ILLINOIS TECH

Bits, Bytes, and Integers

CS351: Systems Programming
Days 3 and 4: Aug. 30 and Sep. 1, 2022

Instructor:

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Slides adapted from Bryant and O'Hallaron

Follow-up from last time

- **Q1: Why did we split our C program into multiple files?**
  - As a code-base gets larger, it'll involve multiple files.
  - Each file groups together related definitions, like a module.
  - Take a look at a large C program, such as the Linux kernel.

- **Q2: Why write in assembly if you call C code?**
  - One take-away: it doesn't matter what language you write code in, it'll be able to interoperate with code written in other languages.
  - Another take-away: you might not have the source code of the C-written object file.
  - Another take-away: reusing code from a library rather than write it from scratch – in our example, the library was C's standard library.

From Day 2

What else is your ASM program doing?

```
[nsultana@fourier l1]$ strace ./l1_helloworld_asm >\dev\null
execve("./l1_helloworld_asm", ["./l1_helloworld_asm"], 0x7fffb3b4ec50 /* 25 vars */) = 0
write(1, "Hello, world!\n", 14)          = 14
exit(0)                                 = ?
+++ exited with 0 +++
```

From Day 2

What else is your C program doing?

```
[nsultana@fourier l1]$ strace ./l1_helloworld_c >\dev\null
execve("./l1_helloworld_c", ["./l1_helloworld_c"], 0x7ffe4c6f2350 /* 25 vars */) = 0
brk(NULL)                               = 0x2302000
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fd518cc9000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=47878, ...}) = 0
mmap(NULL, 47878, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7fd518cbd000
close(3)                                = 0
open("/lib64/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0`&\2\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=2156664, ...}) = 0
mmap(NULL, 3985920, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7fd5186db000
mprotect(0x7fd51889f000, 2093056, PROT_NONE) = 0
mmap(0x7fd518a9e000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1c3000) …
mmap(0x7fd518aa4000, 16896, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) …
close(3)                                = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fd518cbc000
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fd518cba000
arch_prctl(ARCH_SET_FS, 0x7fd518cba740) = 0
access("/etc/sysconfig/strcasecmp-nonascii", F_OK) = -1 ENOENT (No such file or directory)
access("/etc/sysconfig/strcasecmp-nonascii", F_OK) = -1 ENOENT (No such file or directory)
mprotect(0x7fd518a9e000, 16384, PROT_READ) = 0
mprotect(0x600000, 4096, PROT_READ)     = 0
mprotect(0x7fd518cca000, 4096, PROT_READ) = 0
munmap(0x7fd518cbd000, 47878)           = 0
fstat(1, {st_mode=S_IFREG|0664, st_size=0, ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7fd518cc8000
write(1, "Hello, world!\n", 14)          = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

What is your (ASM-written) C program doing?

What is your (ASM-written) C program doing?

```
[nsultana@fourier l2]$ strace ./l2_helloworld_asm > /dev/null
execve("./l2_helloworld_asm", ["./l2_helloworld_asm"], 0x7ffeb3faf050 /* 27 vars */) = 0
brk(NULL)                               = 0x1292000
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f13600fa000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=47878, ...}) = 0
mmap(NULL, 47878, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f13600ee000
close(3)                                = 0
open("/lib64/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0`&\2\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=2156664, ...}) = 0
mmap(NULL, 3985920, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f135fb0c000
mprotect(0x7f135fcd0000, 2093056, PROT_NONE) = 0
mmap(0x7f135fecf000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1c3000) …
mmap(0x7f135fed5000, 16896, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) …
close(3)                                = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f13600ed000
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f13600eb000
arch_prctl(ARCH_SET_FS, 0x7f13600eb740) = 0
access("/etc/sysconfig/strcasecmp-nonascii", F_OK) = -1 ENOENT (No such file or directory)
access("/etc/sysconfig/strcasecmp-nonascii", F_OK) = -1 ENOENT (No such file or directory)
mprotect(0x7f135fecf000, 16384, PROT_READ) = 0
mprotect(0x600000, 4096, PROT_READ)     = 0
mprotect(0x7f13600fb000, 4096, PROT_READ) = 0
munmap(0x7f13600ee000, 47878)           = 0
fstat(1, {st_mode=S_IFCHR|0666, st_rdev=makedev(1, 3), ...}) = 0
ioctl(1, TCGETS, 0x7fffc305c290)        = -1 ENOTTY (Inappropriate ioctl for device)
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f13600f9000
write(1, "Hello, world!\n", 14)          = 14
exit_group(14)                          = ?
+++ exited with 14 +++
```

Follow-up from last time

- **Q3: Does the C compiler produce assembly?**
  - Yes!
  - Use the “-S” parameter

```
[nsultana@fourier l1]$ gcc -O0 -S l1_helloworld.c -o-
        .file   "l1_helloworld.c"
        .section        .rodata
.LC0:
        .string "Hello, world!"
        .text
        .globl  main
        .type   main, @function
main:
.LFB0:
        .cfi_startproc
        pushq   %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq    %rsp, %rbp
        .cfi_def_cfa_register 6
        subq    $16, %rsp
        movl    %edi, -4(%rbp)
        movq    %rsi, -16(%rbp)
        movl    $.LC0, %edi
        call    puts
        leave
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE0:
        .size   main, .-main
        .ident  "GCC: (GNU) 4.8.5 20150623 (Red Hat 4.8.5-44.0.3)"
        .section        .note.GNU-stack,"",@progbits
```

Calendar

Monday	Tuesday
Aug 22	Aug 23 **LEC 1:** Introduction **Preparation:** Read CS:APP Chapter 1
Aug 29 **LAB**	Aug 30 **LEC 3:** Bits, Bytes, and Ints: Part 1 **Preparation:** Read CS:APP 2.1 **Assigned:** Lab 1: Preliminaries
Sep 05 Labor Day	Sep 06 **LEC 5:** Floating Point **Preparation:** Read CS:APP 2.4
Sep 12 **LAB** **DUE:** Lab 1 (Preliminaries)	Sep 13 **LEC 7:** Machine Prog: Control **Preparation:** Read CS:APP 3.6 **Assigned:** Lab 2: Datalab and Data Representations

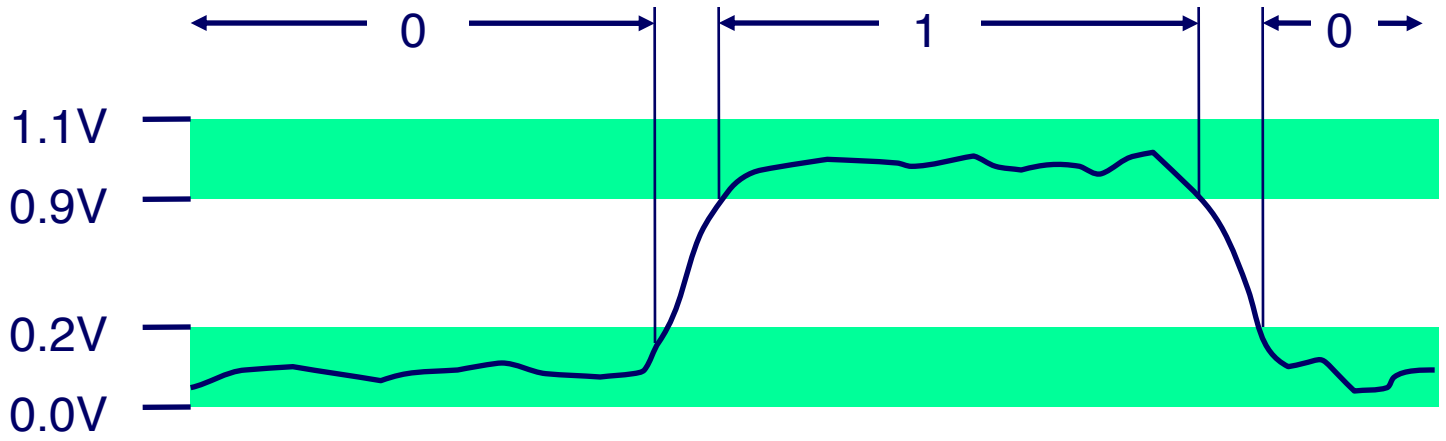
Today: Bits, Bytes, and Integers

- **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

Let's look at Hello World again.

- **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



