



Bits, Bytes and Integers – Part 1

15-213/18-213/15-513: Introduction to Computer Systems
2nd Lecture, Aug. 31, 2017

Today's Instructor:
Randy Bryant

Announcements

- Recitations are on Mondays, but next Monday (9/4) is Labor Day, so recitations are cancelled
- Linux Boot Camp Monday evening 7pm, Rashid Auditorium
- Lab 0 is now available via course web page and Autolab.
 - Due Thu Sept. 7, 11:59pm
 - No grace days
 - No late submissions
 - Just do it!

Waitlist questions

- 15-213: Mary Widom (marwidom@cs.cmu.edu)
- 18-213: ECE Academic services
ece-asc@andrew.cmu.edu
- 15-513: Mary Widom (marwidom@cs.cmu.edu)

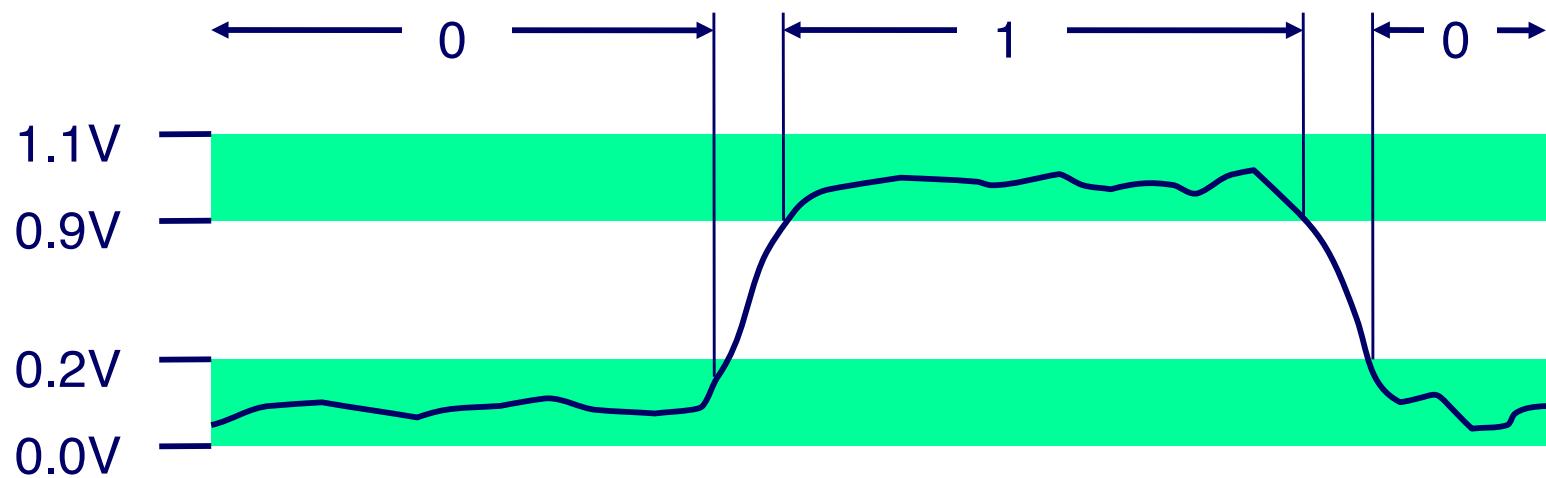
- Please don't contact the instructors with waitlist questions.

