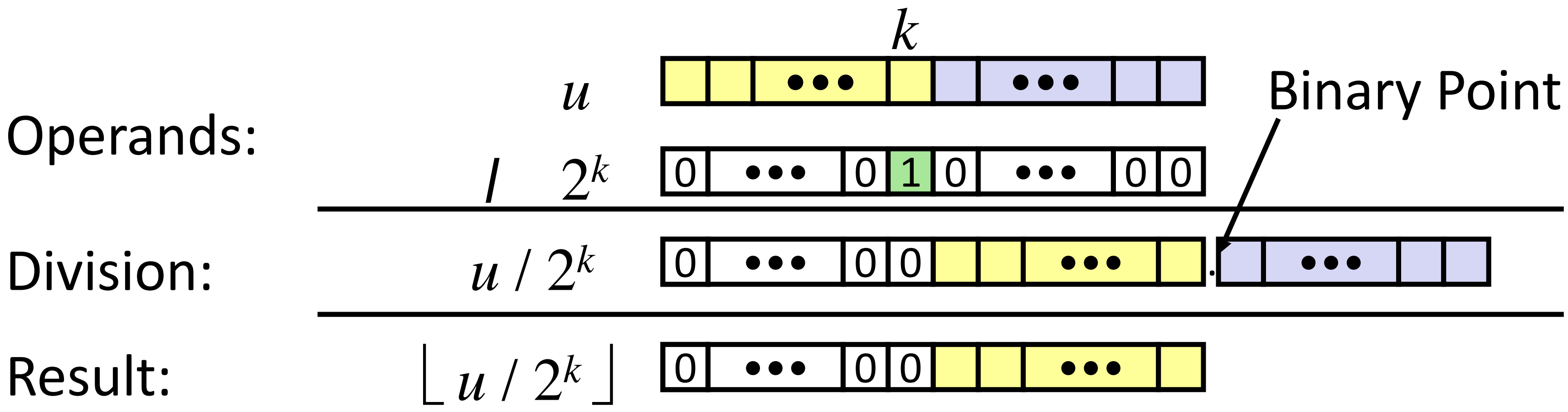
Discard $k$ bits: $w$ bits




- **Examples**
  - `u << 3          ==   u * 8`
  - `(u << 5) - (u << 3)==     u * 24`
  - Most machines shift and add faster than multiply
    - Compiler generates this code automatically

# Unsigned Power-of-2 Divide with Shift

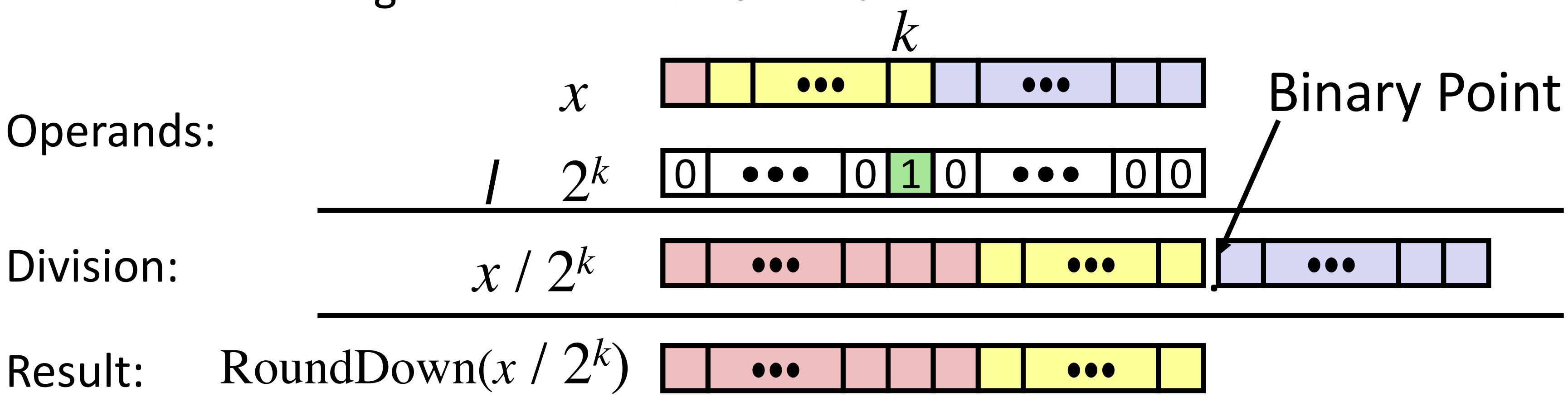
- **Quotient of Unsigned by Power of 2**
  - `u >> k` gives $\lfloor \texttt{u} / 2^k \rfloor$
  - Uses logical shift




| | Division | Computed | Hex | Binary |
|---|---|---|---|---|
| `x` | 15213 | 15213 | `3B 6D` | `00111011 01101101` |
| `x >> 1` | 7606.5 | 7606 | `1D B6` | `00011101 10110110` |
| `x >> 4` | 950.8125 | 950 | `03 B6` | `00000011 10110110` |
| `x >> 8` | 59.4257813 | 59 | `00 3B` | `00000000 00111011` |