```
0000000: 7f45 4c46 0201 0100 0000 0000 0000 0000  .ELF............
0000010: 0200 3e00 0100 0000 b000 4000 0000 0000  ..>.......@.....
0000020: 4000 0000 0000 0000 4002 0000 0000 0000  @.......@.......
0000030: 0000 0000 4000 3800 0200 4000 0600 0500  ....@.8...@.....
0000040: 0100 0000 0500 0000 0000 0000 0000 0000  ................
0000050: 0000 4000 0000 0000 0000 4000 0000 0000  ..@.......@.....
0000060: d700 0000 0000 0000 d700 0000 0000 0000  ................
0000070: 0000 2000 0000 0000 0100 0000 0600 0000  .. ............
0000080: d800 0000 0000 0000 d800 6000 0000 0000  ..........`.....
0000090: d800 6000 0000 0000 0e00 0000 0000 0000  ..`.............
00000a0: 0e00 0000 0000 0000 0000 2000 0000 0000  .......... .....
00000b0: b801 0000 00bf 0100 0000 48be d800 6000  ..........H...`.
00000c0: 0000 0000 ba0e 0000 000f 05b8 3c00 0000  ............<...
00000d0: bf00 0000 000f 0500 4865 6c6c 6f2c 2077  ........Hello, w
00000e0: 6f72 6c64 210a 0000 0000 0000 0000 0000  orld!...........
00000f0: 0000 0000 0000 0000 0000 0000 0000 0000  ................
0000100: 0000 0000 0300 0100 b000 4000 0000 0000  ..........@.....
0000110: 0000 0000 0000 0000 0000 0000 0300 0200  ................
0000120: d800 6000 0000 0000 0000 0000 0000 0000  ..`.............
0000130: 0100 0000 0400 f1ff 0000 0000 0000 0000  ................
0000140: 0000 0000 0000 0000 1300 0000 0000 0200  ................
0000150: d800 6000 0000 0000 0000 0000 0000 0000  ..`.............
0000160: 1b00 0000 0000 f1ff 0e00 0000 0000 0000  ................
0000170: 0000 0000 0000 0000 2c00 0000 1000 0100  ........,.......
0000180: b000 4000 0000 0000 0000 0000 0000 0000  ..@.............
0000190: 2700 0000 1000 0200 e600 6000 0000 0000  '.........`.....
00001a0: 0000 0000 0000 0000 3300 0000 1000 0200  ........3.......
00001b0: e600 6000 0000 0000 0000 0000 0000 0000  ..`.............
00001c0: 3a00 0000 1000 0200 e800 6000 0000 0000  :.........`.....
00001d0: 0000 0000 0000 0000 006c 315f 6865 6c6c  .........l1_hell
00001e0: 6f77 6f72 6c64 2e61 736d 006d 6573 7361  oworld.asm.messa
00001f0: 6765 006d 6573 7361 6765 5f6c 656e 005f  ge.message_len._
0000200: 5f62 7373 5f73 7461 7274 005f 6564 6174  _bss_start._edat
0000210: 6100 5f65 6e64 0000 2e73 796d 7461 6200  a._end...symtab.
0000220: 2e73 7472 7461 6200 2e73 6873 7472 7461  .strtab..shstrta
0000230: 6200 2e74 6578 7400 2e64 6174 6100 0000  b..text..data...
0000240: 0000 0000 0000 0000 0000 0000 0000 0000  ................
```

```
$ objdump -M intel -d ../l1/l1_helloworld_asm

../l1/l1_helloworld_asm:     file format elf64-x86-64


Disassembly of section .text:

00000000004000b0 <_start>:
  4000b0:       b8 01 00 00 00          mov    eax,0x1
  4000b5:       bf 01 00 00 00          mov    edi,0x1
  4000ba:       48 be d8 00 60 00 00    movabs rsi,0x6000d8
  4000c1:       00 00 00
  4000c4:       ba 0e 00 00 00          mov    edx,0xe
  4000c9:       0f 05                   syscall
  4000cb:       b8 3c 00 00 00          mov    eax,0x3c
  4000d0:       bf 00 00 00 00          mov    edi,0x0
  4000d5:       0f 05                   syscall
```

For example, can count in binary

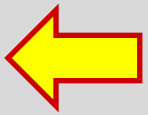
- **Base 2 Number Representation**
  - Represent 15213_{10} as 11101101101101_2
  - Represent 1.20_{10} as $1.0011001100110011[0011]\ldots_2$
  - Represent 1.5213×10^4 as $1.1101101101101_2 \times 2^{13}$

```c
#include <stdio.h>

int number1 = 15213;
float number2 = 1.20;
float number3 = 1.5213 * (10*10*10*10);

int
main (int argc, const char *argv[]) {
  printf("%d %f %f\n", number1, number2, number3);
  return 0;
}
```

