

# Bits, Bytes, and Integers

CS230: System Programming  
2<sup>nd</sup> Lecture

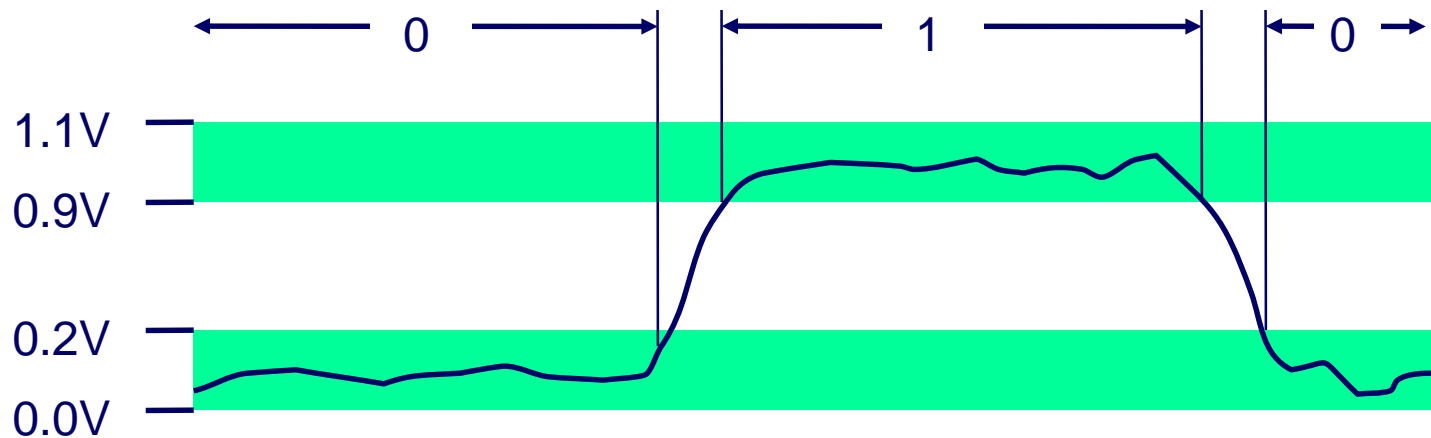
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# Today: Bits, Bytes, and Integers

- **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 bistable 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
<code>char</code>	1	1	1
<code>short</code>	2	2	2
<code>int</code>	4	4	4
<code>long</code>	4	8	8
<code>float</code>	4	4	4
<code>double</code>	8	8	8
<code>long double</code>	–	–	10/16
<code>pointer</code>	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

- $\sim A = 1$  when  $A=0$

$\sim$	
0	1
1	0

### Exclusive-Or (Xor)

- $A \wedge B = 1$  when either  $A=1$  or  $B=1$ , but not both

$\wedge$	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
<u>          </u>	<u>          </u>	<u>          </u>	<u>          </u>
01000001	01111101	00111100	10101010

## ■ All of the Properties of Boolean Algebra Apply

# Example: Representing & Manipulating Sets

## ■ Representation

- Width  $w$  bit vector represents subsets of  $\{0, \dots, w-1\}$
- $a_j = 1$  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 -> 0xBE`
  - `~010000012 -> 101111102`
- `~0x00 -> 0xFF`
  - `~000000002 -> 111111112`
- `0x69 & 0x55 -> 0x41`
  - `011010012 & 010101012  $\rightsquigarrow$  010000012`
- `0x69 | 0x55 -> 0x7D`
  - `011010012 | 010101012  $\rightsquigarrow$  011111012`

# 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 “False”
  - Anything non-zero
  - Always returns 0 or 1
  - **Early** evaluation

## ■ Example

- `!0x41 -> 0`
- `!0x00 -> 1`
- `!!0x41 -> 1`

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

Watch out for `&&` vs. `&` (and `||` vs. `|`)...  
one of the more common oopsies in  
C programming

# Shift Operations

## ■ Left Shift: $x \ll y$

- Shift bit-vector  $x$  left  $y$  positions
  - Throw away extra bits on left
  - Fill with 0's on right

## ■ Right Shift: $x \gg y$

- 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  $\geq$  word size

Argument $x$	01100010
$\ll 3$	00010000
Log. $\gg 2$	00011000
Arith. $\gg 2$	00011000

Argument $x$	10100010
$\ll 3$	00010000
Log. $\gg 2$	00101000
Arith. $\gg 2$	11101000

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# Encoding Integers

## Unsigned

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

## Two's Complement

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

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

Sign  
Bit



### ■ C short 2 bytes long

	Decimal	Hex	Binary
<b>x</b>	15213	3B 6D	00111011 01101101
<b>y</b>	-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
<b>Sum</b>	<b>15213</b>		<b>-15213</b>	

# 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
<b>UMax</b>	<b>65535</b>	<b>FF FF</b>	<b>11111111 11111111</b>
<b>TMax</b>	<b>32767</b>	<b>7F FF</b>	<b>01111111 11111111</b>
<b>TMin</b>	<b>-32768</b>	<b>80 00</b>	<b>10000000 00000000</b>
<b>-1</b>	<b>-1</b>	<b>FF FF</b>	<b>11111111 11111111</b>
<b>0</b>	<b>0</b>	<b>00 00</b>	<b>00000000 00000000</b>

# Values for Different Word Sizes

	W			
	8	16	32	64
<b>UMax</b>	255	65,535	4,294,967,295	18,446,744,073,709,551,615
<b>TMax</b>	127	32,767	2,147,483,647	9,223,372,036,854,775,807
<b>TMin</b>	-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

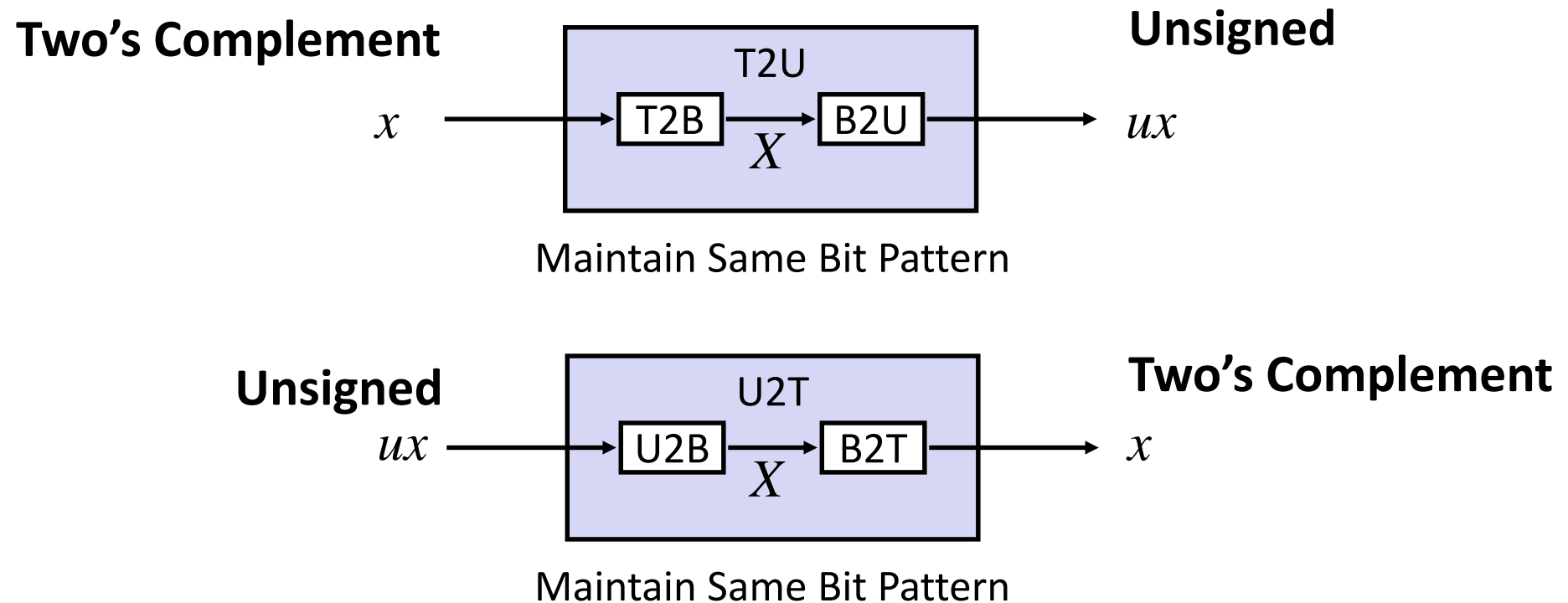
## ■ $\Rightarrow$ Can Invert Mappings

- $U2B(x) = B2U^{-1}(x)$ 
  - 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



