Introduction to Computer Systems

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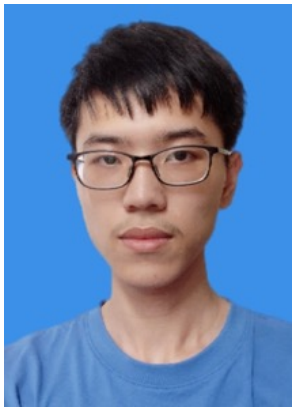

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Rules

- **Attendance**
- **Quite vs Talktive**
- **Portrait Photo**
  - 240 (width) x 320 (height)
  - 学号_姓名.jpg

Why this course?

- You are going to learn:
- How to avoid strange numerical errors
- How to optimize your C code
- How the compiler implements procedure calls
- How to recognize and avoid nasty errors
- How to write your own dynamic storage allocation package
- How to...

Why this course?

From: torvalds@klaava.Helsinki.FI (Linus Benedict Torvalds)

Newsgroups: comp.os.minix

Subject: What would you like to see most in minix?

Summary: small poll for my new operating system

Date: 25 Aug 91 20:57:08 GMT

Hello everybody out there using minix –

I'm doing a (free) operating system (just a hobby, won't be big and professional like gnu) for 386(486) AT clones. This has been brewing since April, and is starting to get ready. I'd like any feedback on things people like/dislike in minix, as my OS resembles it somewhat (same physical layout of the file-system (due to practical reasons) among other things).

I've currently ported bash(1.08) and gcc(1.40), and things seem to work. This implies that I'll get something practical within a few months, and I'd like to know what features most people would want. Any suggestions are welcome, but I won't promise I'll implement them :-)

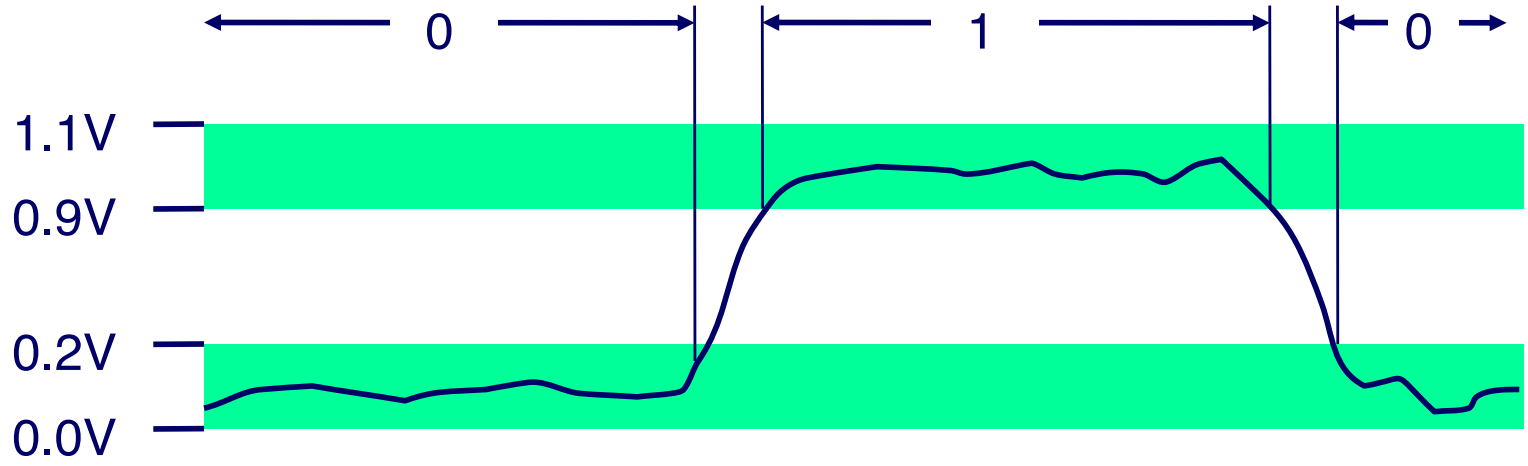
Bits, Bytes, and Integers

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
- **Floating Point**
- **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 $1.0011001100110011[0011]\ldots_2$
  - Represent $1.5213 \text{ X } 10^4$ as $1.1101101101101_2 \text{ X } 2^{13}$