```
[nsultana@fourier l3]$ gdb ./a.out
GNU gdb (GDB) Red Hat Enterprise Linux 7.6.1-120.0.1.el7
Copyright (C) 2013 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.  Type "show copying"
and "show warranty" for details.
This GDB was configured as "x86_64-redhat-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
Reading symbols from /home/nsultana/examples/l3/a.out...(no debugging symbols
found)...done.
(gdb) p number1
$1 = 15213
(gdb) p/f number2
$2 = 1.20000005
(gdb) p/f number3
$3 = 15213
(gdb) p/t number1
$4 = 11101101101101
(gdb) p/t number2
$5 = 11111110011001100110011010
(gdb) p/t number3
$6 = 10001100110110110110000000000
(gdb)
```



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

Today: Bits, Bytes, and Integers

- Representing information as bits
- **Bit-level manipulations**
- Integers
  - Representation: unsigned and signed
  - Conversion, casting
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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 → 0xBE`
    - $\sim 01000001_2 \rightarrow 10111110_2$
  - `~0x00 → 0xFF`
    - $\sim 00000000_2 \rightarrow 11111111_2$
  - `0x69 & 0x55 → 0x41`
    - $01101001_2 \;\&\; 01010101_2 \rightarrow 01000001_2$
  - `0x69 | 0x55 → 0x7D`
    - $01101001_2 \mid 01010101_2 \rightarrow 01111101_2$

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 oopsies 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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- **Integers**
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- Summary

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 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