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

# Mapping Signed $\leftrightarrow$ 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

$\xrightarrow{\text{T2U}}$ 
 $\xleftarrow{\text{U2T}}$

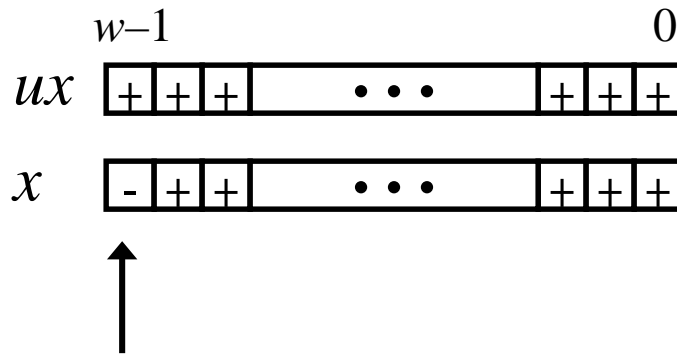
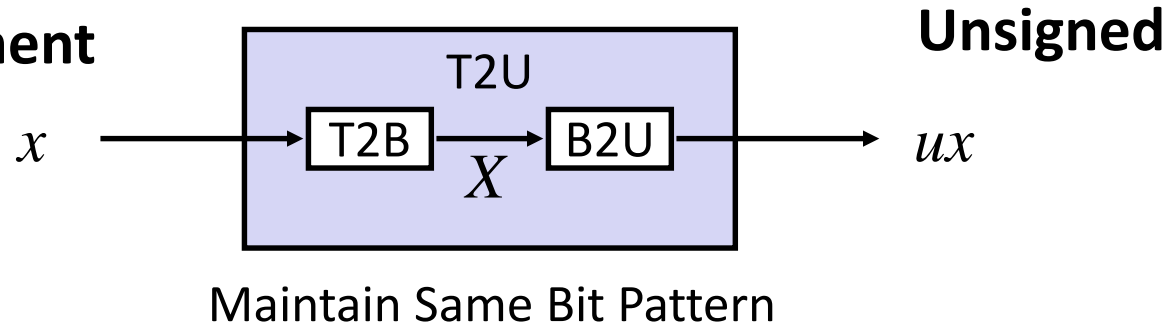
# Mapping Signed $\leftrightarrow$ Unsigned

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	+/- 16	8
1001	-7		9
1010	-6		10
1011	-5		11
1100	-4		12
1101	-3		13
1110	-2		14
1111	-1		15



# Relation between Signed & Unsigned

Two's Complement

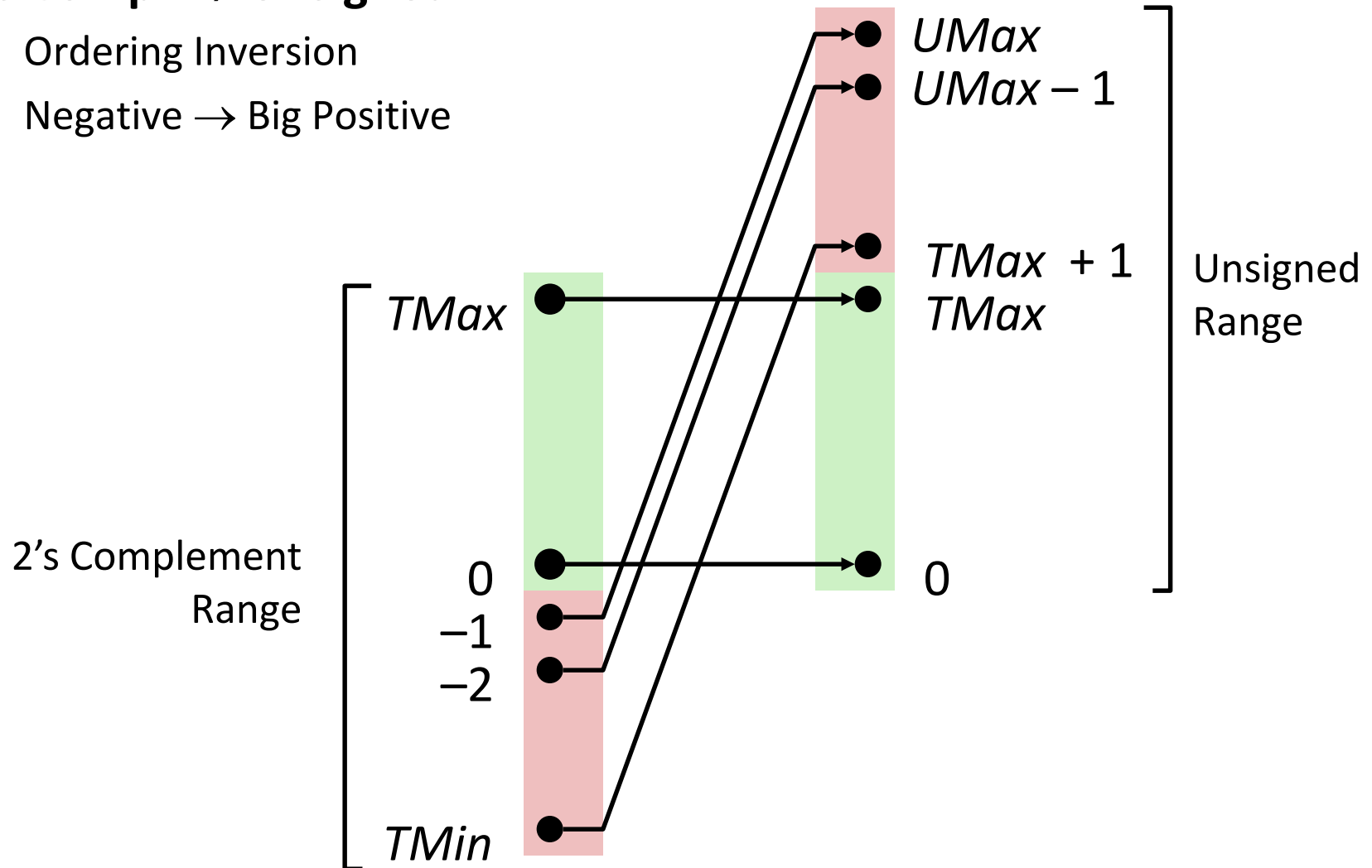


**Large negative weight**  
*becomes*  
**Large positive weight**

# 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 <sub>1</sub>	Constant <sub>2</sub>	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 $\leftrightarrow$ 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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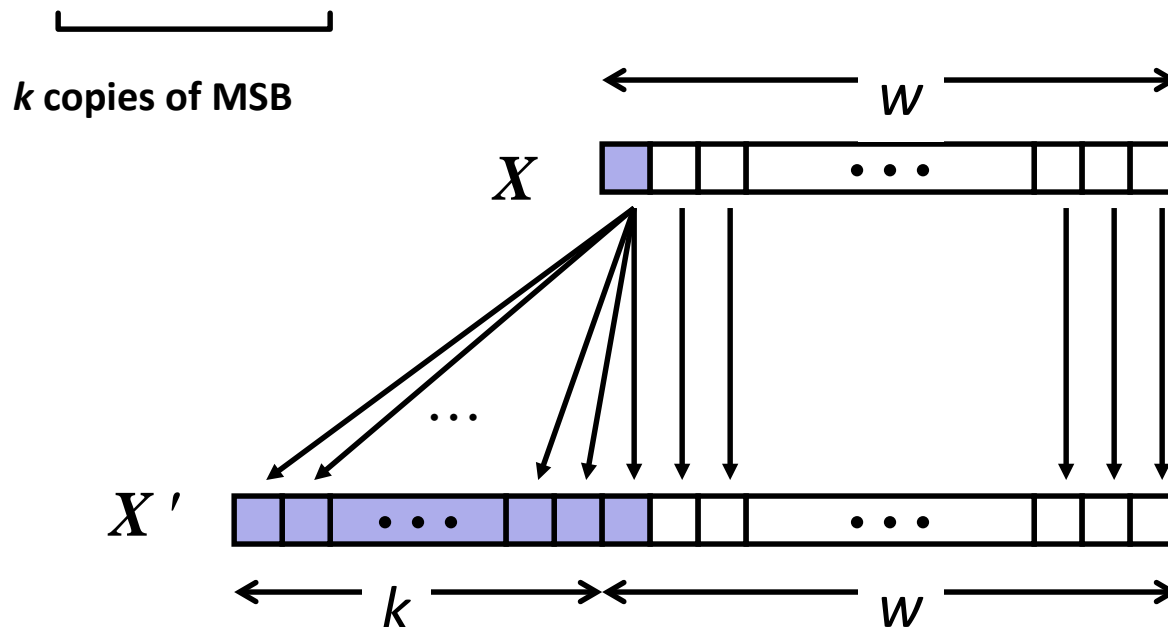
# Sign Extension

## ■ Task:

- Given  $w$ -bit signed integer  $x$
- Convert it to  $w+k$ -bit integer with same value

## ■ Rule:

- Make  $k$  copies of sign bit:
- $X' = \underbrace{x_{w-1}, \dots, x_{w-1}}_{k \text{ copies of MSB}}, x_{w-1}, x_{w-2}, \dots, x_0$