# Signed Power-of-2 Divide with Shift

- **Quotient of Signed by Power of 2**
  - `x >> k` gives $\lfloor$ `x / 2`$^k$ $\rfloor$
  - Uses arithmetic shift
  - Rounds wrong direction when `u < 0`

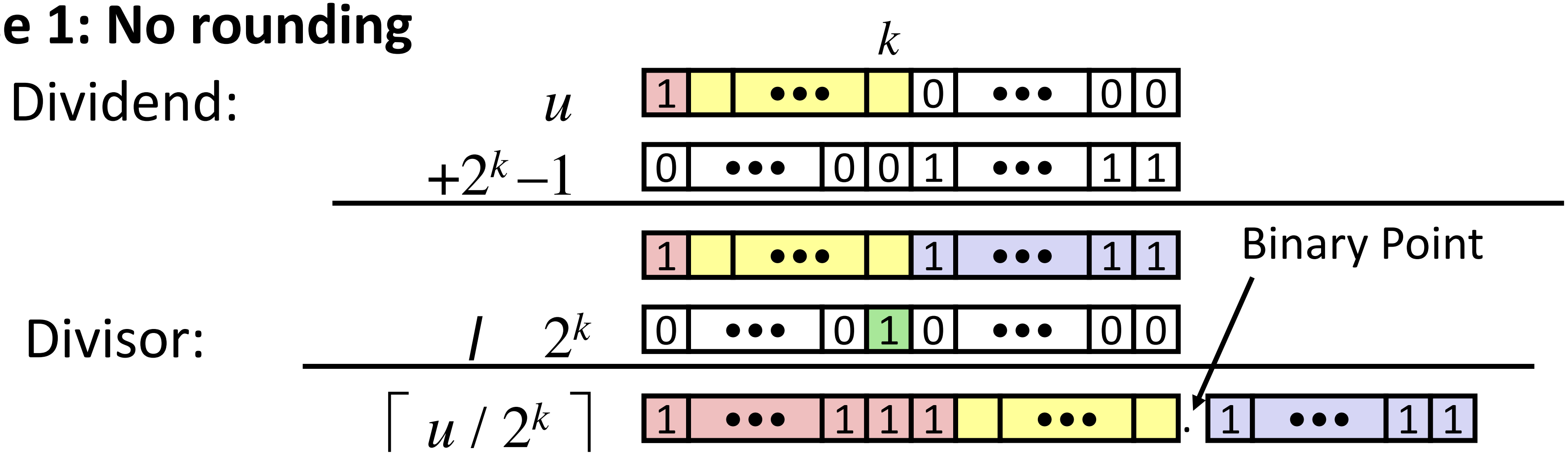



| | Division | Computed | Hex | Binary |
|---|---|---|---|---|
| `y` | -15213 | -15213 | `C4 93` | `11000100 10010011` |
| `y >> 1` | -7606.5 | -7607 | `E2 49` | `11100010 01001001` |
| `y >> 4` | -950.8125 | -951 | `FC 49` | `11111100 01001001` |
| `y >> 8` | -59.4257813 | -60 | `FF C4` | `11111111 11000100` |

# Correct Power-of-2 Divide

- **Quotient of Negative Number by Power of 2**
  - Want $\lceil \texttt{x} \ / \ 2^k \rceil$ (Round Toward 0)
  - Compute as $\lfloor (\texttt{x}+2^k-1) / \ 2^k \rfloor$
    - In C: `(x + (1<<k)-1) >> k`
    - Biases dividend toward 0