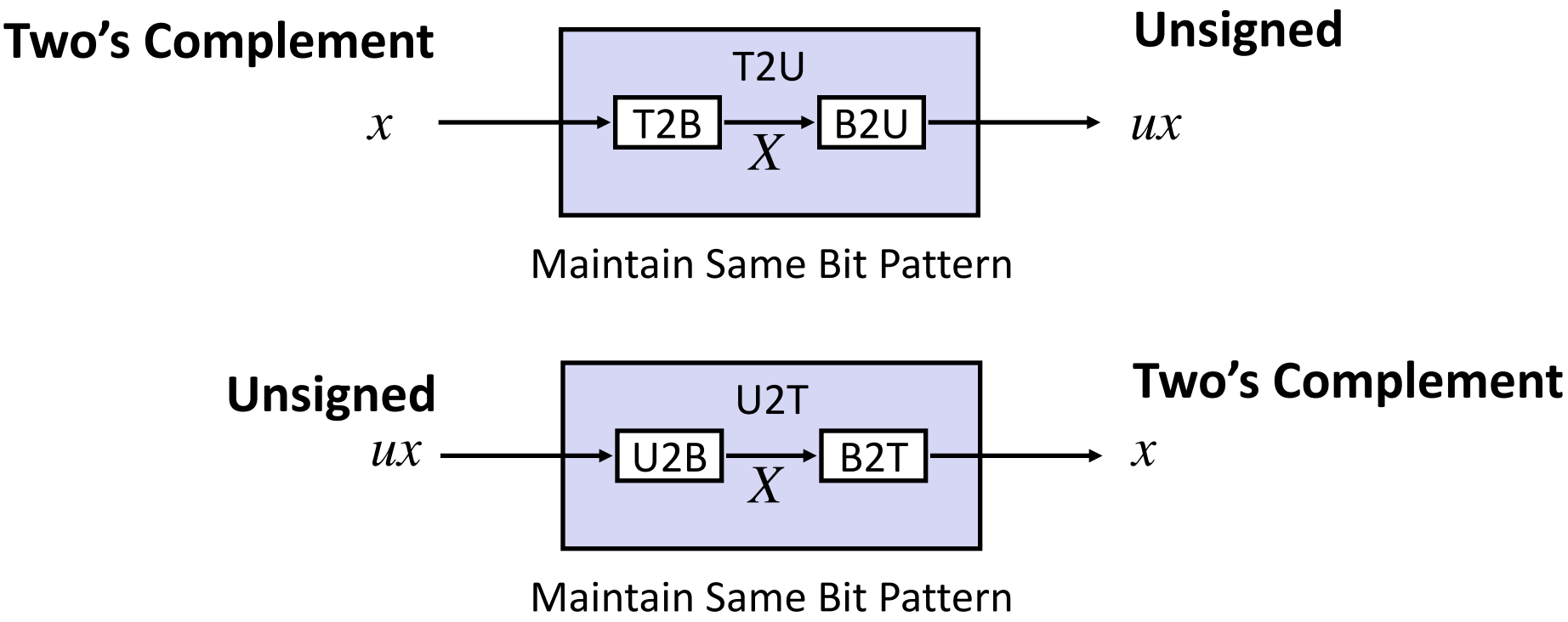
X	B2U(*X*)	B2T(*X*)
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	–8
1001	9	–7
1010	10	–6
1011	11	–5
1100	12	–4
1101	13	–3
1110	14	–2
1111	15	–1

- **Equivalence**
  - Same encodings for nonnegative values
- **Uniqueness**
  - Every bit pattern represents unique integer value
  - Each representable integer has unique bit encoding
- **⇒ 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

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

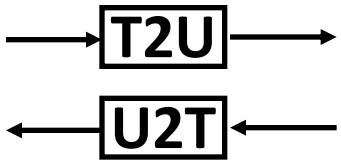
Mapping Between Signed & Unsigned



- **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



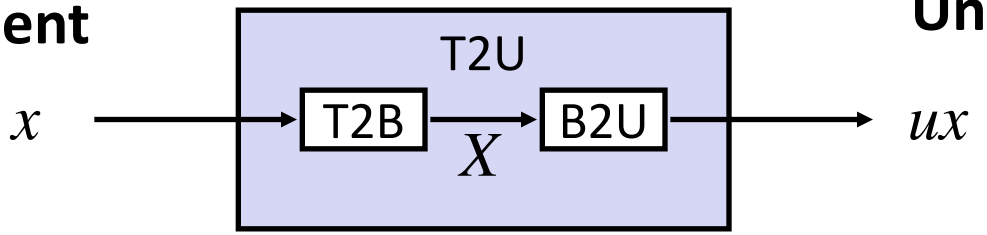
Mapping Signed ↔ Unsigned

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	+/- 16	11
1100	-4		12
1101	-3		13
1110	-2		14
1111	-1		15

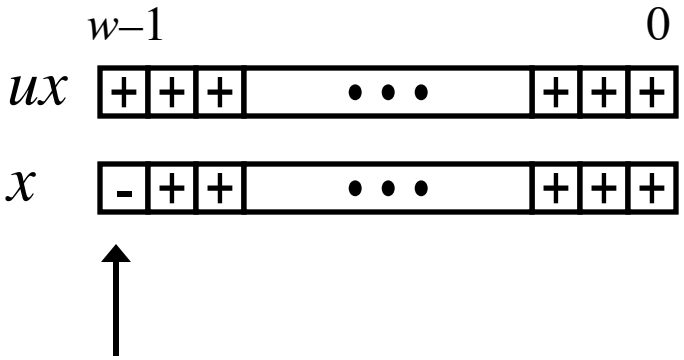
Relation between Signed & Unsigned

Two's Complement

Unsigned



Maintain Same Bit Pattern



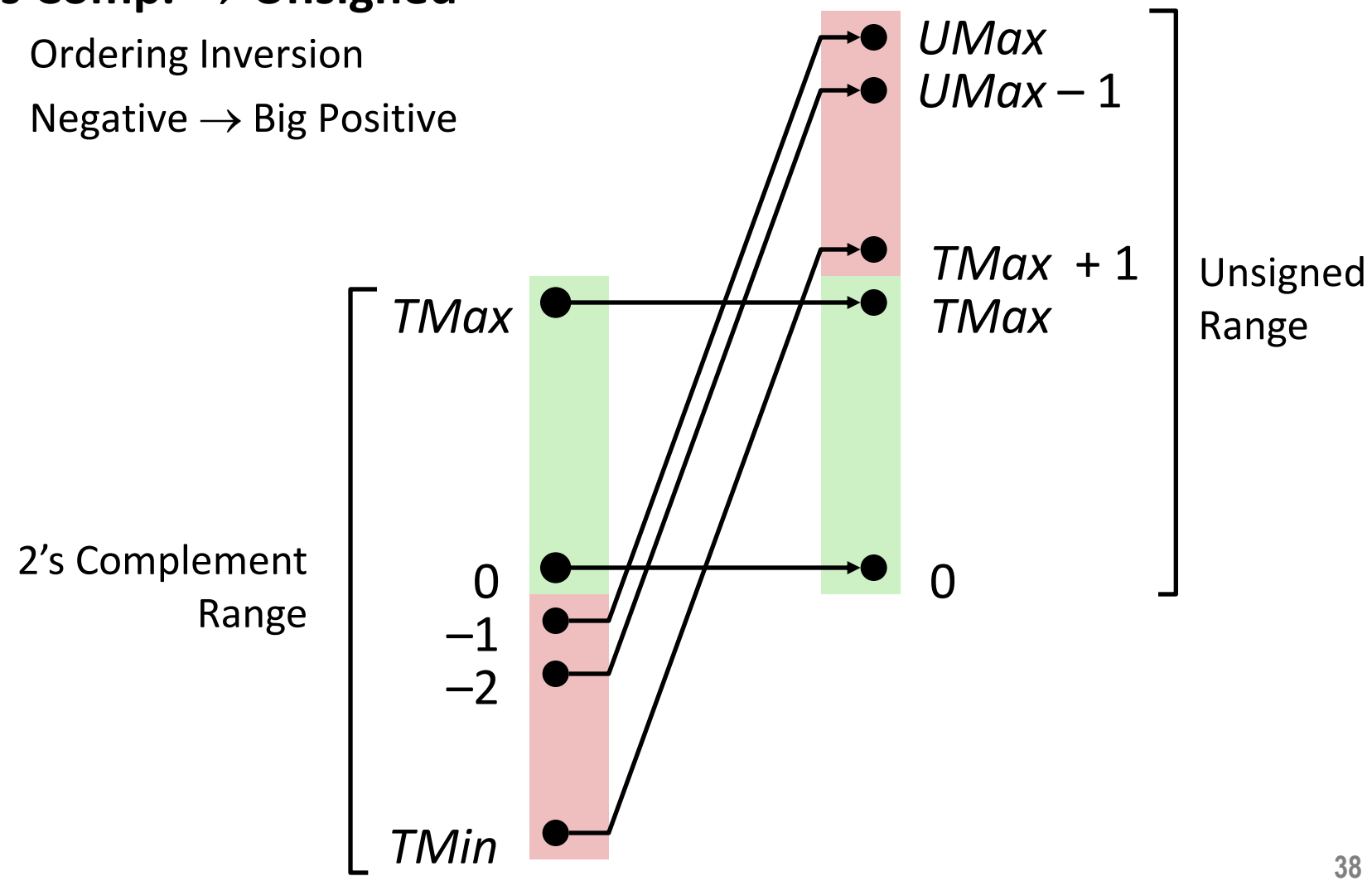
Large negative weight

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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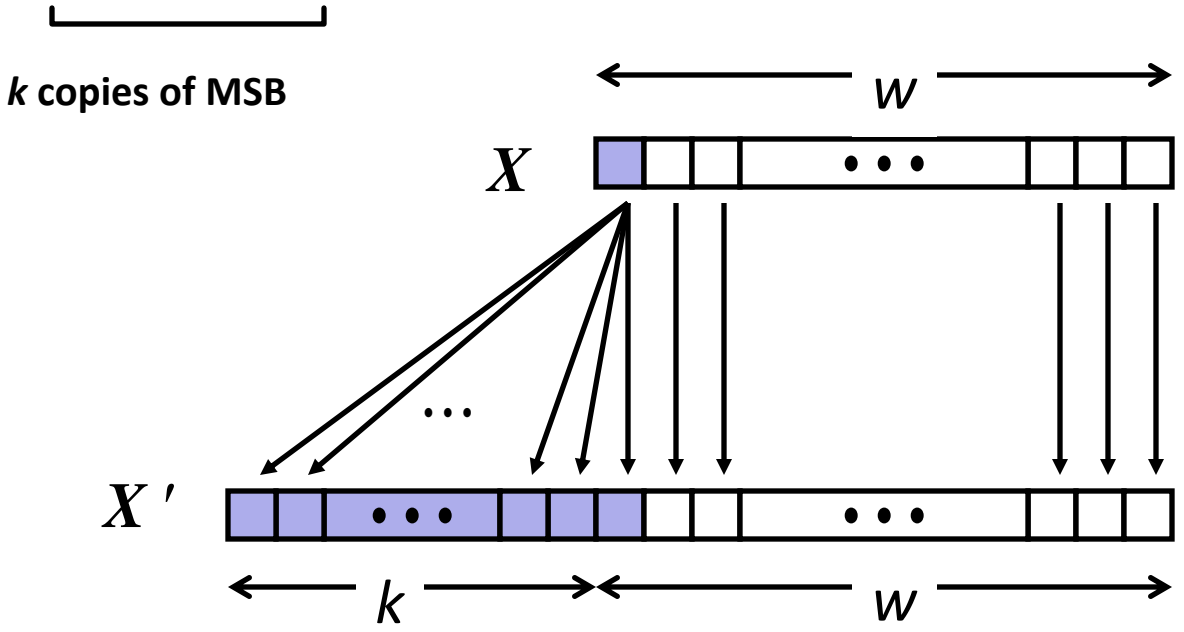
  - **Expanding, truncating**
  - Addition, negation, multiplication, shifting
  - Summary
- Representations in memory, pointers, strings

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:
  - $X' = x_{w-1}, \ldots, x_{w-1}, x_{w-1}, x_{w-2}, \ldots, x_0$



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

Today: Bits, Bytes, and Integers

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- Bit-level manipulations
- **Integers**
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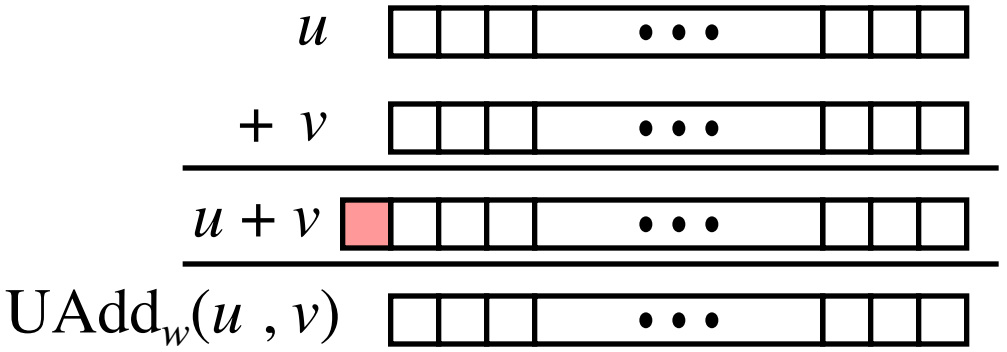