# Sign Extension Example

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

	Decimal	Hex	Binary
<b>x</b>	15213	3B 6D	00111011 01101101
<b>ix</b>	15213	00 00 3B 6D	00000000 00000000 00111011 01101101
<b>y</b>	-15213	C4 93	11000100 10010011
<b>iy</b>	-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

$u$  

$+ v$  

True Sum:  $w+1$  bits

$u + v$  

Discard Carry:  $w$  bits

$\text{UAdd}_w(u, v)$  

## ■ Standard Addition Function

- Ignores carry output

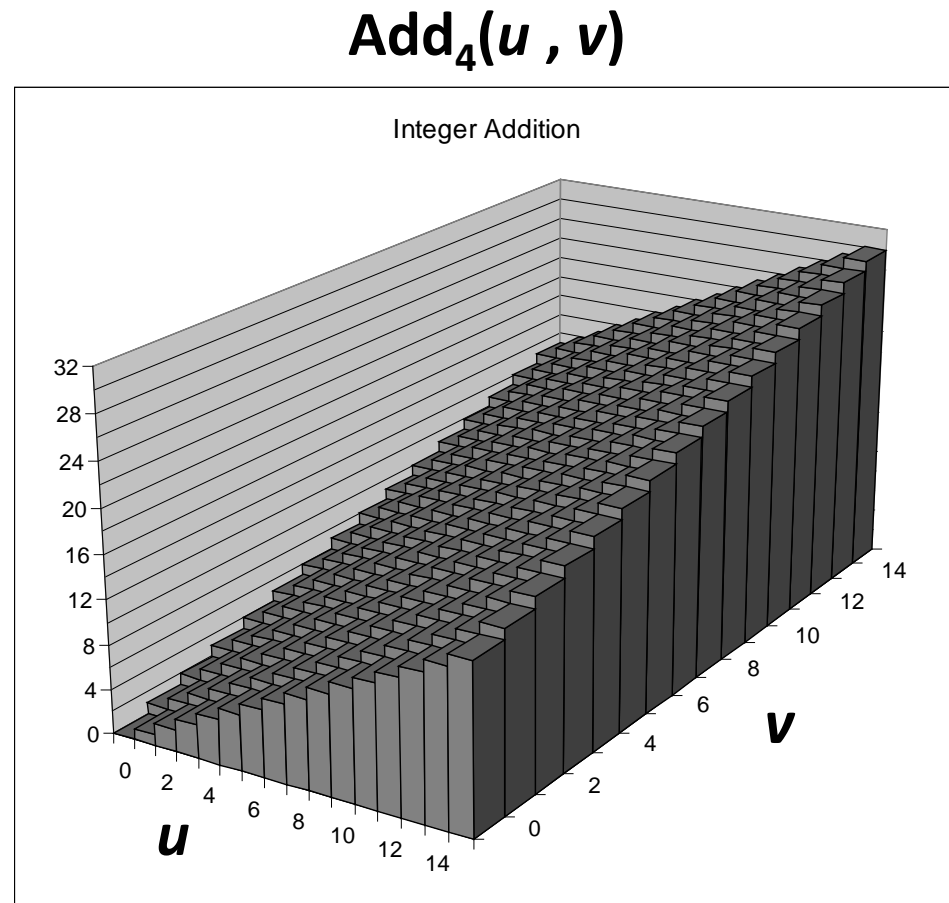
## ■ Implements Modular Arithmetic

$$s = \text{UAdd}_w(u, v) = u + v \bmod 2^w$$

# 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

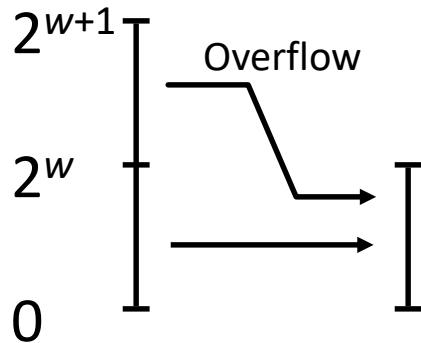


# Visualizing Unsigned Addition

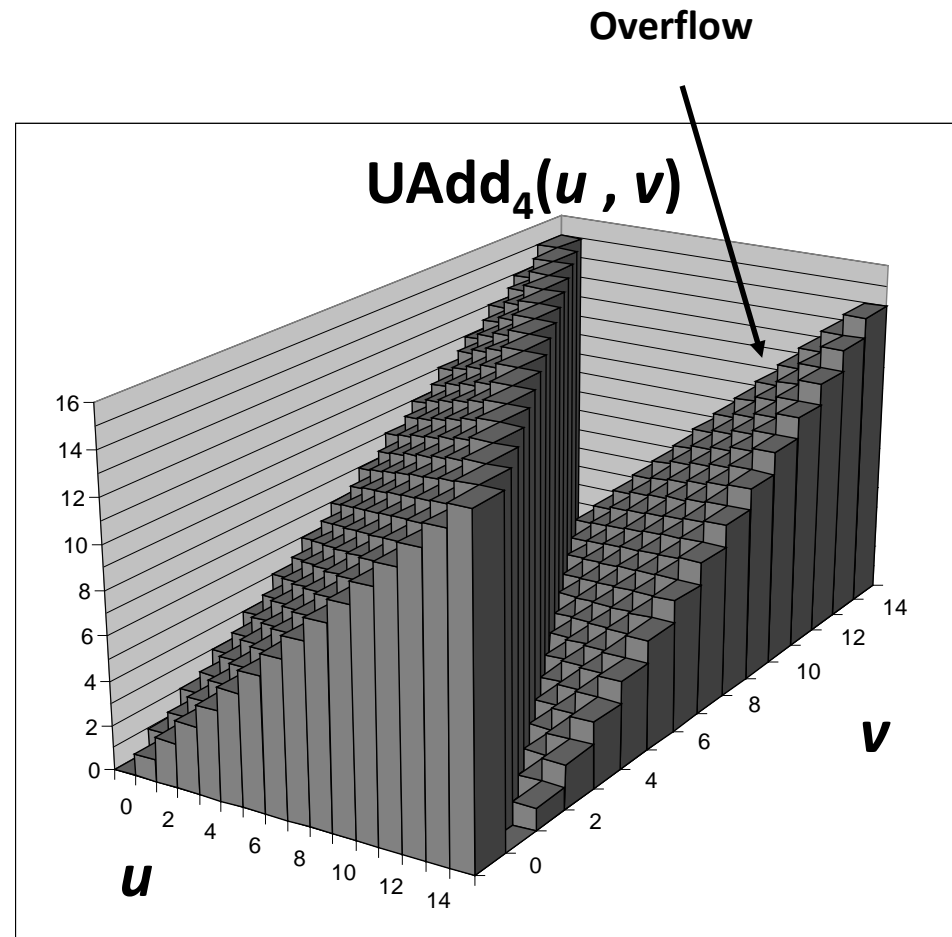
## ■ Wraps Around

- If true sum  $\geq 2^w$
- At most once

True Sum



Modular Sum

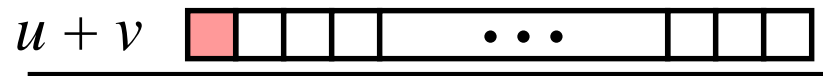


# Two's Complement Addition

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);
```

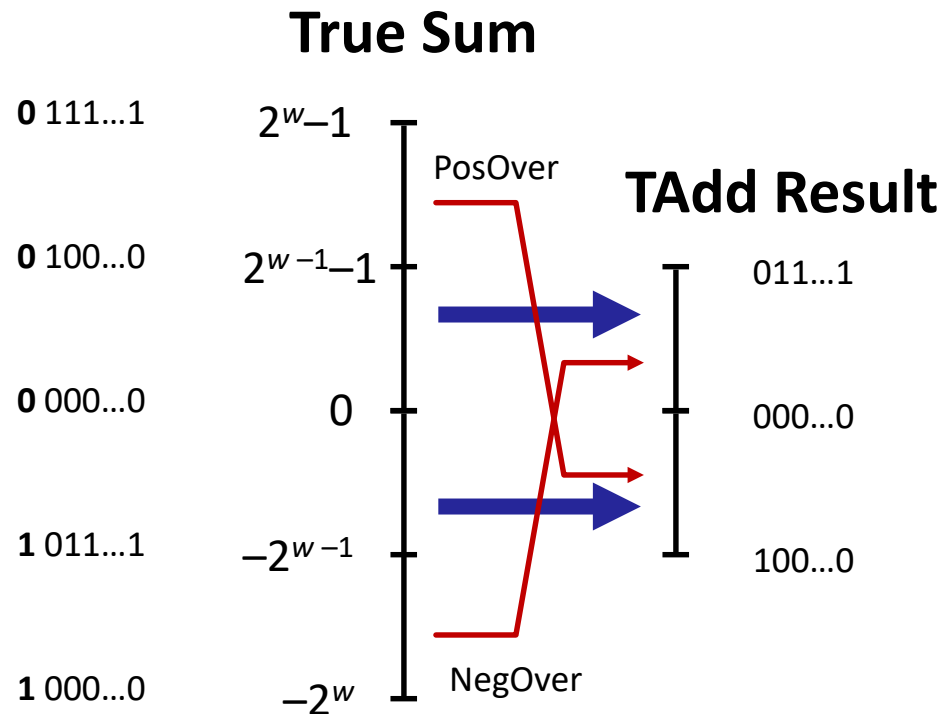
```
t = u + v
```

- 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

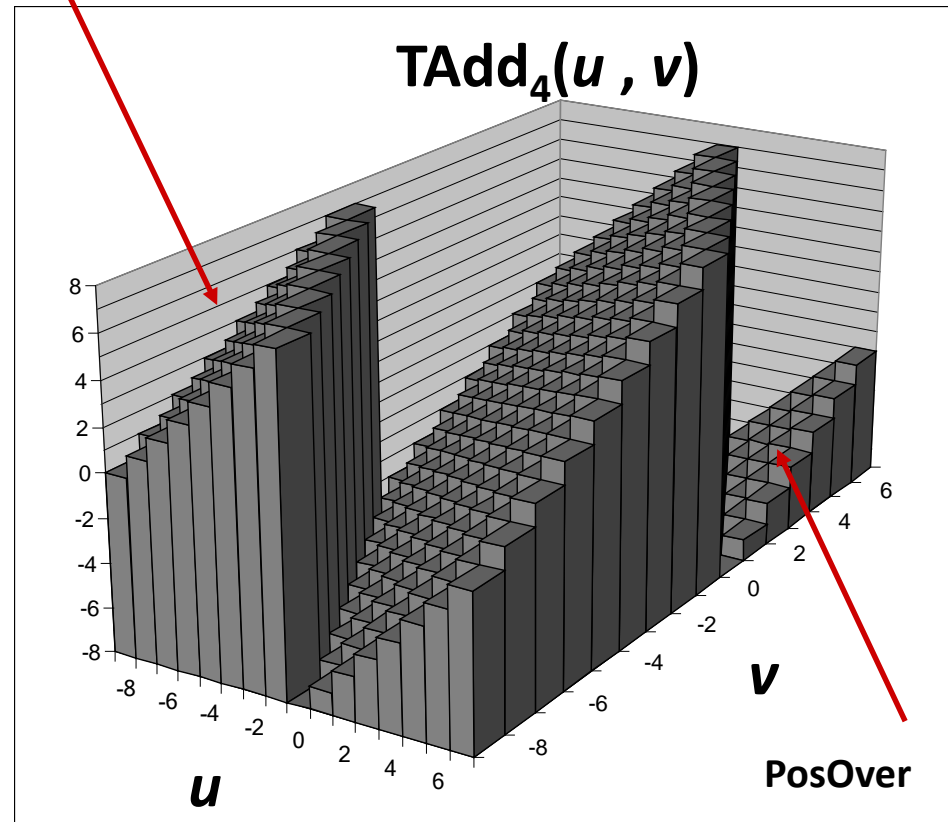
## ■ Values

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

## ■ Wraps Around

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

NegOver

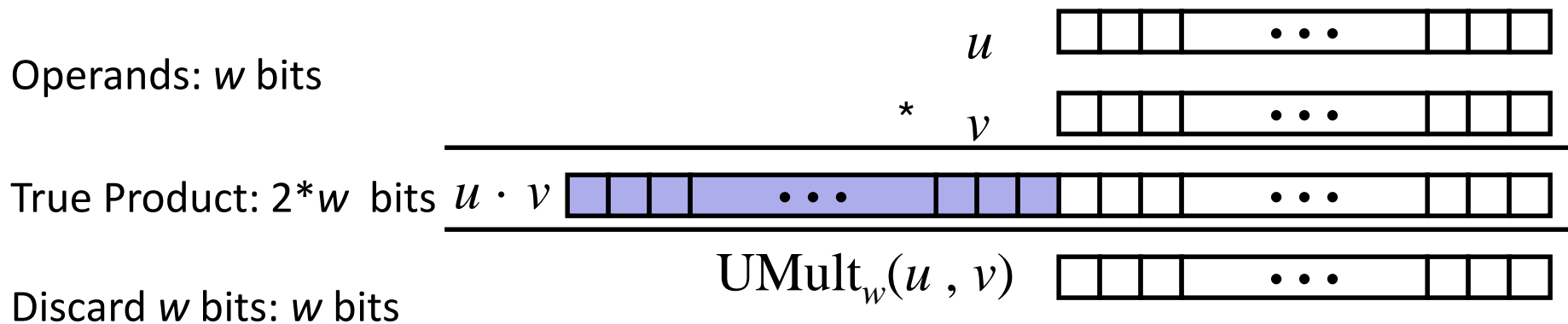




# Multiplication

- **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:  $0 \leq x * y \leq (2^w - 1)^2 = 2^{2w} - 2^{w+1} + 1$
  - Two's complement min (negative): Up to  $2w-1$  bits