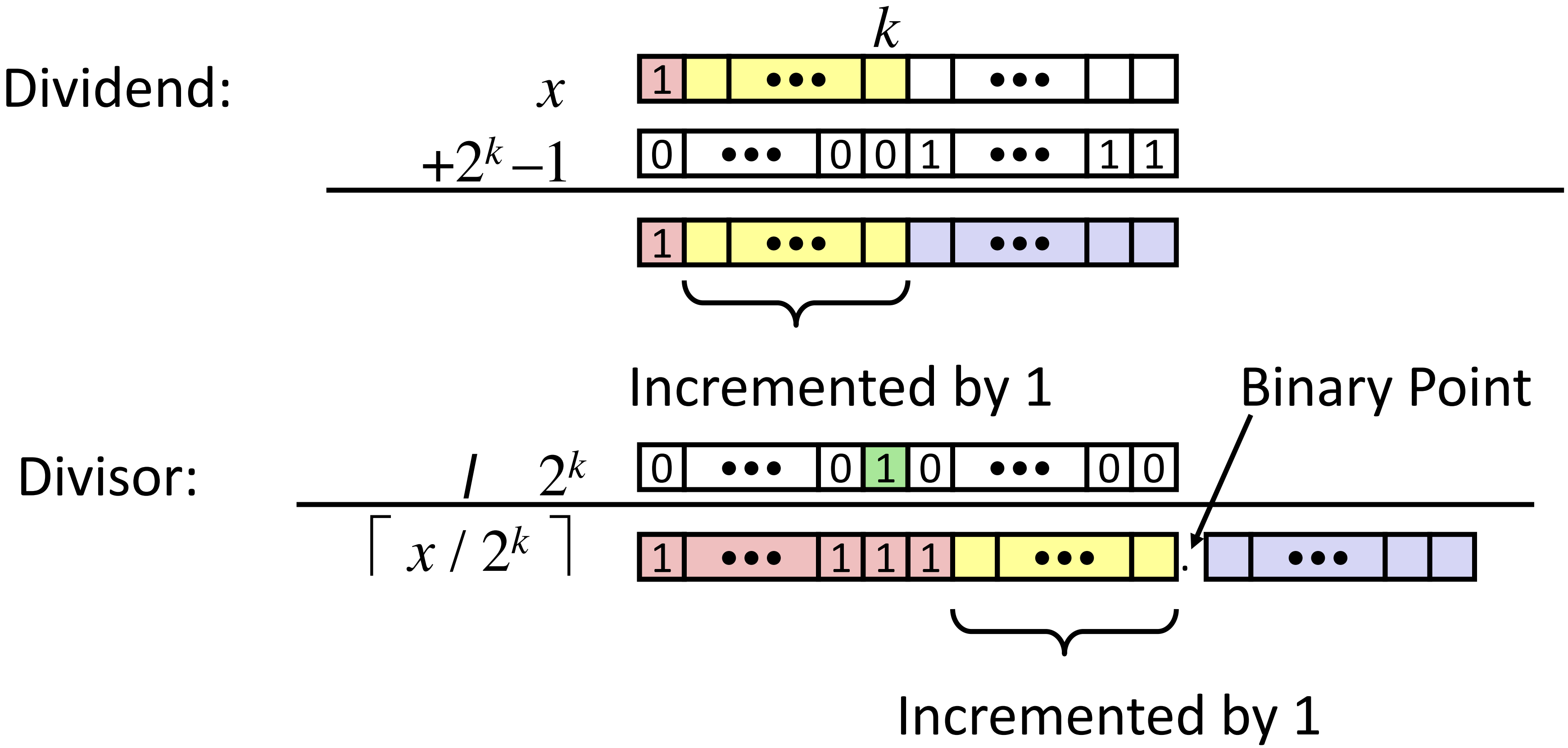
**Case 1: No rounding**




***Biasing has no effect***

# Correct Power-of-2 Divide (Cont.)

## Case 2: Rounding




***Biasing adds 1 to final result***

# 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

# Arithmetic: Basic Rules

- **Addition:**
  - Unsigned/signed: Normal addition followed by truncate, same operation on bit level
  - Unsigned: addition mod $2^w$
    - Mathematical addition + possible subtraction of $2^w$
  - Signed: modified addition mod $2^w$ (result in proper range)
    - Mathematical addition + possible addition or subtraction of $2^w$

- **Multiplication:**
  - Unsigned/signed: Normal multiplication followed by truncate, same operation on bit level
  - Unsigned: multiplication mod $2^w$
  - Signed: modified multiplication mod $2^w$ (result in proper range)

# Why Should I Use Unsigned?

- ***Don't*** **use without understanding implications**
  - Easy to make mistakes

```
unsigned i;
for (i = cnt-2; i >= 0; i--)
  a[i] += a[i+1];
```