- Summary

Unsigned Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



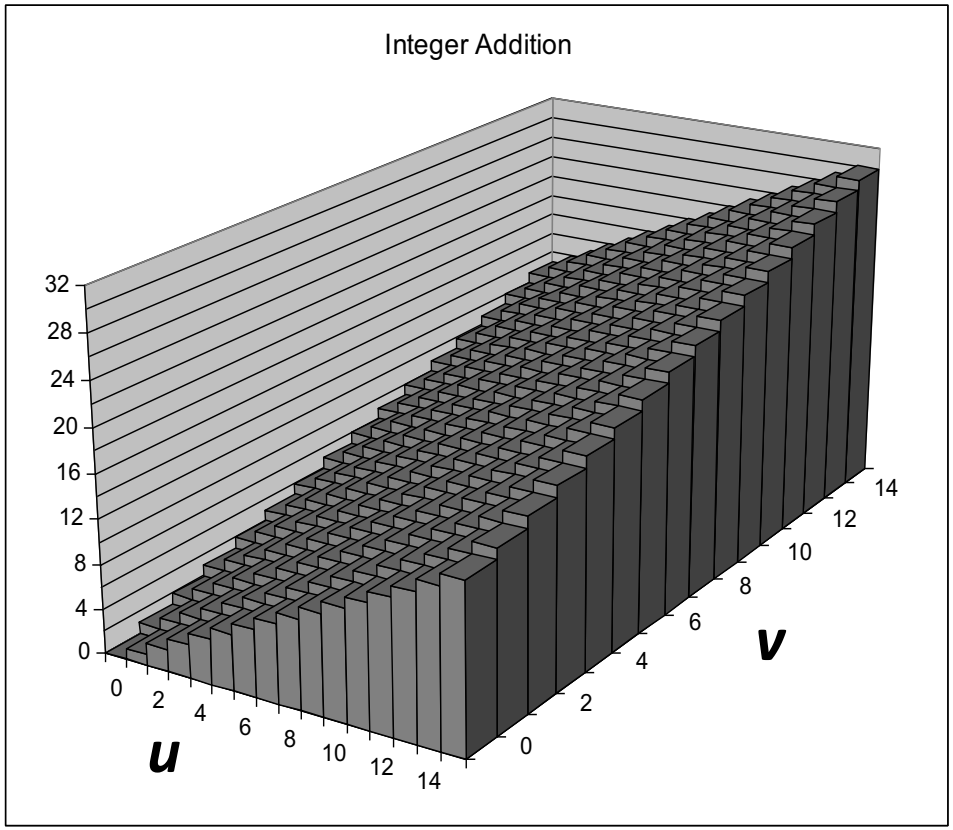
- **Standard Addition Function**
  - Ignores carry output
- **Implements Modular Arithmetic**

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

Visualizing (Mathematical) Integer Addition

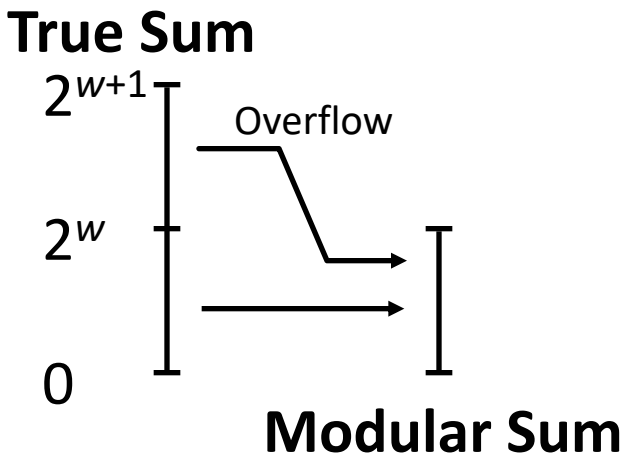
- **Integer Addition**
  - 4-bit integers *u*, *v*
  - Compute true sum $\text{Add}_4(u , v)$
  - Values increase linearly with *u* and *v*
  - Forms planar surface

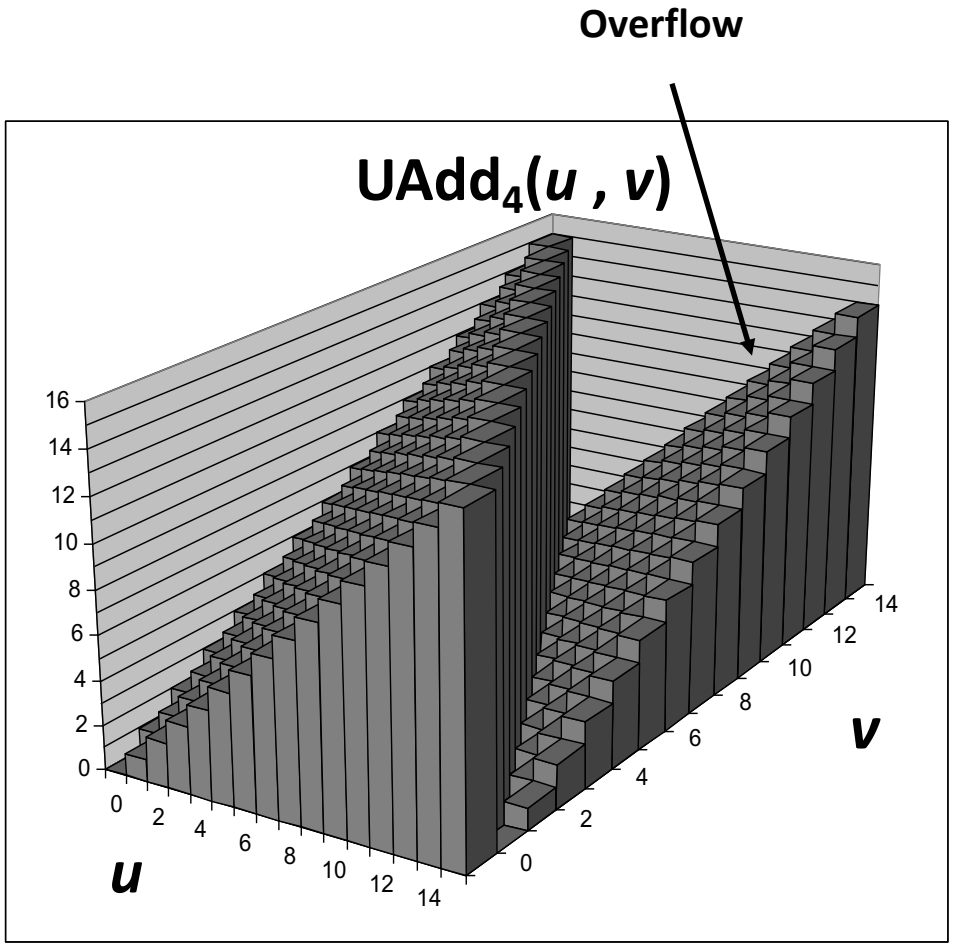
$\text{Add}_4(u , v)$



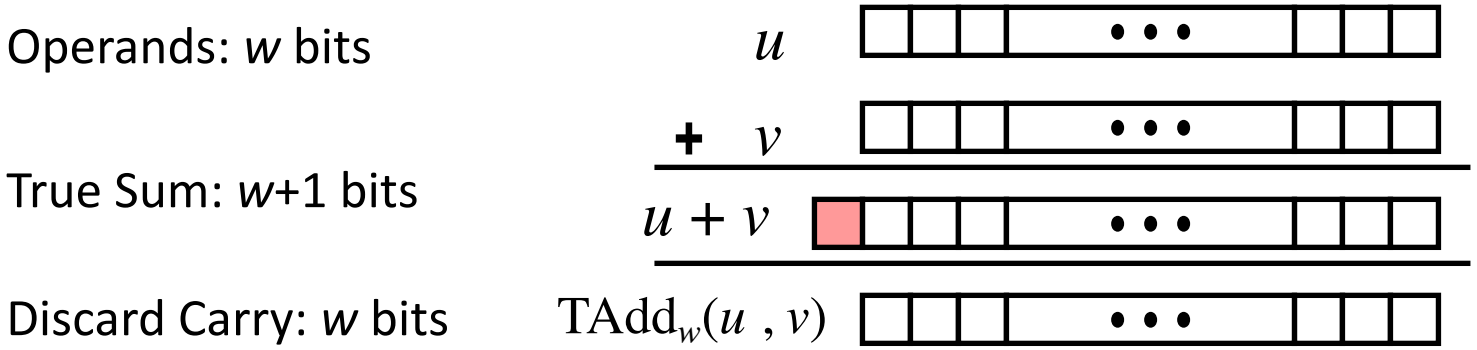
Visualizing Unsigned Addition

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





Two's Complement Addition



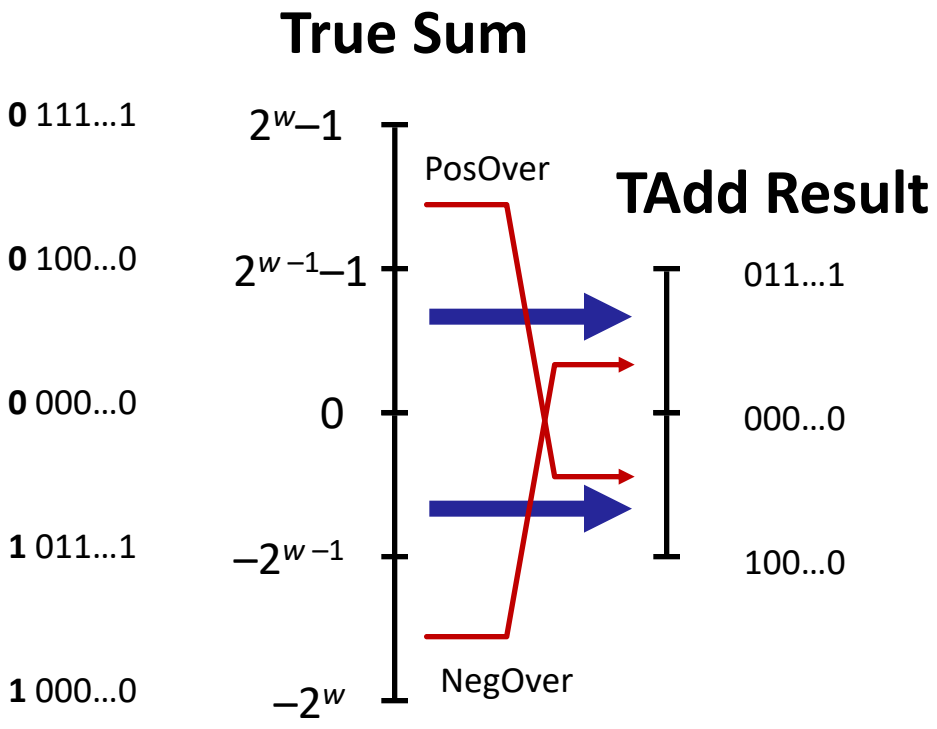
- **TAdd and UAdd have Identical Bit-Level Behavior**
  - Signed vs. unsigned addition in C:

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

  - Will give `s == t`

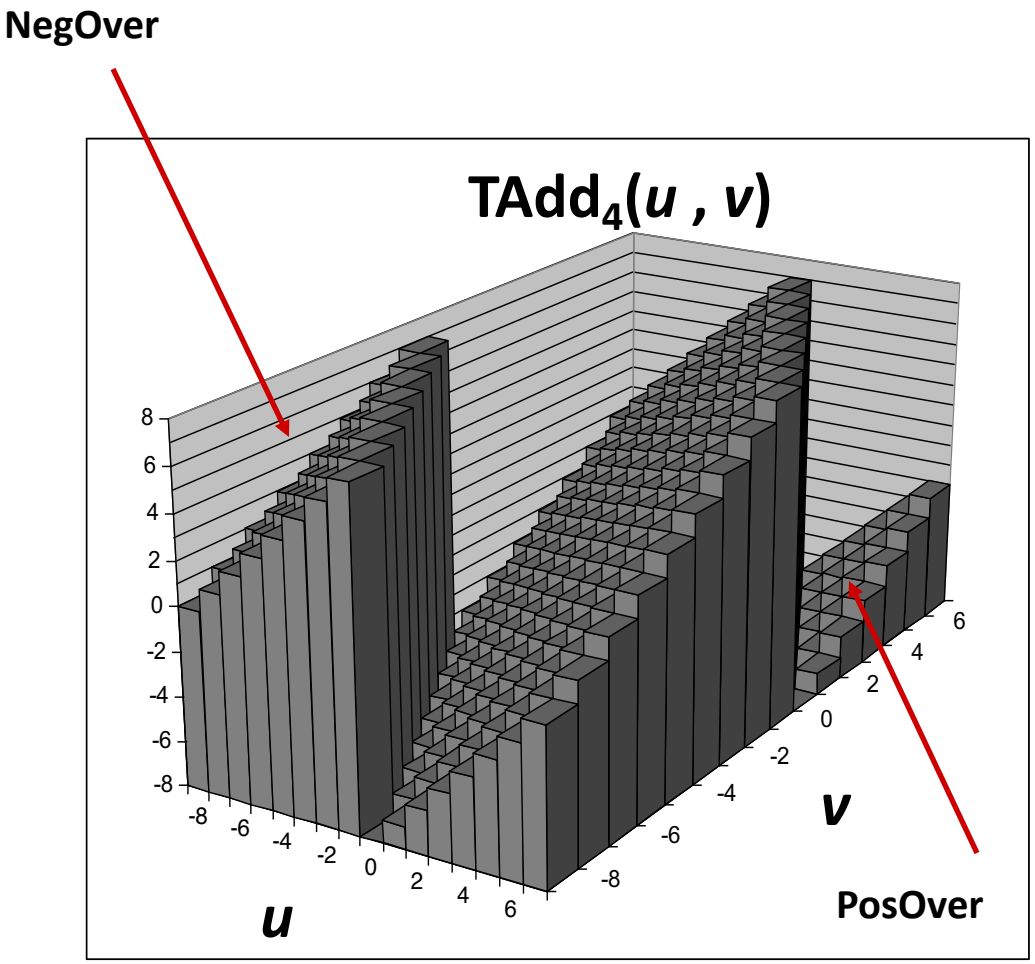
TAdd Overflow

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



Visualizing 2's Complement Addition

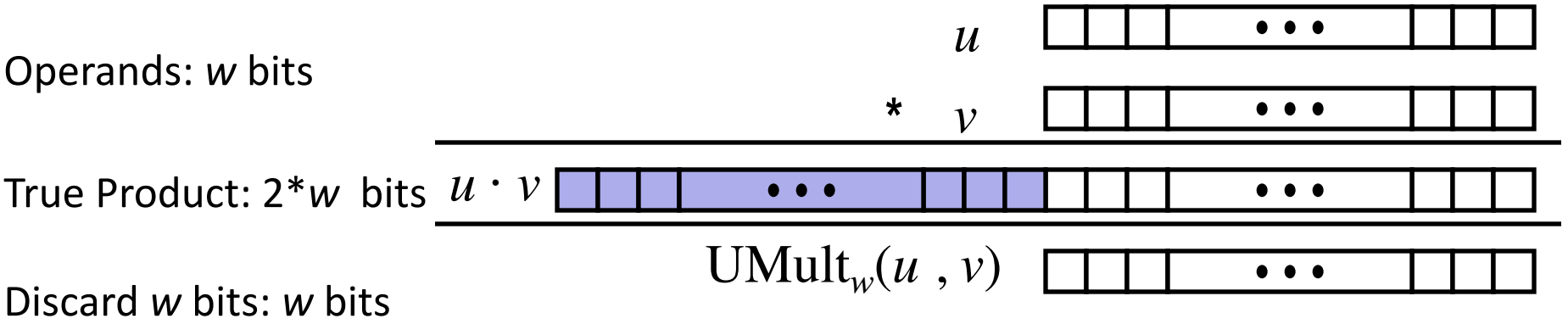
- **Values**
  - 4-bit two's comp.
  - Range from -8 to +7
- **Wraps Around**
  - If sum $\geq 2^{w-1}$
    - Becomes negative
    - At most once
  - If sum $< -2^{w-1}$
    - Becomes positive
    - At most once



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

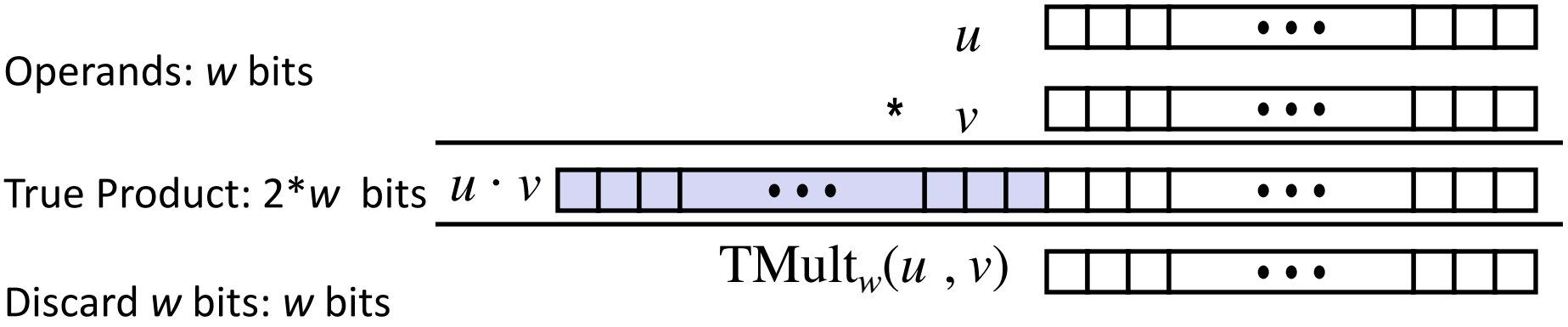
Unsigned Multiplication in C



- **Standard Multiplication Function**
  - Ignores high order *w* bits
- **Implements Modular Arithmetic**