    - Result range:  $x * y \geq (-2^{w-1}) * (2^{w-1} - 1) = -2^{2w-2} + 2^{w-1}$
  - Two's complement max (positive): Up to  $2w$  bits, but only for  $(TMin_w)^2$ 
    - Result range:  $x * y \leq (-2^{w-1})^2 = 2^{2w-2}$
- **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



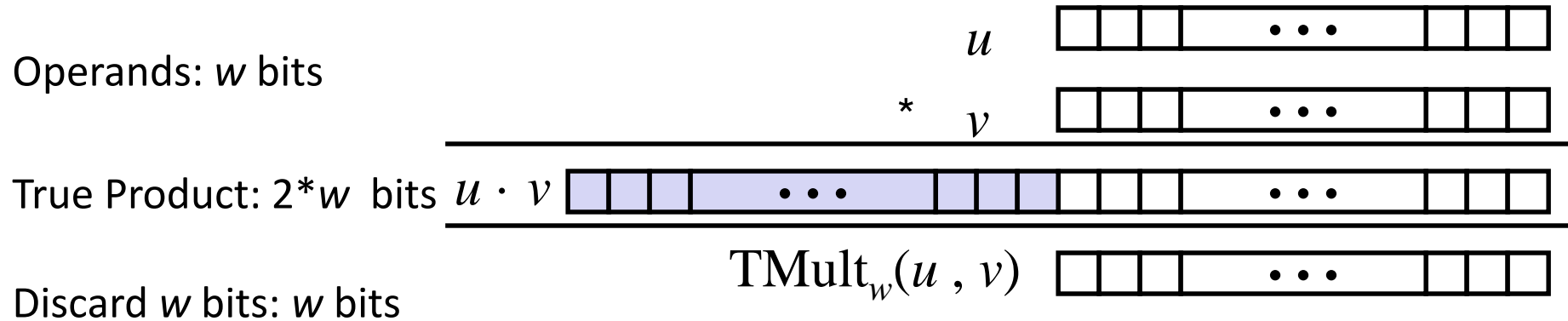
## ■ Standard Multiplication Function

- Ignores high order  $w$  bits

## ■ Implements Modular Arithmetic

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

# Signed Multiplication in C



## ■ Standard Multiplication Function

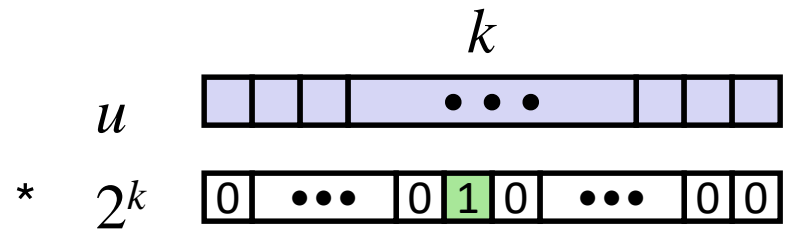
- Ignores high order  $w$  bits
- Some of which are different for signed vs. unsigned multiplication
- Lower bits are the same

# Power-of-2 Multiply with Shift

## ■ Operation

- $u \ll k$  gives  $u * 2^k$
- Both signed and unsigned

Operands:  $w$  bits



True Product:  $w+k$  bits

Discard  $k$  bits:  $w$  bits

$\text{UMult}_w(u, 2^k)$

$\text{TMult}_w(u, 2^k)$

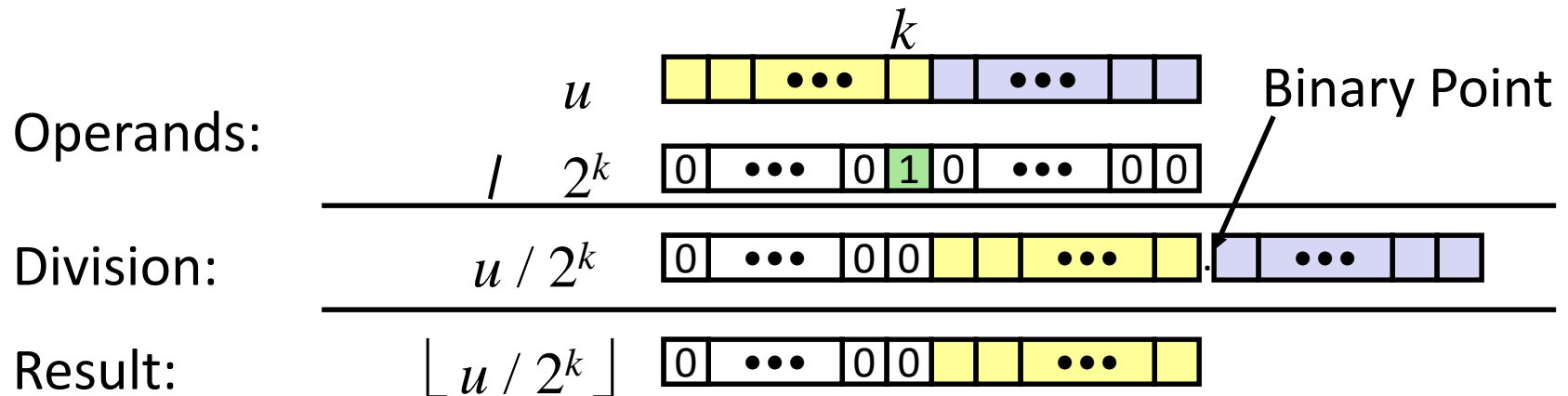
## ■ Examples

- $u \ll 3 \quad == \quad u * 8$
- $(u \ll 5) - (u \ll 3) == u * 24$
- 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

- $u \gg k$  gives  $\lfloor u / 2^k \rfloor$
- Uses logical shift



	Division	Computed	Hex	Binary
<b>x</b>	<b>15213</b>	<b>15213</b>	3B 6D	00111011 01101101
<b>x &gt;&gt; 1</b>	<b>7606.5</b>	<b>7606</b>	1D B6	00011101 10110110
<b>x &gt;&gt; 4</b>	<b>950.8125</b>	<b>950</b>	03 B6	00000011 10110110