  - Can be very subtle

```
#define DELTA sizeof(int)
int i;
for (i = CNT; i-DELTA >= 0; i-= DELTA)
  . . .
```

# Counting Down with Unsigned

- **Proper way to use unsigned as loop index**

```
unsigned i;
for (i = cnt-2; i < cnt; i--)
  a[i] += a[i+1];
```

- **See Robert Seacord, *Secure Coding in C and C++***
  - C Standard guarantees that unsigned addition will behave like modular arithmetic
    - 0 – 1 → *UMax*
- **Even better**

```
size_t i;
for (i = cnt-2; i < cnt; i--)
  a[i] += a[i+1];
```

  - Data type `size_t` defined as unsigned value with length = word size
  - Code will work even if `cnt` = *UMax*
  - What if `cnt` is signed and < 0?

# Why Should I Use Unsigned? (cont.)

- ***Do*** **Use When Performing Modular Arithmetic**
  - Multiprecision arithmetic
- ***Do*** **Use When Using Bits to Represent Sets**
  - Logical right shift, no sign extension

# Integer C Puzzles

```
1.  x < 0                 →   ((x*2) < 0)
2.  ux >= 0
3.  x & 7 == 7            →   (x<<30) < 0
4.  ux > -1
5.  x > y                 →   -x < -y
6.  x * x >= 0
7.  x > 0 && y > 0        →   x + y > 0
8.  x >= 0                →   -x <= 0
9.  x <= 0                →   -x >= 0
10. (x|-x)>>31 == -1
11. ux >> 3 == ux/8
12. x >> 3 == x/8
13. x & (x-1) != 0
```

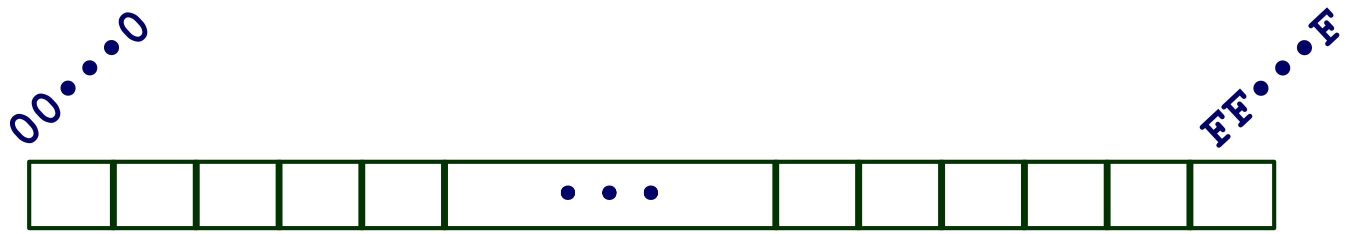
### Initialization

```
int x = foo();
int y = bar();
unsigned ux = x;
unsigned uy = y;
```

# 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**

# Byte-Oriented Memory Organization




- **Programs refer to data by address**
  - Conceptually, envision it as a very large array of bytes
    - In reality, it’s not, but can think of it that way
  - An address is like an index into that array
    - and, a pointer variable stores an address