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

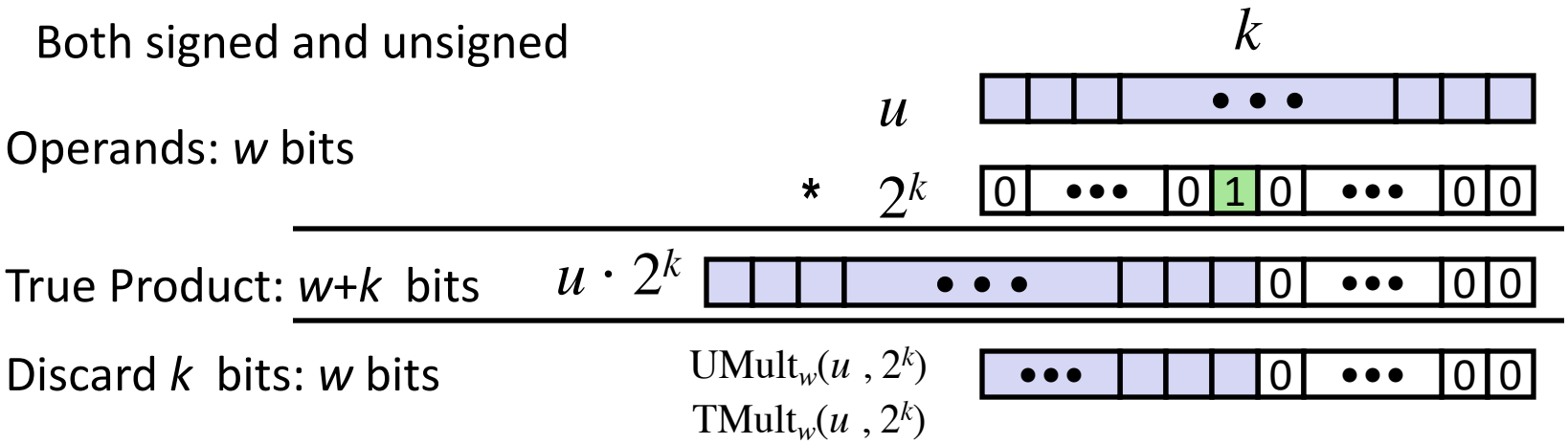
Signed Multiplication in C



- **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

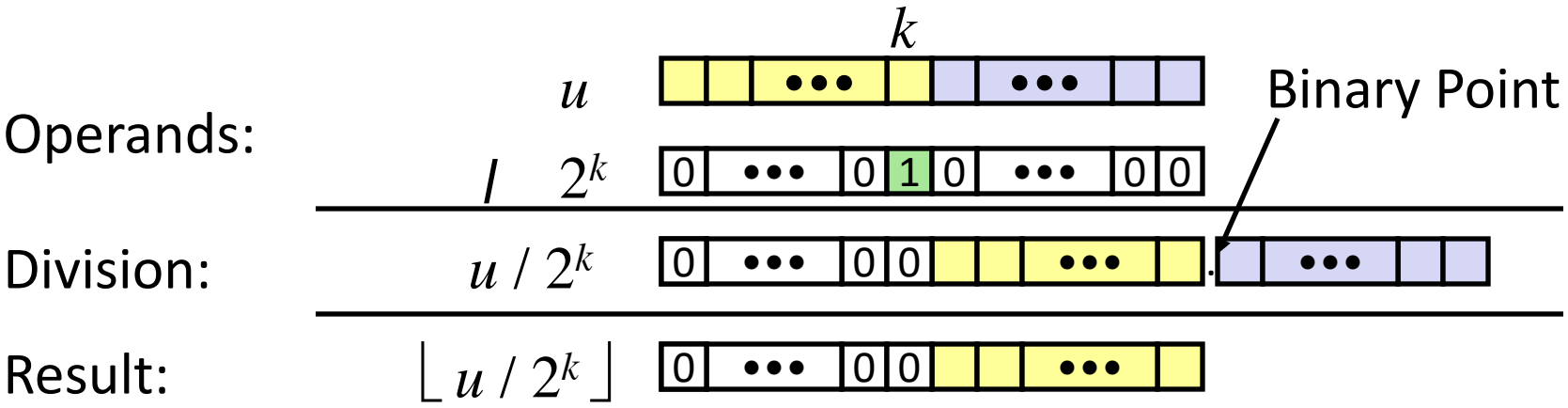
- **Operation**
  - `u << k` gives `u * 2^k`
  - Both signed and unsigned



- **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 $\lfloor$ `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`

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  - **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

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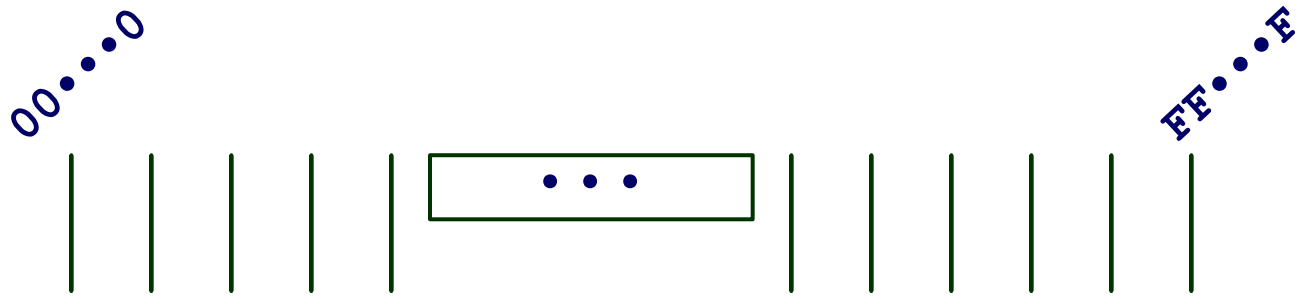
Byte-Oriented Memory Organization



- **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

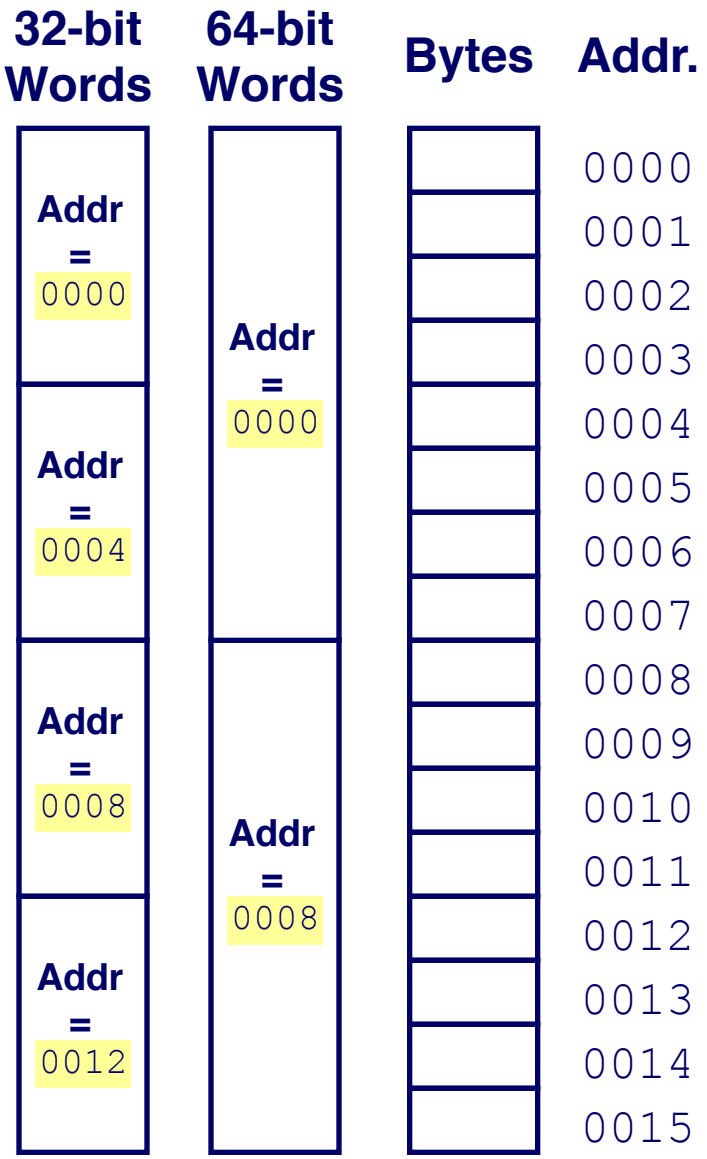
- **Note: system provides private address spaces to each "process"**
  - Think of a process as a program being executed
  - So, a program can clobber its own data, but not that of others

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 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

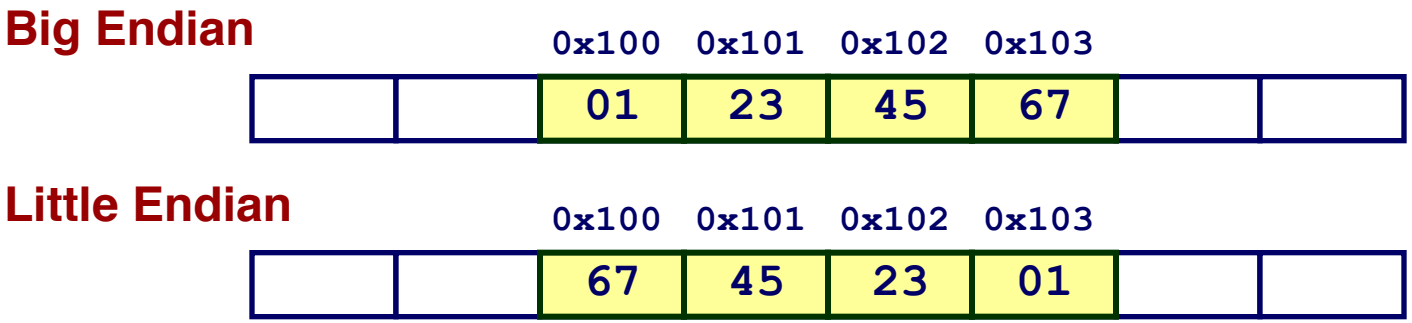
C Data Type	Typical 32-bit	Typical 64-bit	x86-64
`char`	1	1	1
`short`	2	2	2
`int`	4	4	4
`long`	4	8	8
`float`	4	4	4
`double`	8	8	8
`long double`	–	–	10/16
pointer	4	8	8

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

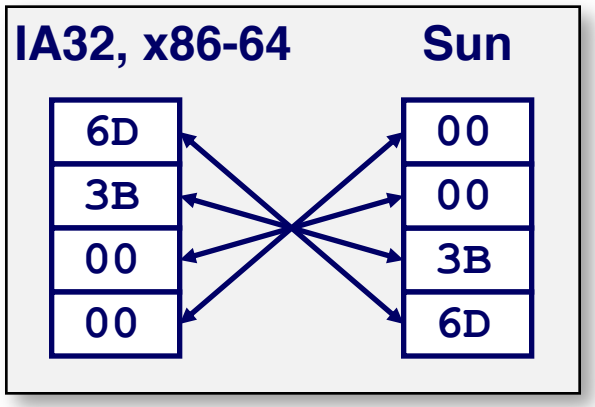
- **Example**
  - Variable x has 4-byte value of 0x01234567
  - Address given by &x is 0x100



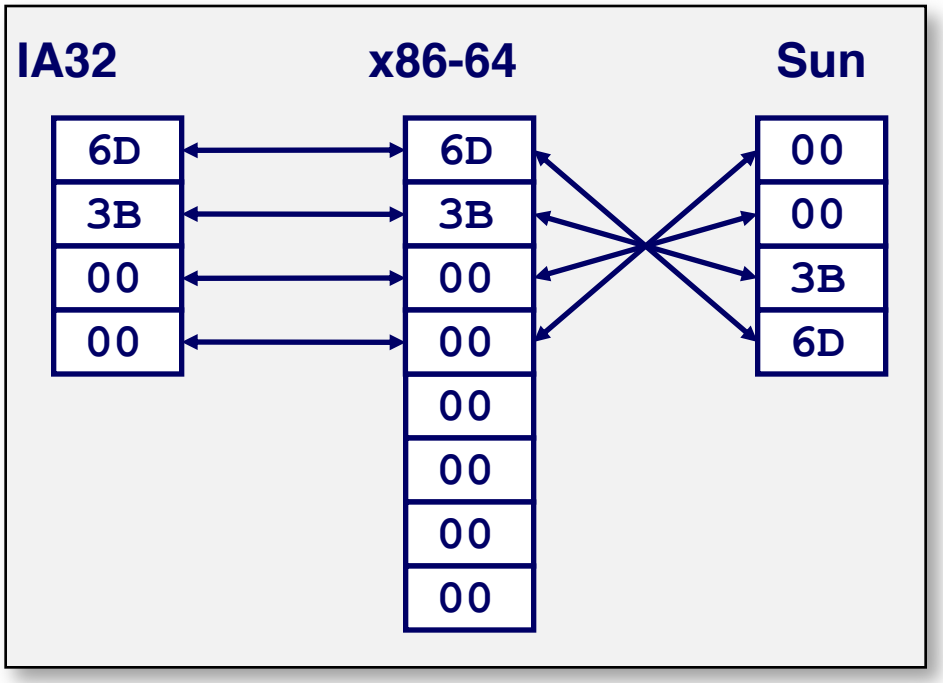
Representing Integers

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

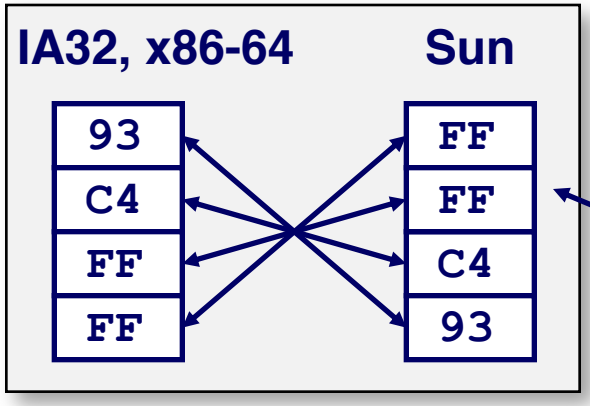
```
int A = 15213;
```