<b>x &gt;&gt; 8</b>	<b>59.4257813</b>	<b>59</b>	00 3B	00000000 00111011

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  - 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
  - $0 - 1 \rightarrow UMax$

## ■ 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`?

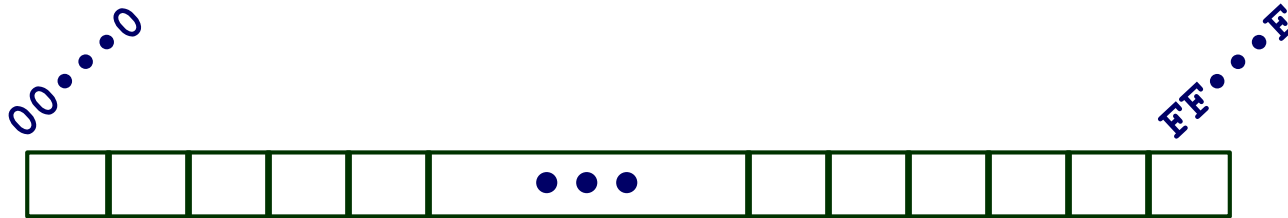
# Why Should I Use Unsigned? (cont.)

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

# 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

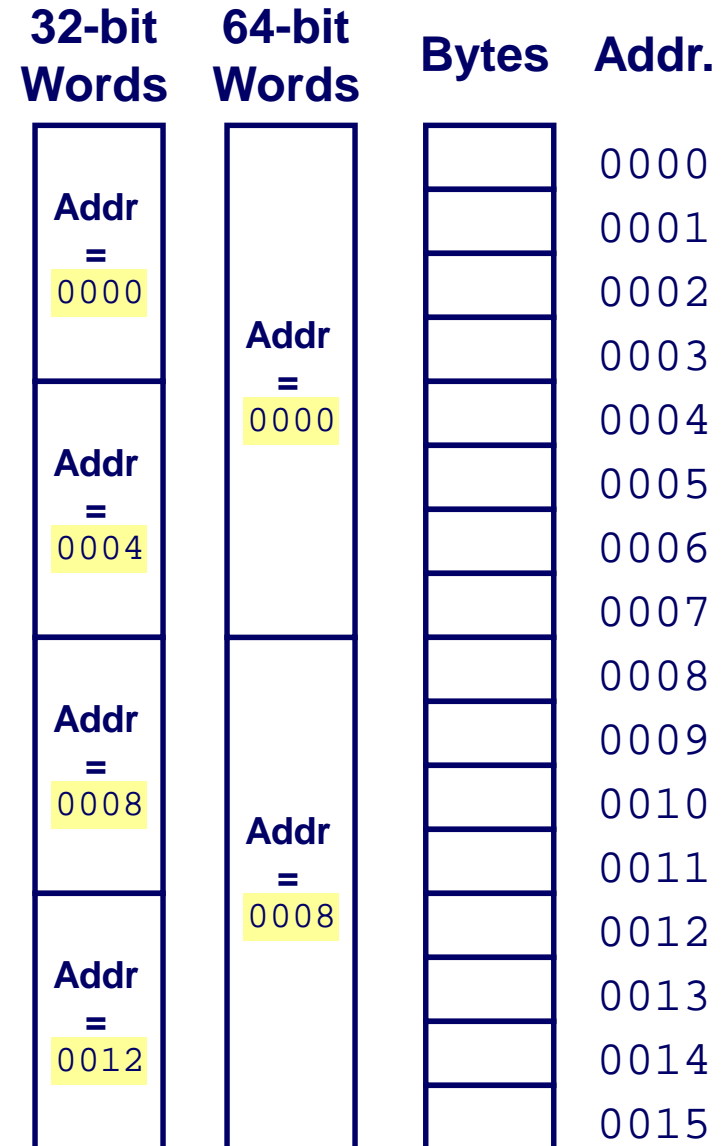
# Machine Words

- **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 18 EB (exabytes) of addressable memory
    - That's  $18.4 \times 10^{18}$
  - 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
<code>char</code>	1	1	1
<code>short</code>	2	2	2
<code>int</code>	4	4	4
<code>long</code>	4	8	8
<code>float</code>	4	4	4
<code>double</code>	8	8	8
<code>long double</code>	–	–	10/16
<code>pointer</code>	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

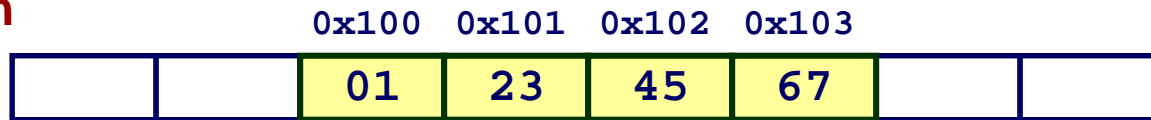


# Byte Ordering Example

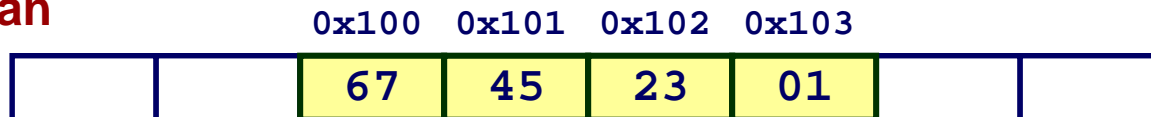
## ■ Example

- Variable x has 4-byte value of 0x01234567
- Address given by &x is 0x100

### Big Endian



### Little Endian



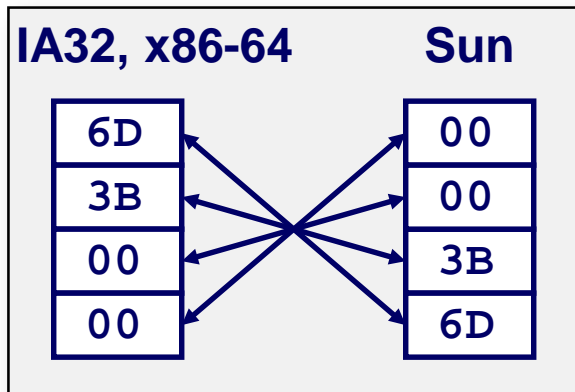
# Representing Integers

Decimal: 15213

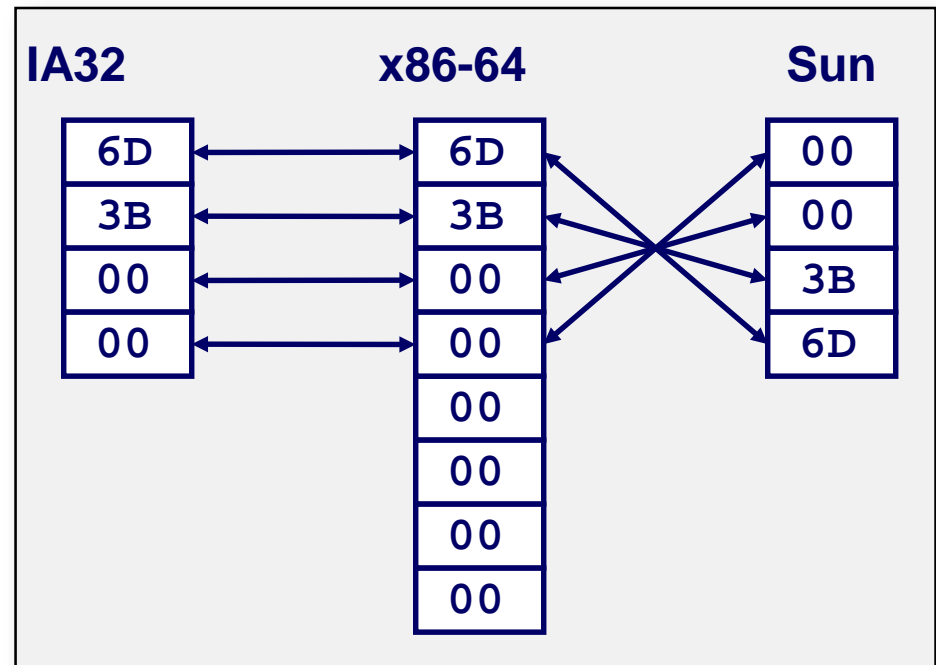
Binary: 0011 1011 0110 1101

Hex: 3 B 6 D

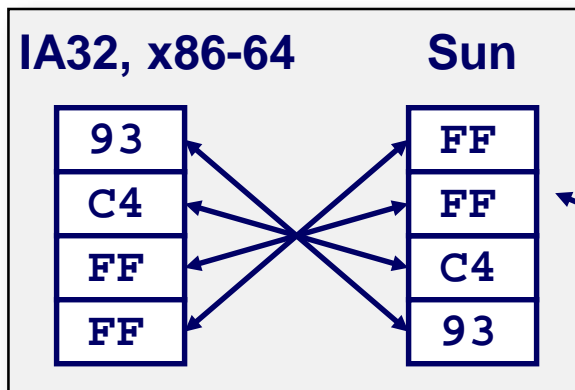
`int A = 15213;`



`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;  
0x7ffffb7f71dbc    6d  
0x7ffffb7f71dbd    3b  