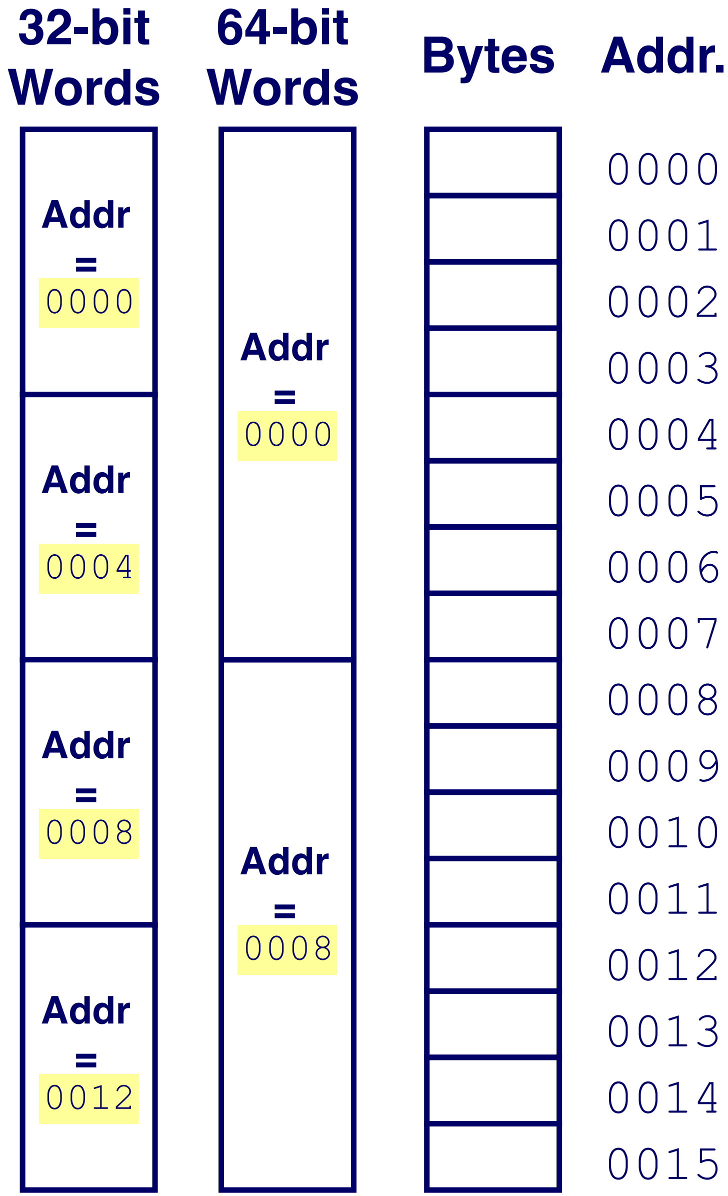
- **Note: system provides private address spaces to each “process”**
  - Think of a process as a program being executed
  - So, a program can clobber its own data, but not that of others

# Machine Words

- **Any given computer has a "Word Size"**
  - Nominal size of integer-valued data
    - and of addresses
  - Until recently, most machines used 32 bits (4 bytes) as word size
    - Limits addresses to 4GB ($2^{32}$ bytes)
  - Increasingly, machines have 64-bit word size
    - Potentially, could have 16 EB (exabytes) of addressable memory
    - That's 18.4 X $10^{18}$
  - Machines still support multiple data formats
    - Fractions or multiples of word size
    - Always integral number of bytes

# Word-Oriented Memory Organization

- **Addresses Specify Byte Locations**
  - Address of first byte in word
  - Addresses of successive words differ by 4 (32-bit) or 8 (64-bit)



# Example Data Representations

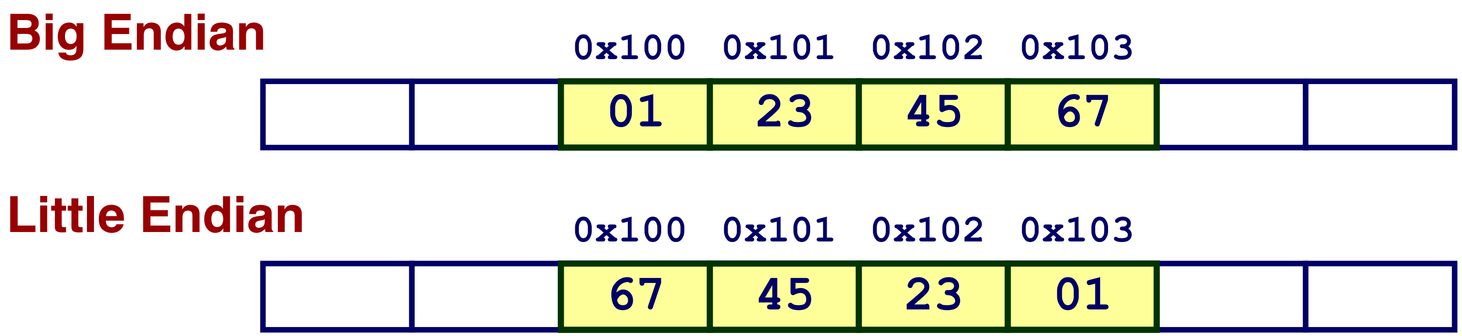
| C Data Type | Typical 32-bit | Typical 64-bit | x86-64 |
|---|---|---|---|
| `char` | 1 | 1 | 1 |
| `short` | 2 | 2 | 2 |
| `int` | 4 | 4 | 4 |
| `long` | 4 | 8 | 8 |
| `float` | 4 | 4 | 4 |
| `double` | 8 | 8 | 8 |
| `long double` | − | − | 10/16 |
| pointer | 4 | 8 | 8 |

# Byte Ordering

- **So, how are the bytes within a multi-byte word ordered in memory?**
- **Conventions**
  - Big Endian: Sun, PPC Mac, Internet
    - 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