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

Encoding Byte Values

■ Byte = 8 bits

- Binary 00000000₂ to 11111111₂
- Decimal: 0₁₀ to 255₁₀
- Hexadecimal 00₁₆ to FF₁₆
 - Base 16 number representation
 - Use characters '0' to '9' and 'A' to 'F'
 - Write FA1D37B₁₆ 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: 0011 1011 0110 1101

3 B 6 D

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

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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

$$\begin{array}{r} 01101001 \\ \& 01010101 \\ \hline 01000001 \end{array} \quad \begin{array}{r} 01101001 \\ | 01010101 \\ \hline 01111101 \end{array} \quad \begin{array}{r} 01101001 \\ ^ 01010101 \\ \hline 00111100 \end{array} \quad \begin{array}{r} 01101001 \\ \sim 01010101 \\ \hline 10101010 \end{array}$$

■ 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)
- $\sim 0x41 \rightarrow$
 - $\sim 0x00 \rightarrow$
 - $0x69 \& 0x55 \rightarrow$
 - $0x69 | 0x55 \rightarrow$

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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Bit-Level Operations in C

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- View arguments as bit vectors
- Arguments applied bit-wise

Examples (Char data type)

- $\sim 0x41 \rightarrow 0xBE$
 - $\sim 0100\ 0001_2 \rightarrow 1011\ 1110_2$
- $\sim 0x00 \rightarrow 0xFF$
 - $\sim 0000\ 0000_2 \rightarrow 1111\ 1111_2$
- $0x69 \& 0x55 \rightarrow 0x41$
 - $0110\ 1001_2 \& 0101\ 0101_2 \rightarrow 0100\ 0001_2$
- $0x69 | 0x55 \rightarrow 0x7D$
 - $0110\ 1001_2 | 0101\ 0101_2 \rightarrow 0111\ 1101_2$

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
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Contrast: Logic Operations in C

■ Contrast to Bit-Level Operators

■ Logic Operations `&`, `||`, `!`

- View 0 as “False”
- Anything nonzero is “True”
- Always short-circuit
- Early exit

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

■ Examples

- `!0x41` → `0x00`
- `!0x00` → `0x01`
- `!!0x41` → `0x01`
- `0x69 && 0x55` → `0x01`
- `0x69 || 0x55` → `0x01`
- `p && *p` (avoids null pointer access)

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

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

■ Undefined Behavior

- Shift amount < 0 or \geq word size

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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
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: Simple Example

$$\begin{array}{rccccc} & -16 & 8 & 4 & 2 & 1 \\ 10 = & 0 & 1 & 0 & 1 & 0 & \quad 8+2 = 10 \end{array}$$

$$\begin{array}{rccccc} & -16 & 8 & 4 & 2 & 1 \\ -10 = & 1 & 0 & 1 & 1 & 0 & \quad -16+4+2 = -10 \end{array}$$

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
- 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

Quiz Time!

Check out:

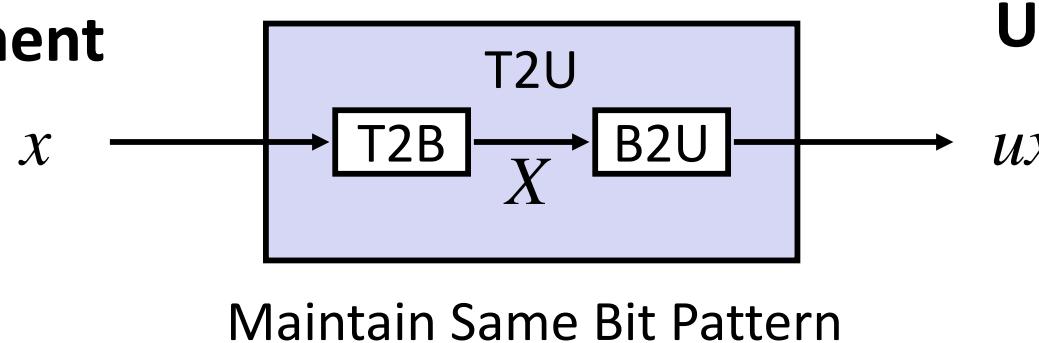
<https://canvas.cmu.edu/courses/1221>

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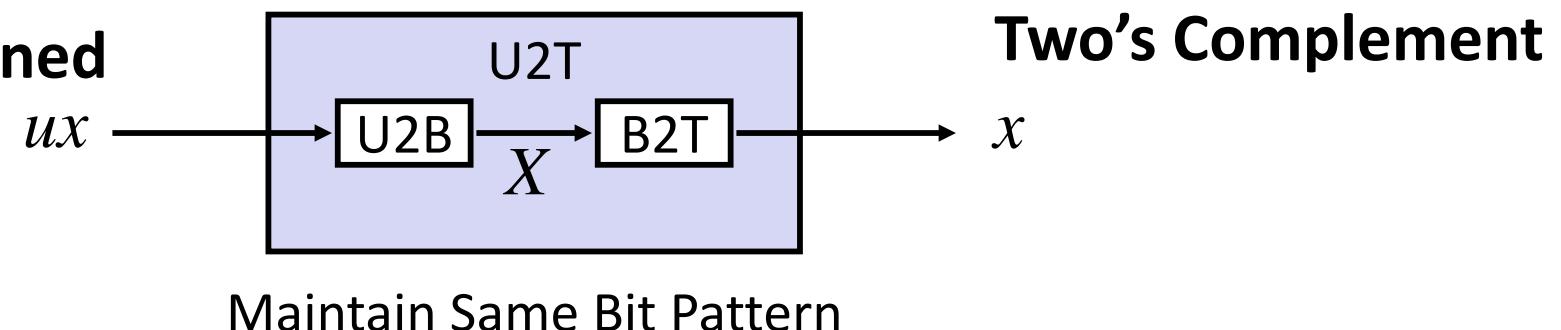
Mapping Between Signed & Unsigned