0x7ffffb7f71dbe    00  
0x7ffffb7f71dbf    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

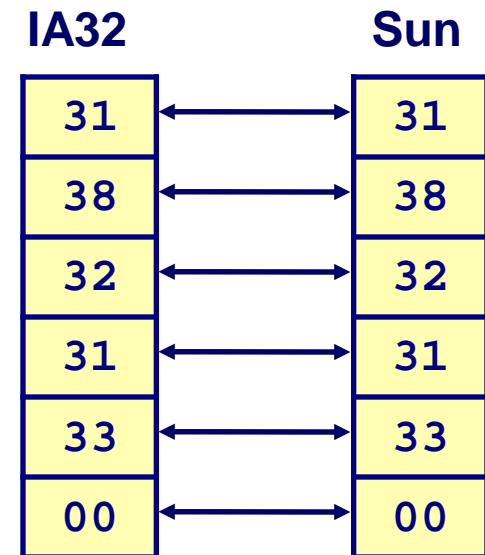
```
char S[6] = "18213";
```

## ■ 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



# Initialization

- $x < 0 \Rightarrow ((x * 2) < 0)$
- $ux \geq 0$
- $x \& 7 == 7 \Rightarrow (x \ll 30) < 0$
- $ux > -1$
- $x > y \Rightarrow -x < -y$
- $x * x \geq 0$
- $x > 0 \&\& y > 0 \Rightarrow x + y > 0$
- $x \geq 0 \Rightarrow -x \leq 0$
- $x \leq 0 \Rightarrow -x \geq 0$
- $(x \mid -x) \gg 31 == -1$
- $ux \gg 3 == ux / 8$
- $x \gg 3 == x / 8$
- $x \& (x - 1) != 0$

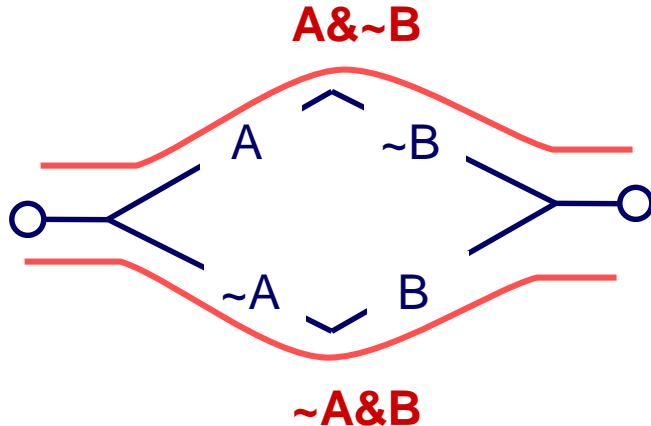
# Bonus extras



# Application of Boolean Algebra

## ■ Applied to Digital Systems by Claude Shannon

- 1937 MIT Master's Thesis
- Reason about networks of relay switches
  - Encode closed switch as 1, open switch as 0



Connection when

$$A \& \sim B \mid \sim A \& B$$

$$= A \wedge B$$

# Binary Number Property

## Claim

$$1 + 1 + 2 + 4 + 8 + \dots + 2^{w-1} = 2^w$$


$$1 + \sum_{i=0}^{w-1} 2^i = 2^w$$

■ **w = 0:**

■  $1 = 2^0$

■ **Assume true for w-1:**

■  $1 + 1 + 2 + 4 + 8 + \dots + 2^{w-1} + 2^w = 2^w + 2^w = 2^{w+1}$



$= 2^w$

# Code Security Example

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

- Similar to code found in FreeBSD's implementation of `getpeername`
- There are legions of smart people trying to find vulnerabilities in programs

# Typical Usage

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