```
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

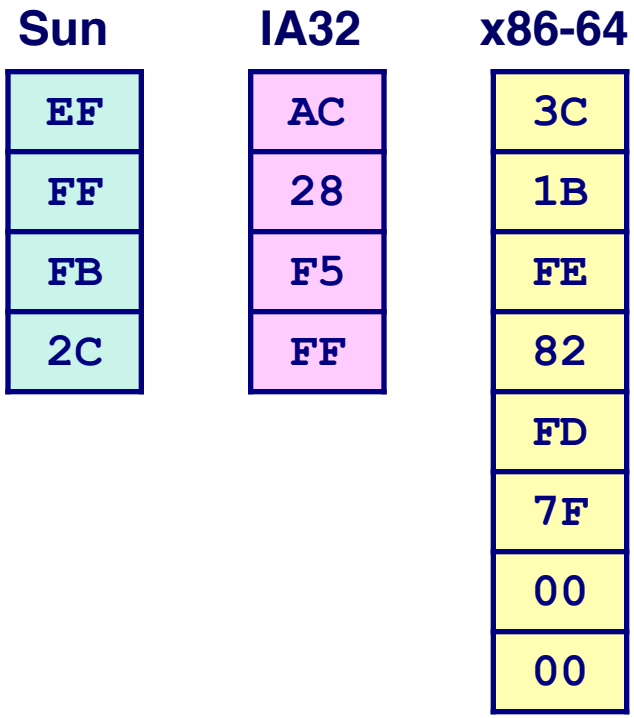
```
int a = 15213;
printf("int a = 15213;\n");
show_bytes((pointer) &a, sizeof(int));
```

Result (Linux x86-64):

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

Representing Pointers

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



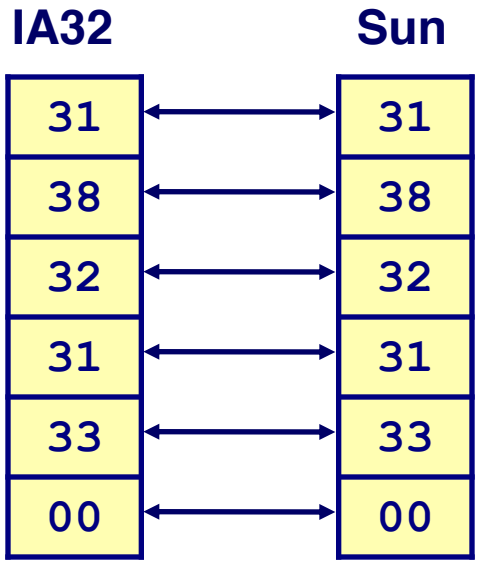
Different compilers & machines assign different locations to objects

Even get different results each time run program

Representing Strings

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

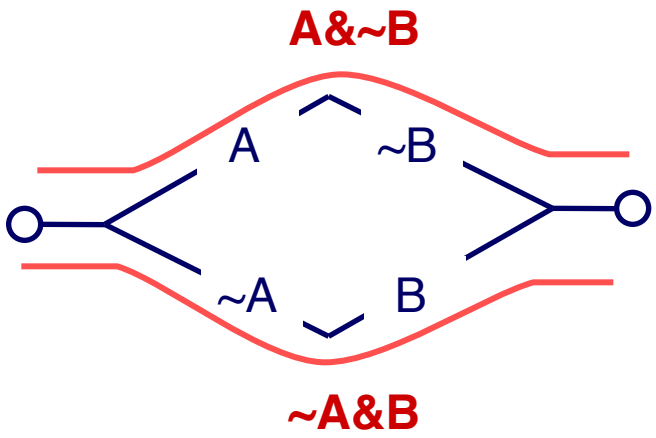
- **Strings in C**
  - Represented by array of characters
  - Each character encoded in ASCII format
    - Standard 7-bit encoding of character set
    - Character “0” has code 0x30
      - Digit *i* has code 0x30+*i*
  - String should be null-terminated
    - Final character = 0
- **Compatibility**
  - Byte ordering not an issue



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&~B | ~A&B

= A^B

Binary Number Property

Claim

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

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

- **w = 0:**
  - $1 = 2^0$
- **Assume true for w-1:**
  - $\underbrace{1 + 1 + 2 + 4 + 8 + \ldots + 2^{w-1}} + 2^w = 2^w + 2^w = 2^{w+1}$

$$= 2^w$$

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

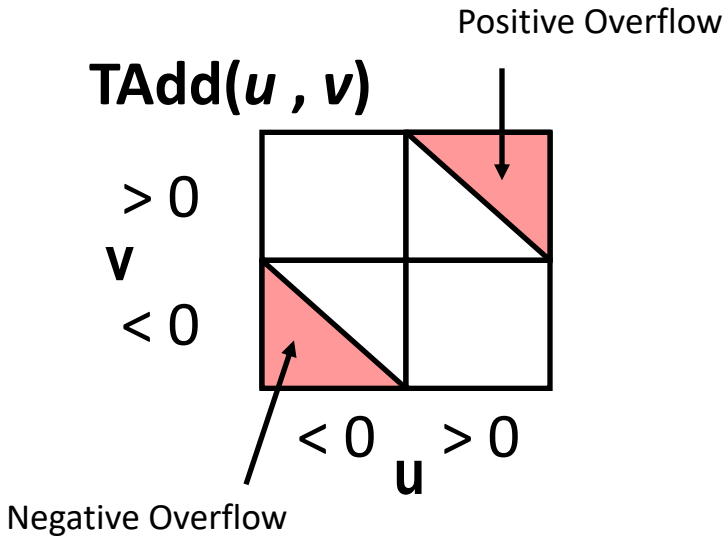
- **Isomorphic Group to unsigneds with UAdd**
  - $\text{TAdd}_w(u, v) = \text{U2T}(\text{UAdd}_w(\text{T2U}(u), \text{T2U}(v)))$
    - Since both have identical bit patterns

- **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



$$TAdd_w(u,v) = \begin{cases} u+v+2^{w-1} & u+v < TMin_w \quad \textbf{(NegOver)} \\ u+v & TMin_w \le u+v \le TMax_w \\ u+v-2^{w-1} & TMax_w < u+v \quad \textbf{(PosOver)} \end{cases}$$