Two's Complement



Unsigned

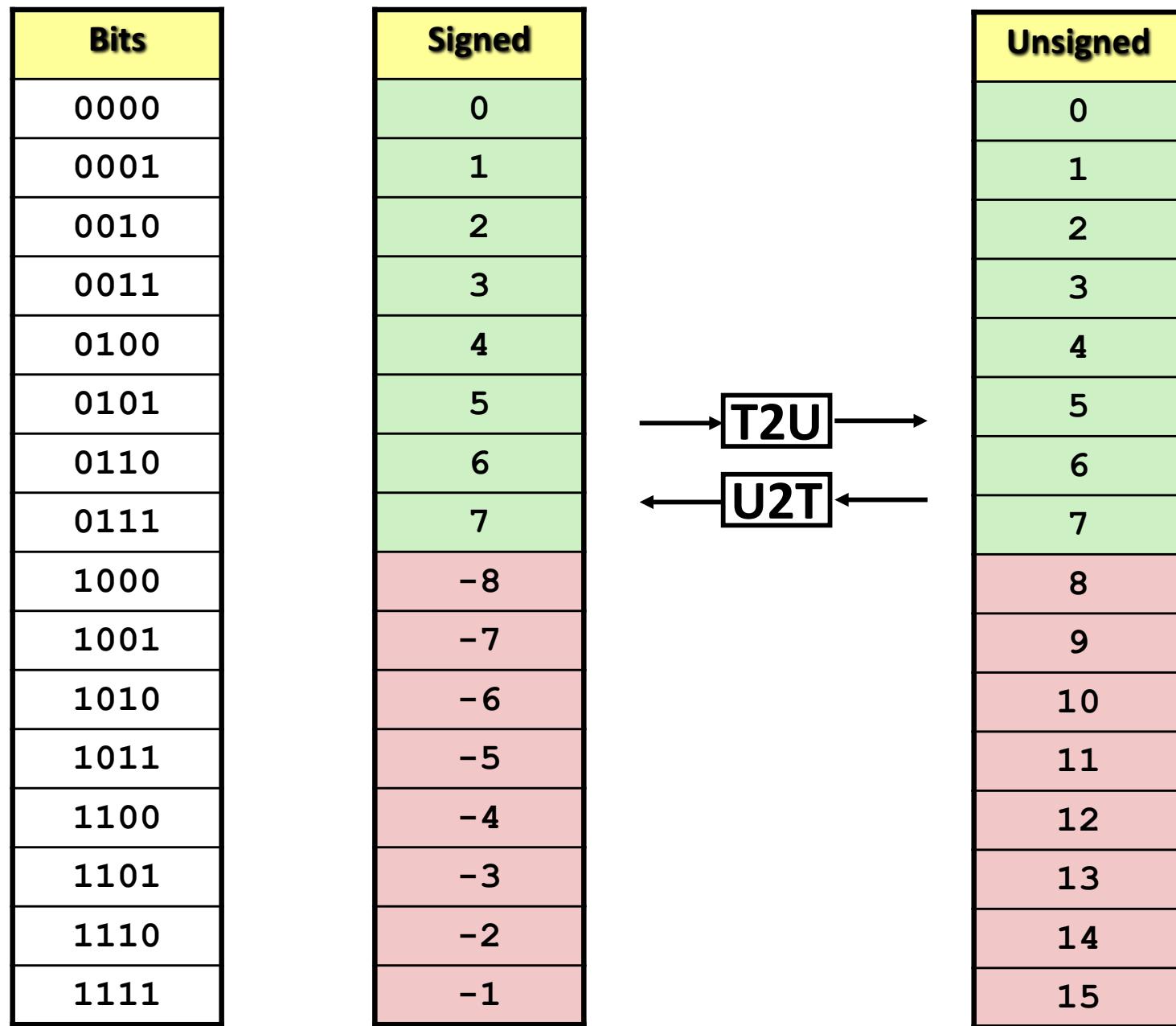
Unsigned



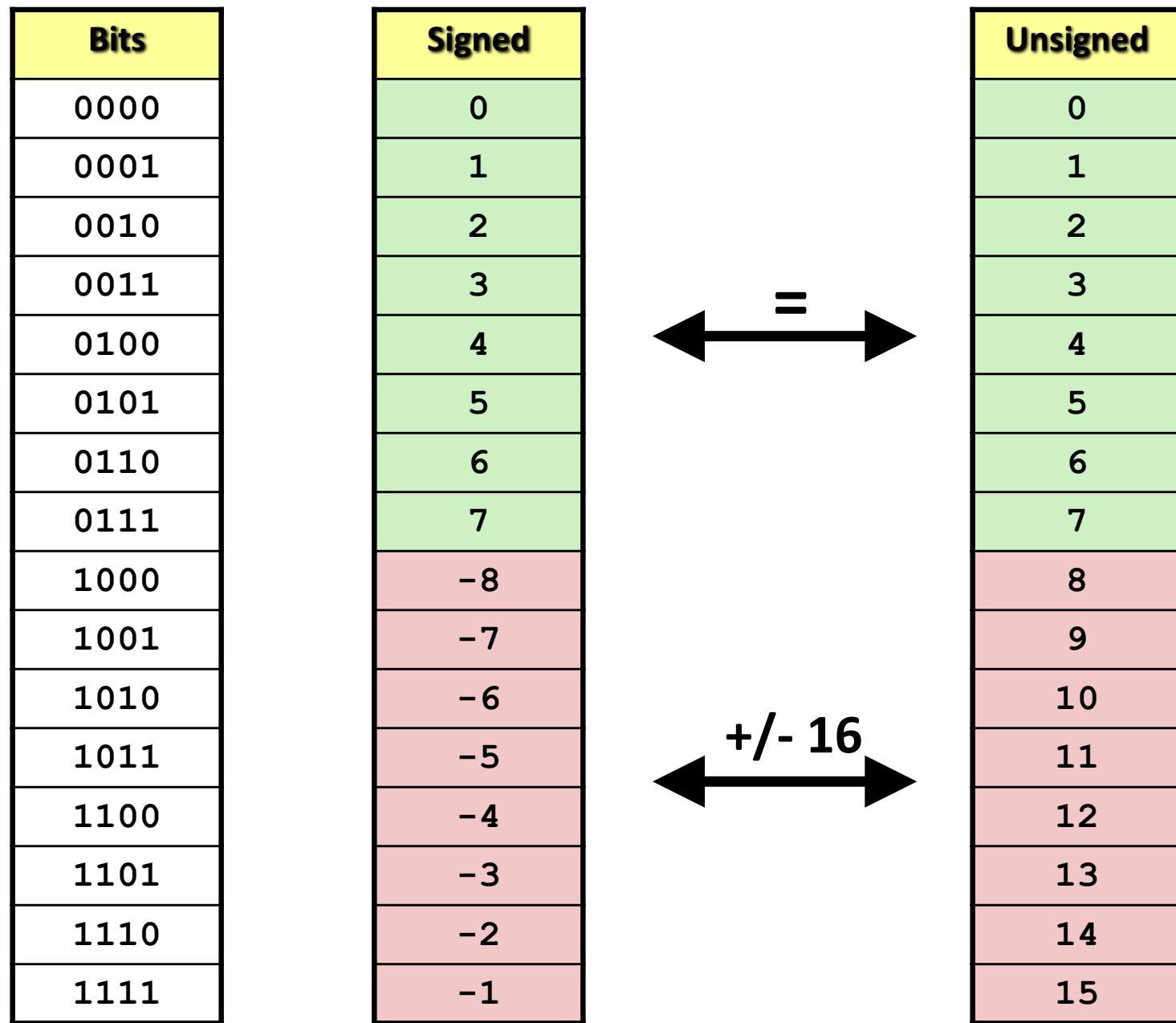