```
#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, MSIZE);
    printf("%s\n", mybuf);
}
```

# Malicious Usage

```
/* Declaration of library function memcpy */
void *memcpy(void *dest, void *src, size_t n);
```

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

```
#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, -MSIZE);
    . . .
}
```

# Mathematical Properties

## ■ Modular Addition Forms an *Abelian Group*

- **Closed** under addition

$$0 \leq \text{UAdd}_w(u, v) \leq 2^w - 1$$

- **Commutative**

$$\text{UAdd}_w(u, v) = \text{UAdd}_w(v, u)$$

- **Associative**

$$\text{UAdd}_w(t, \text{UAdd}_w(u, v)) = \text{UAdd}_w(\text{UAdd}_w(t, u), v)$$

- **0** is additive identity

$$\text{UAdd}_w(u, 0) = u$$

- Every element has additive **inverse**

- Let  $\text{UComp}_w(u) = 2^w - u$   
 $\text{UAdd}_w(u, \text{UComp}_w(u)) = 0$

# Mathematical Properties of TAdd

## ■ Isomorphic Group to unsigneds with UAdd

- $TAdd_w(u, v) = U2T(UAdd_w(T2U(u), T2U(v)))$ 
  - Since both have identical bit patterns

## ■ Two's Complement Under TAdd Forms a Group

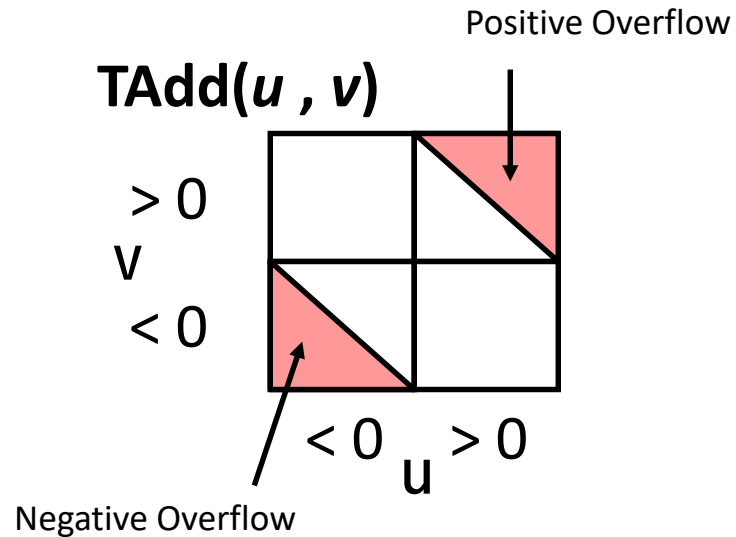
- Closed, Commutative, Associative, 0 is additive identity
- Every element has additive inverse

$$TComp_w(u) = \begin{cases} -u & u \neq TMin_w \\ TMin_w & u = TMin_w \end{cases}$$

# Characterizing TAdd

## ■ Functionality

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



$$\mathcal{M}_w(u, v) = \begin{cases} u + v + 2^w & u + v < \mathcal{M}_w \quad (\text{NegOver}) \\ u + v & \mathcal{M}_w \leq u + v \leq \mathcal{M}_w \\ u + v - 2^w & \mathcal{M}_w < u + v \quad (\text{PosOver}) \end{cases}$$



# Negation: Complement & Increment

## ■ Claim: Following Holds for 2's Complement

$$\sim x + 1 == -x$$

## ■ Complement

- Observation:  $\sim x + x == 1111\dots111 == -1$

$$\begin{array}{r}
 x \quad 10011101 \\
 + \quad \sim x \quad 01100010 \\
 \hline
 -1 \quad 11111111
 \end{array}$$

## ■ Complete Proof?

# Complement & Increment Examples

**x = 15213**

	Decimal	Hex	Binary
<b>x</b>	<b>15213</b>	<b>3B 6D</b>	<b>00111011 01101101</b>
<b>~x</b>	<b>-15214</b>	<b>C4 92</b>	<b>11000100 10010010</b>
<b>~x+1</b>	<b>-15213</b>	<b>C4 93</b>	<b>11000100 10010011</b>
<b>y</b>	<b>-15213</b>	<b>C4 93</b>	<b>11000100 10010011</b>

**x = 0**

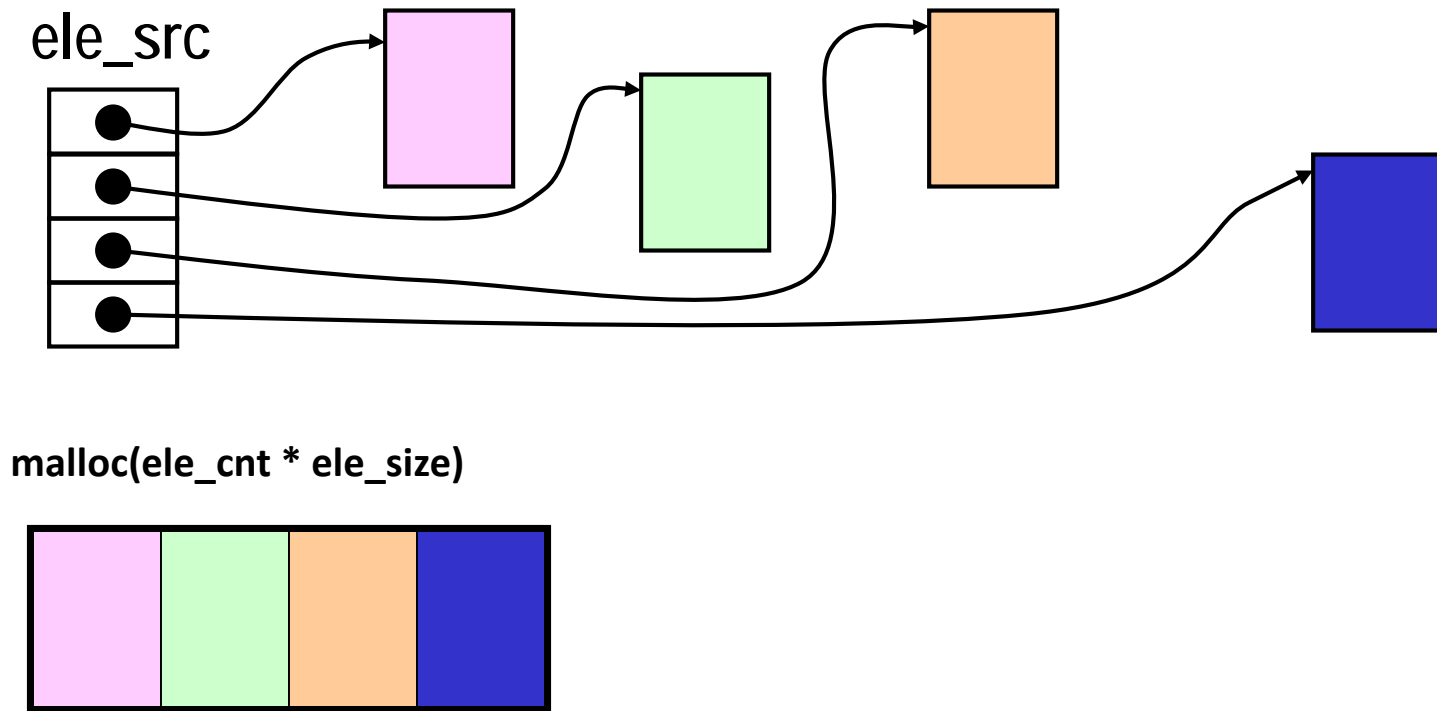
	Decimal	Hex	Binary
<b>0</b>	<b>0</b>	<b>00 00</b>	<b>00000000 00000000</b>
<b>~0</b>	<b>-1</b>	<b>FF FF</b>	<b>11111111 11111111</b>
<b>~0+1</b>	<b>0</b>	<b>00 00</b>	<b>00000000 00000000</b>

# Code Security Example #2

## ■ SUN XDR library

- Widely used library for transferring data between machines

```
void* copy_elements(void *ele_src[], int ele_cnt, size_t ele_size);
```



# XDR Code

```
void* copy_elements(void *ele_src[], int ele_cnt, size_t ele_size) {  
    /*  
     * Allocate buffer for ele_cnt objects, each of ele_size bytes  
     * and copy from locations designated by ele_src  
     */  
    void *result = malloc(ele_cnt * ele_size);  
    if (result == NULL)  
        /* malloc failed */  
        return NULL;  
    void *next = result;  
    int i;  
    for (i = 0; i < ele_cnt; i++) {  
        /* Copy object i to destination */  
        memcpy(next, ele_src[i], ele_size);  
        /* Move pointer to next memory region */  
        next += ele_size;  
    }  
    return result;  
}
```

# XDR Vulnerability

`malloc(ele_cnt * ele_size)`

## ■ What if:

- `ele_cnt` =  $2^{20} + 1$
- `ele_size` = 4096 =  $2^{12}$
- Allocation = ??

## ■ How can I make this function secure?

# Compiled Multiplication Code

## C Function

```
long mul12(long x)
{
    return x*12;
}
```

## Compiled Arithmetic Operations

```
leaq (%rax,%rax,2), %rax
salq $2, %rax
```

## Explanation

```
t <- x+x*2
return t << 2;
```

- C compiler automatically generates shift/add code when multiplying by constant

# Compiled Unsigned Division Code

## C Function

```
unsigned long udiv8
(unsigned long x)
{
    return x/8;
}
```

## Compiled Arithmetic Operations