Negation: Complement & Increment

- **Claim: Following Holds for 2's Complement**

  `~x + 1 == -x`

- **Complement**
  - Observation: `~x + x == 1111…111 == -1`

	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

- **Complete Proof?**

Complement & Increment Examples

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

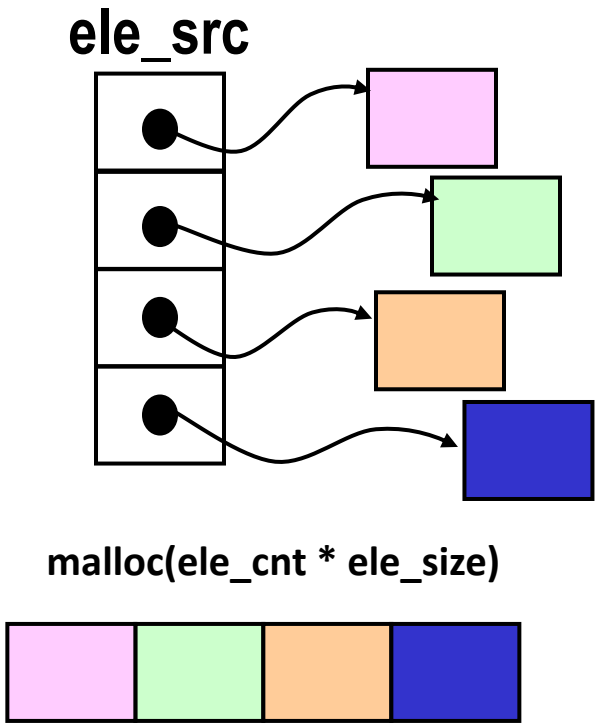
x = 0

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

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
```

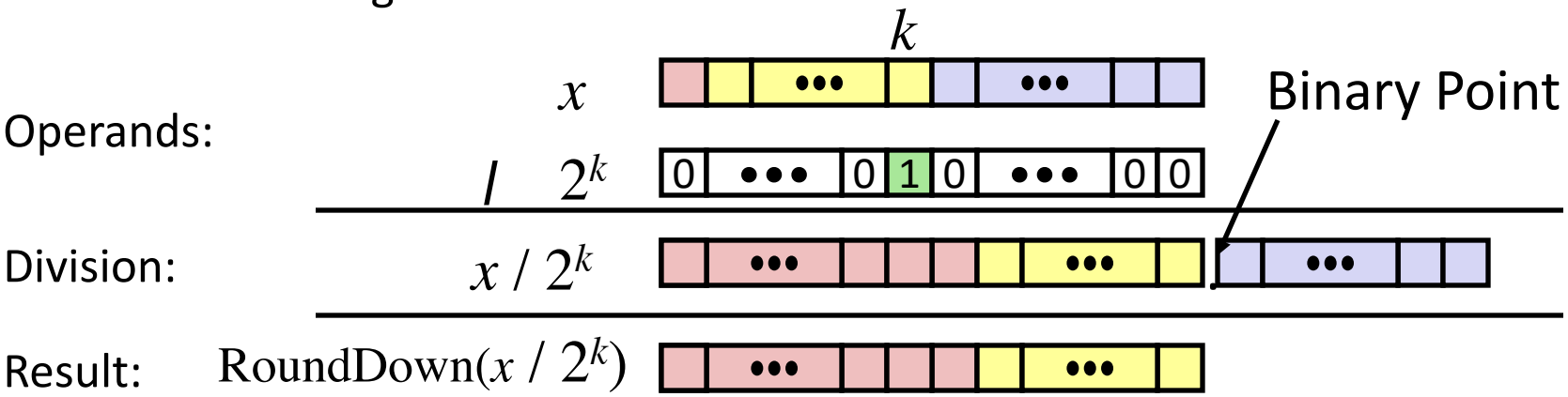
Explanation

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

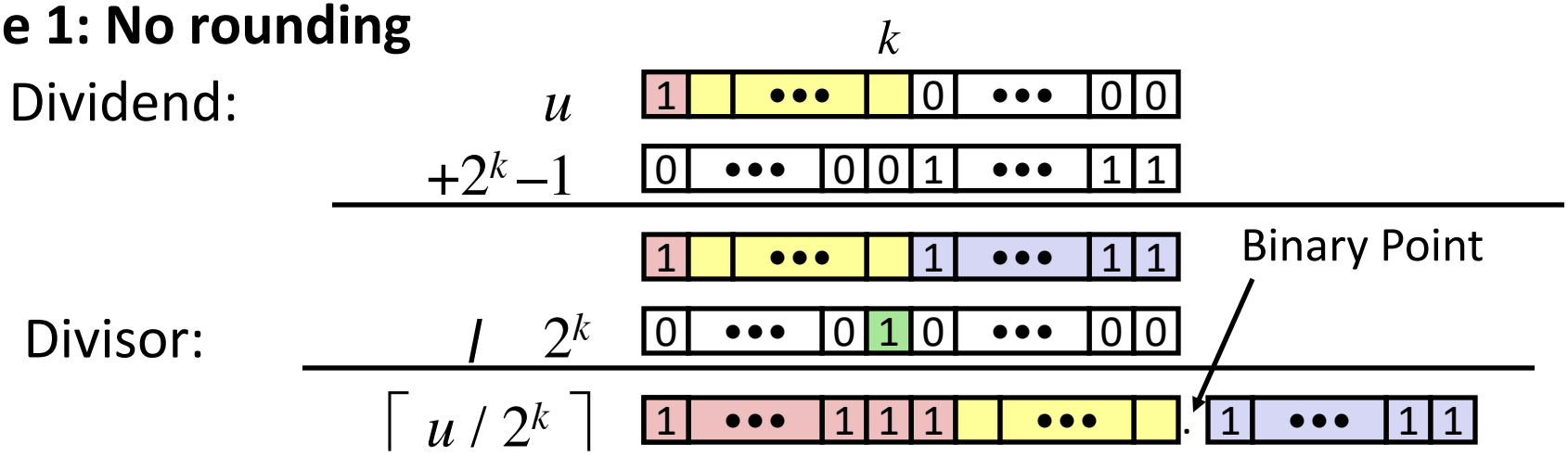


	Division	Computed	Hex	Binary
`y`	-15213	-15213	`C4 93`	`11000100 10010011`
`y >> 1`	-7606.5	-7607	`E2 49`	`11100010 01001001`
`y >> 4`	-950.8125	-951	`FC 49`	`11111100 01001001`
`y >> 8`	-59.4257813	-60	`FF C4`	`11111111 11000100`

Correct Power-of-2 Divide

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

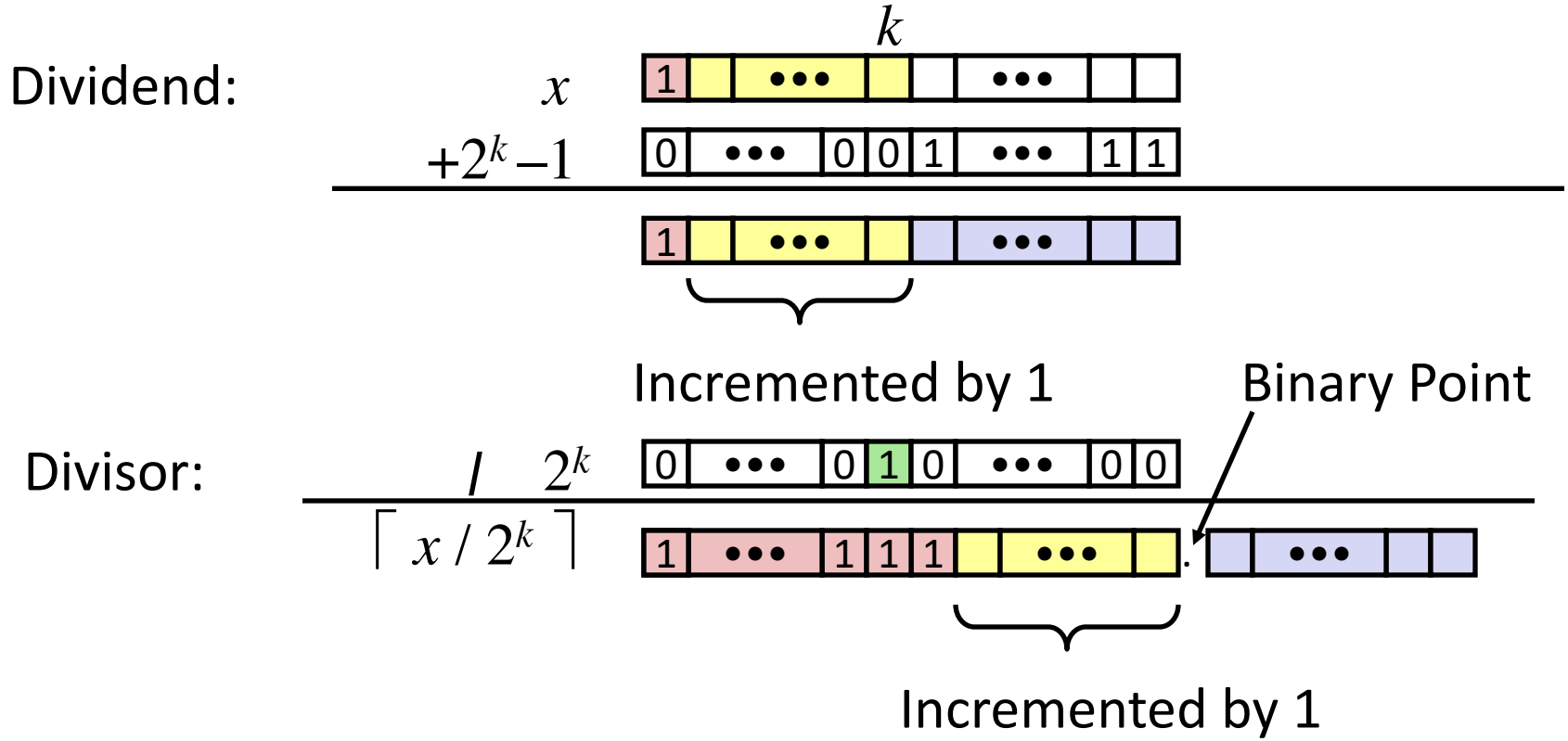
Case 1: No rounding



Biasing has no effect

Correct Power-of-2 Divide (Cont.)

Case 2: Rounding



Biasing adds 1 to final result

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 addtion

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

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 (16-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: 0x12ab
  - Pad to 32 bits: 0x000012ab
  - Split into bytes: 00 00 12 ab
  - Reverse: ab 12 00 00

Per-lecture feedback

- Better sooner rather than later!
- I can help with issues sooner.
- There is a per-lecture feedback form.
- **The form is anonymous.**
  (It checks that you're at Illinois Tech to filter abuse, but I don't see who submitted any of the forms.)
- https://forms.gle/qoeEbBuTYXo5FiU1A
- I'll remind about this at each lecture.