Two's Complement

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

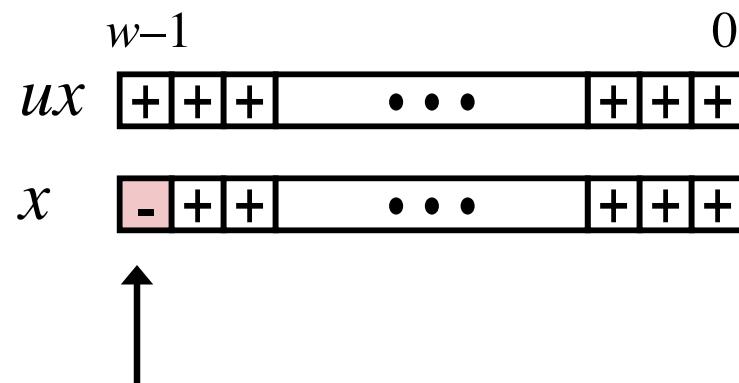
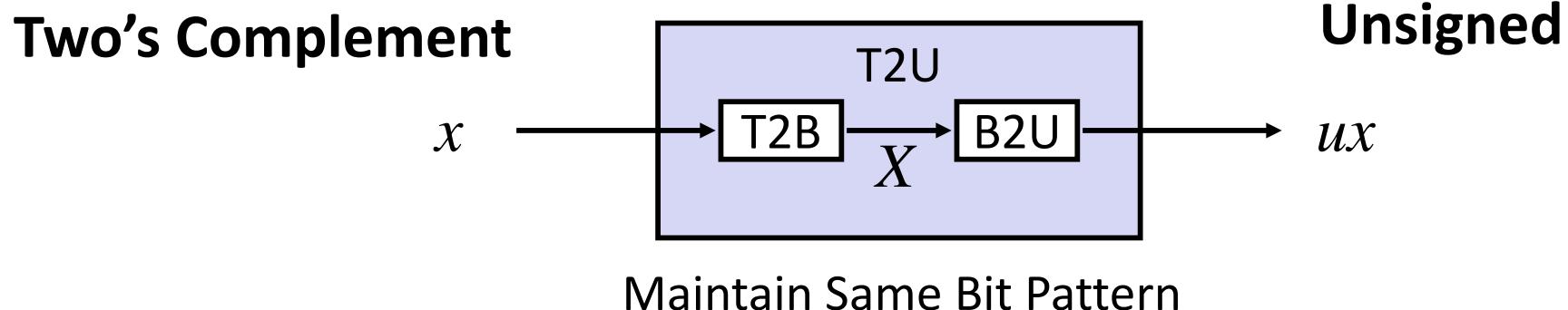
Mapping Signed \leftrightarrow Unsigned