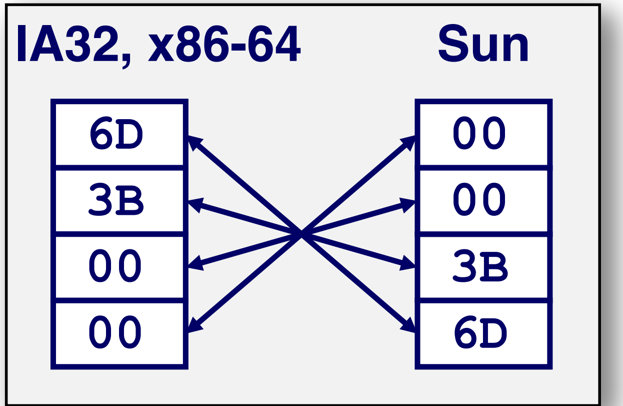
# Representing Integers

**Decimal:** 15213

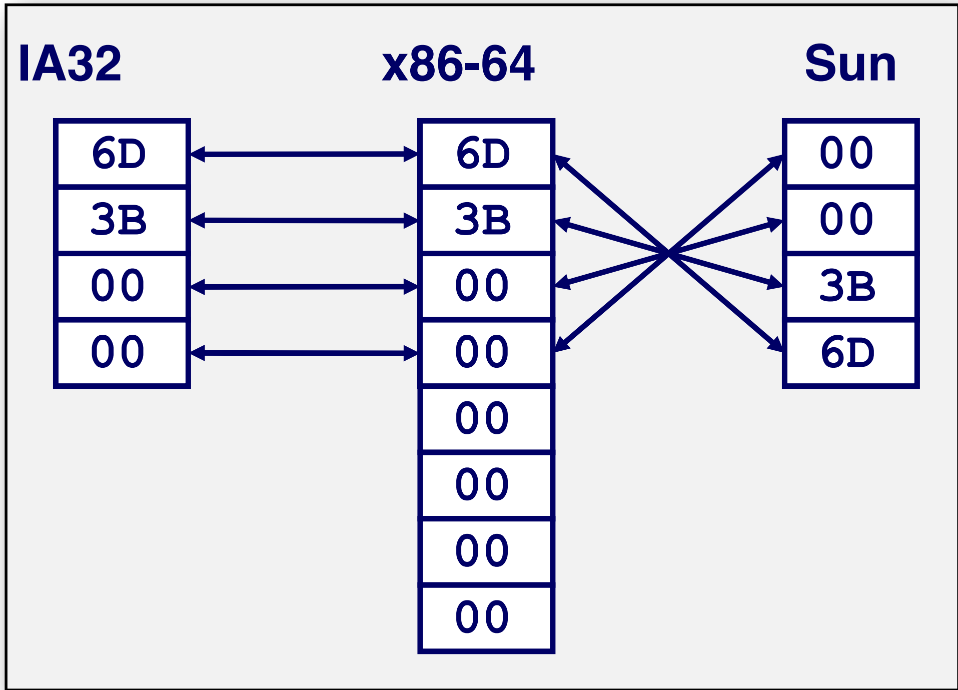
**Binary:** 0011 1011 0110 1101

**Hex:** 3 B 6 D

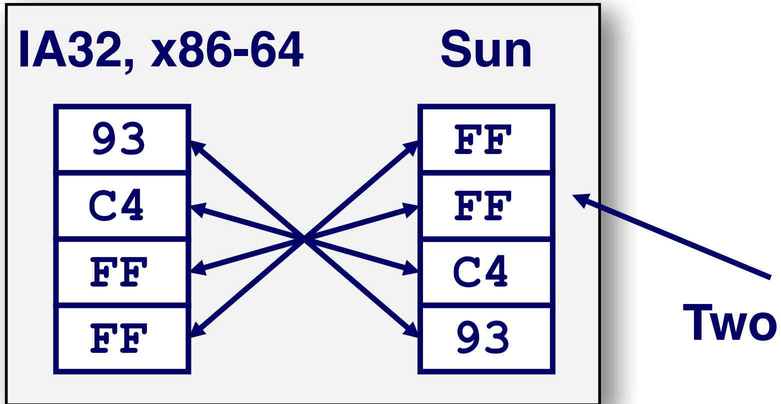
```
int A = 15213;
```




```
long int C = 15213;
```




```
int B = -15213;
```




**Two's complement representation**

# 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
```

# Reading Byte-Reversed Listings

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

# 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