```
shrq $3, %rax
```

## Explanation

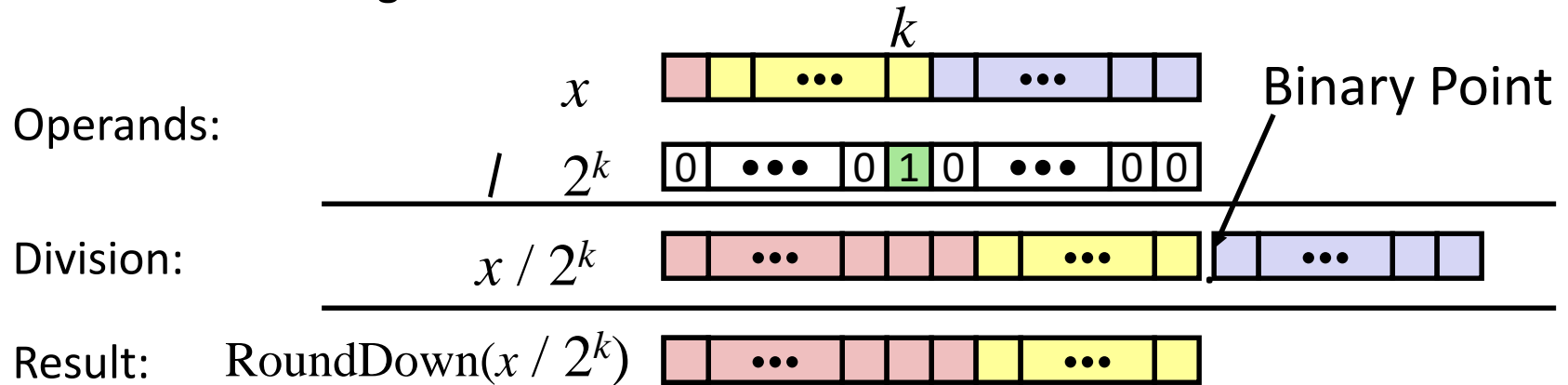
```
# Logical shift
return x >> 3;
```

- Uses logical shift for unsigned
- For Java Users
  - Logical shift written as >>>

# Signed Power-of-2 Divide with Shift

## ■ Quotient of Signed by Power of 2

- $x \gg k$  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
$y \gg 1$	-7606.5	-7607	E2 49	<b>1</b> 1100010 01001001
$y \gg 4$	-950.8125	-951	FC 49	<b>1111</b> 1100 01001001
$y \gg 8$	-59.4257813	-60	FF C4	<b>11111111</b> 11000100

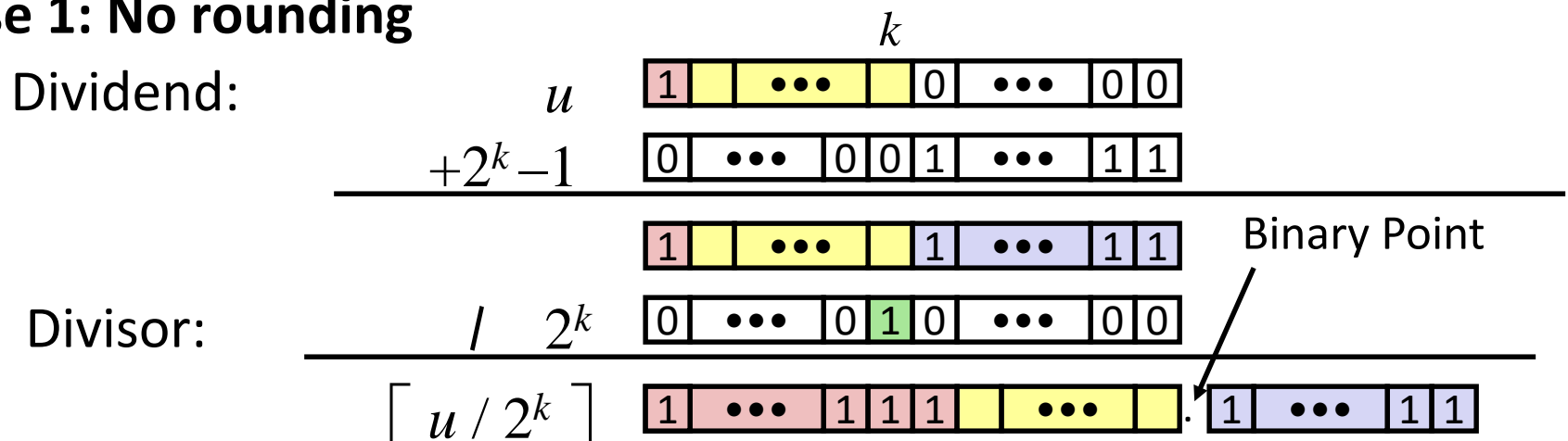


# Correct Power-of-2 Divide

## ■ Quotient of Negative Number by Power of 2

- Want  $\lceil x / 2^k \rceil$  (Round Toward 0)
- Compute as  $\lfloor (x + 2^k - 1) / 2^k \rfloor$ 
  - In C:  $(x + (1 \ll k) - 1) \gg k$
  - Biases dividend toward 0

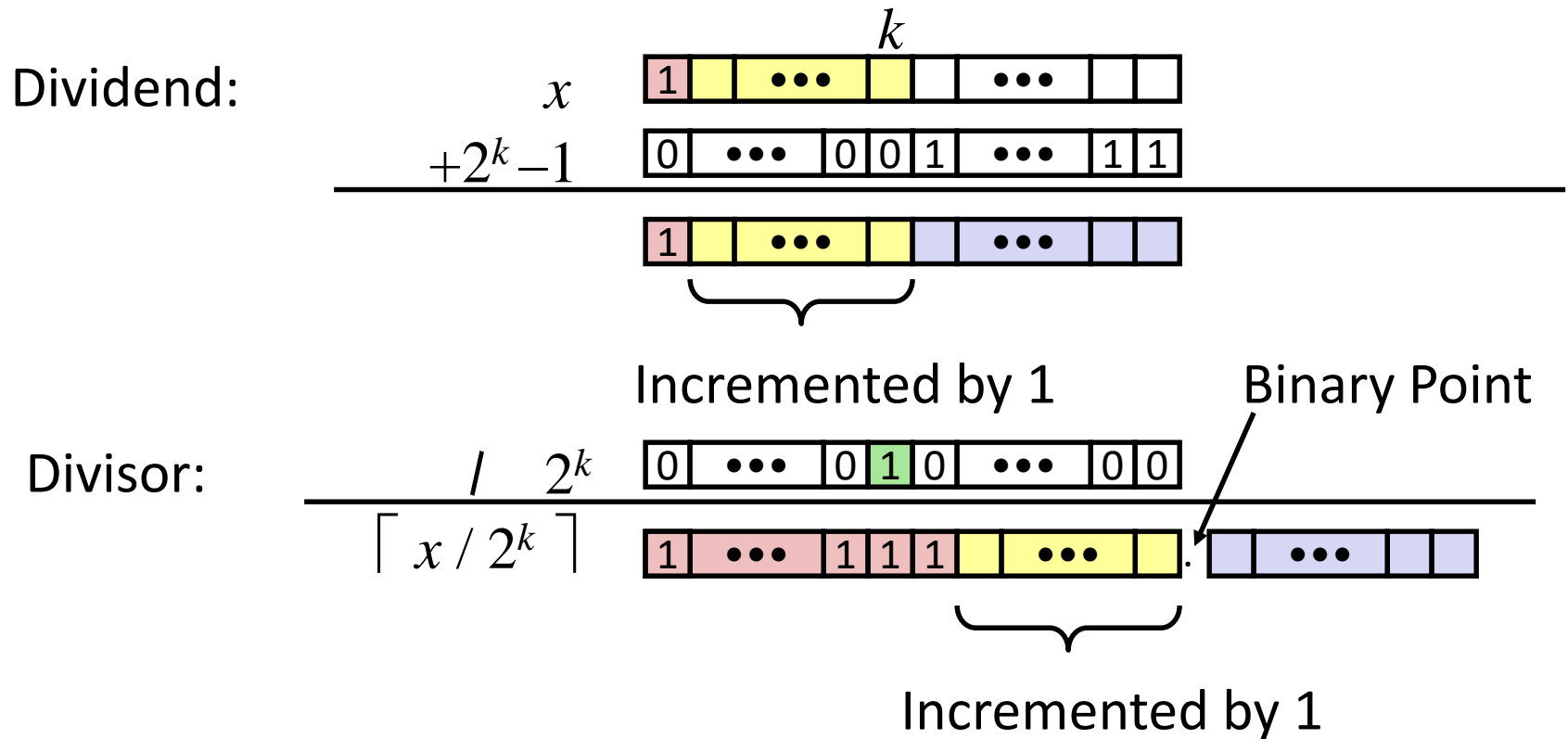
### Case 1: No rounding



***Biassing has no effect***

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

## Case 2: Rounding



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

# Compiled Signed Division Code

## C Function

```
long idiv8(long x)
{
    return x/8;
}
```

## Compiled Arithmetic Operations

```
    testq %rax, %rax
    js    L4
L3:
    sarq $3, %rax
    ret
L4:
    addq $7, %rax
    jmp  L3
```

## Explanation

```
    if x < 0
        x += 7;
    # Arithmetic shift
    return x >> 3;
```

- Uses arithmetic shift for int
- For Java Users
  - Arith. shift written as >>

# Arithmetic: Basic Rules

- **Unsigned ints, 2's complement ints are isomorphic rings:  
isomorphism = casting**
  
- **Left shift**
  - Unsigned/signed: multiplication by  $2^k$
  - Always logical shift
  
- **Right shift**
  - Unsigned: logical shift, div (division + round to zero) by  $2^k$
  - Signed: arithmetic shift
    - Positive numbers: div (division + round to zero) by  $2^k$
    - Negative numbers: div (division + round away from zero) by  $2^k$   
Use biasing to fix

# Properties of Unsigned Arithmetic

## ■ Unsigned Multiplication with Addition Forms Commutative Ring

- Addition is commutative group

- Closed under multiplication

$$0 \leq \text{UMult}_w(u, v) \leq 2^w - 1$$

- Multiplication Commutative

$$\text{UMult}_w(u, v) = \text{UMult}_w(v, u)$$

- Multiplication is Associative

$$\text{UMult}_w(t, \text{UMult}_w(u, v)) = \text{UMult}_w(\text{UMult}_w(t, u), v)$$

- 1 is multiplicative identity

$$\text{UMult}_w(u, 1) = u$$

- Multiplication distributes over addition

$$\text{UMult}_w(t, \text{UAdd}_w(u, v)) = \text{UAdd}_w(\text{UMult}_w(t, u), \text{UMult}_w(t, v))$$

# Properties of Two's Comp. Arithmetic

## ■ Isomorphic Algebras

- Unsigned multiplication and addition
  - Truncating to  $w$  bits
- Two's complement multiplication and addition
  - Truncating to  $w$  bits

## ■ Both Form Rings

- Isomorphic to ring of integers mod  $2^w$

## ■ Comparison to (Mathematical) Integer Arithmetic

- Both are rings
- Integers obey ordering properties, e.g.,

$$u > 0 \quad \Rightarrow \quad u + v > v$$

$$u > 0, v > 0 \quad \Rightarrow \quad u \cdot v > 0$$

- These properties are not obeyed by two's comp. arithmetic

$$TMax + 1 == TMin$$

$$15213 * 30426 == -10030 \quad (16\text{-bit words})$$

# 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:
- Pad to 32 bits:
- Split into bytes:
- Reverse:

0x12ab

0x000012ab

00 00 12 ab

ab 12 00 00