Mapping Signed \leftrightarrow Unsigned



Relation between Signed & Unsigned

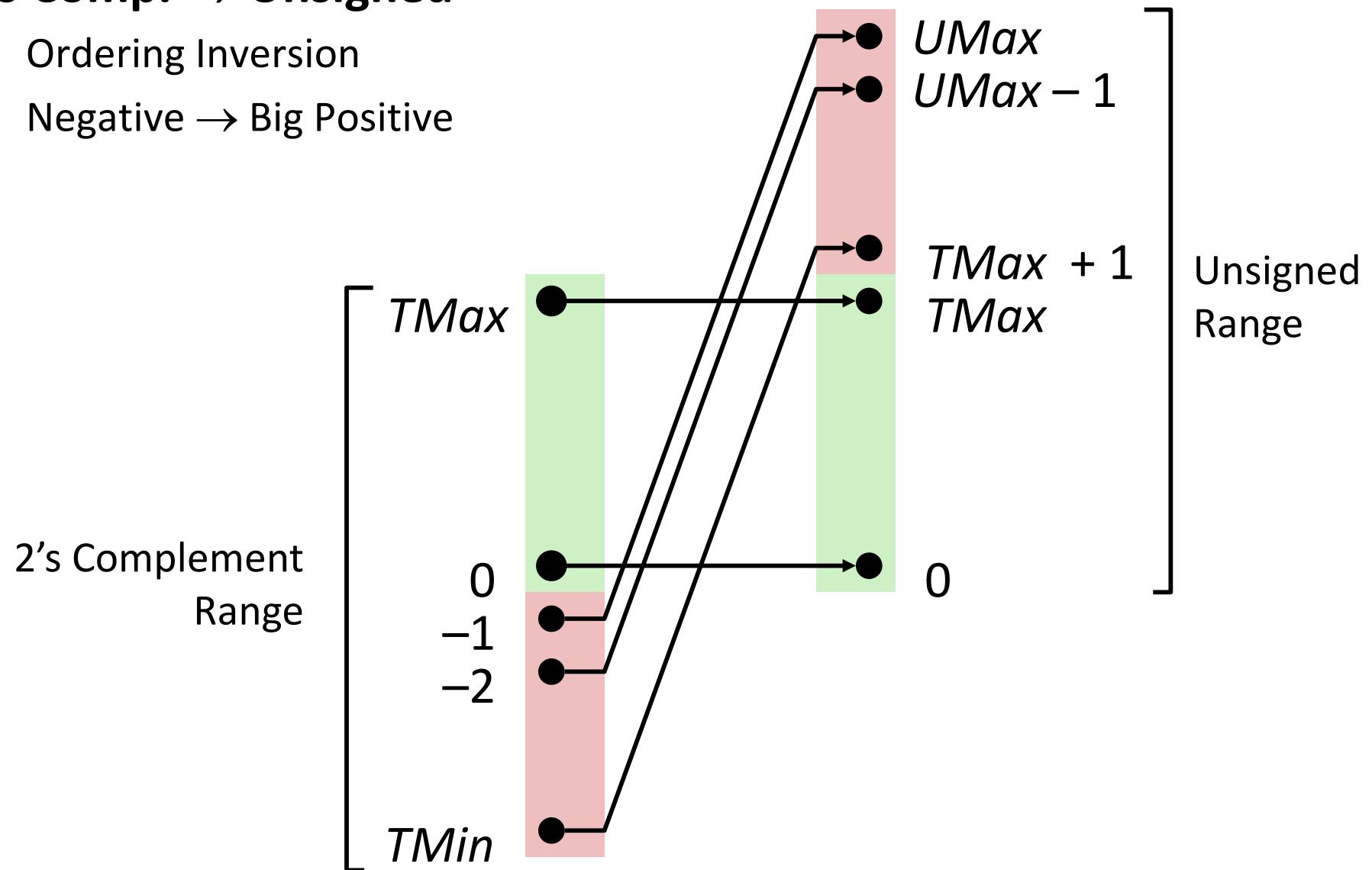


**Large negative weight
becomes
Large positive weight**

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

■ Constant ₁	Constant ₂	Relation	Evaluation
0	0U	<code>==</code>	unsigned
-1	0	<code><</code>	signed
-1	0U	<code>></code>	unsigned
2147483647	-2147483647-1	<code>></code>	signed
2147483647U	-2147483647-1	<code><</code>	unsigned
-1	-2	<code>></code>	signed
(unsigned)-1	-2	<code>></code>	unsigned
2147483647	2147483648U	<code><</code>	unsigned
2147483647	(int) 2147483648U	<code>></code>	signed

Unsigned vs. Signed: 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)  
    . . .
```

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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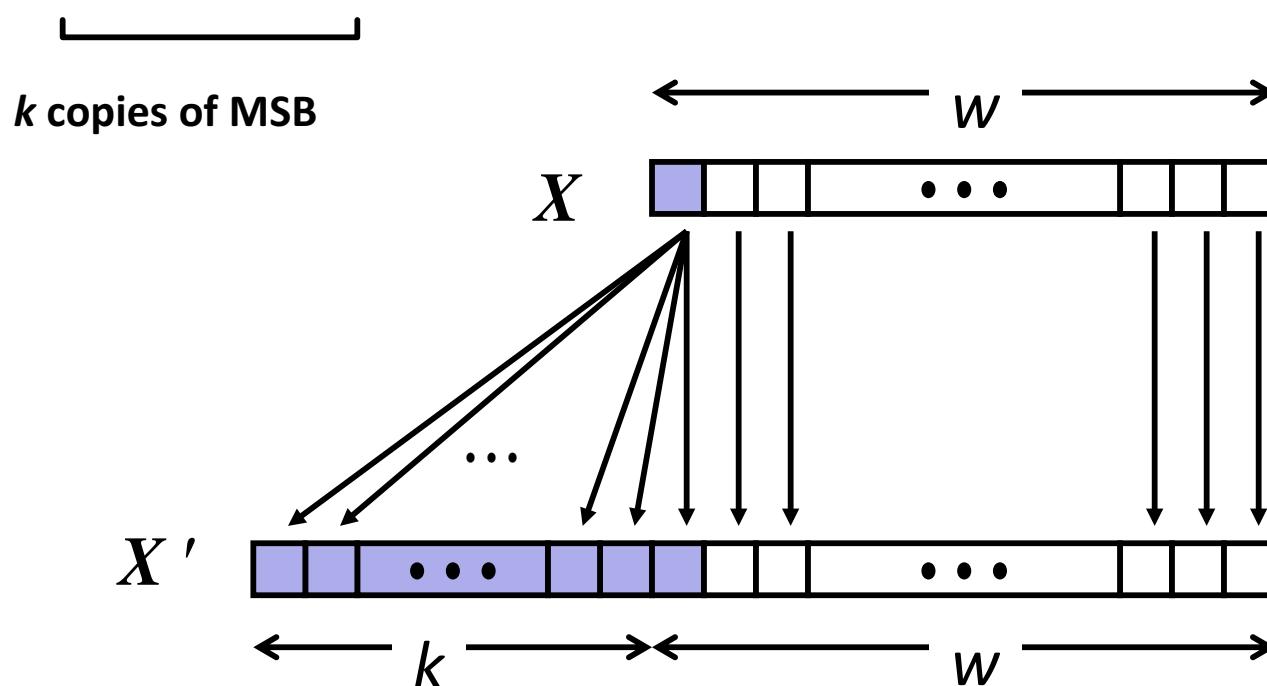
Sign Extension

■ Task:

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

■ Rule:

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



Sign Extension: Simple Example

Positive number

$10 =$

-16	8	4	2	1
0	1	0	1	0

-32	16	8	4	2	1
0	0	1	0	1	0

Negative number

$-10 =$

-16	8	4	2	1
1	0	1	1	0

-32	16	8	4	2	1
1	1	0	1	1	0

Larger 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

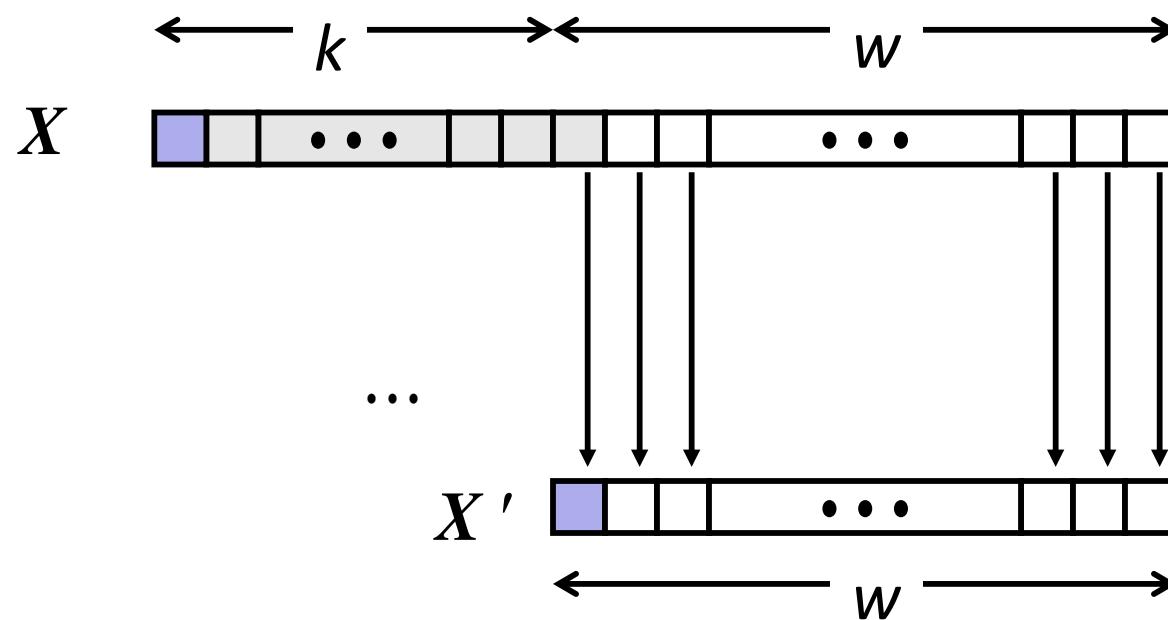
Truncation

■ Task:

- Given $k+w$ -bit signed or unsigned integer X
- Convert it to w -bit integer X' with same value for “small enough” X

■ Rule:

- Drop top k bits:
- $X' = x_{w-1}, x_{w-2}, \dots, x_0$



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	

$$2 \bmod 16 = 2$$

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

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

$$-6 \bmod 16 = 26U \bmod 16 = 10U = -6$$

Sign change

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

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

$$10 \bmod 16 = 10U \bmod 16 = 10U = -6$$

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

	-8	4	2	1	
6 =	0	1	1	0	

$$-10 \bmod 16 = 22U \bmod 16 = 6U = 6$$

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 (in magnitude) numbers yields expected behavior

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