Encoding Byte Values

- **Byte = 8 bits**
  - Binary 00000000_2 to 11111111_2
  - Decimal: 0_{10} to 255_{10}
  - Hexadecimal 00_{16} to FF_{16}
    - Base 16 number representation
    - Use characters ‘0’ to ‘9’ and ‘A’ to ‘F’
    - Write $FA1D37B_{16}$ in C as
      - 0xFA1D37B
      - 0xfa1d37b

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Example Data Representations

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

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Boolean Algebra

- **Developed by George Boole in 19th Century**
  - Algebraic representation of logic
    - Encode “True” as 1 and “False” as 0

And

- A&B = 1 when both A=1 and B=1

&	0	1
0	0	0
1	0	1

Or

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

|	0	1
0	0	1
1	1	1

Not

- ~A = 1 when A=0

~	
0	1
1	0

Exclusive-Or (Xor)

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

^	0	1
0	0	1
1	1	0

General Boolean Algebras

- **Operate on Bit Vectors**
  - Operations applied bitwise

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

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

Example: Representing & Manipulating Sets

- **Representation**
  - Width w bit vector represents subsets of {0, …, w–1}
  - $a_j = 1$ if $j \in A$
    - 01101001 { 0, 3, 5, 6 }
    - *76543210*
    - 01010101 { 0, 2, 4, 6 }
    - *76543210*
- **Operations**

&	Intersection	01000001	{ 0, 6 }
|	Union	01111101	{ 0, 2, 3, 4, 5, 6 }
^	Symmetric difference	00111100	{ 2, 3, 4, 5 }
~	Complement	10101010	{ 1, 3, 5, 7 }

Bit-Level Operations in C

- **Operations &, |, ~, ^ Available in C**
  - Apply to any "integral" data type
    - `long, int, short, char, unsigned`
  - View arguments as bit vectors
  - Arguments applied bit-wise
- **Examples (Char data type)**
  - `~0x41 → 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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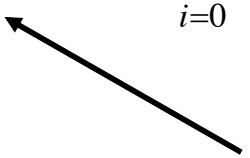
Encoding Integers

Unsigned

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

Two's Complement

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



Sign Bit

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

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

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

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

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

- **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

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

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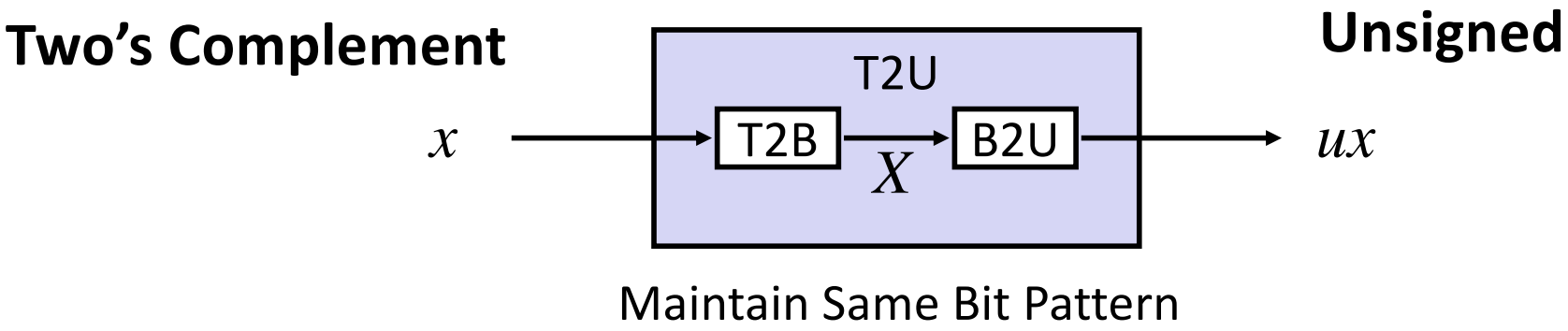
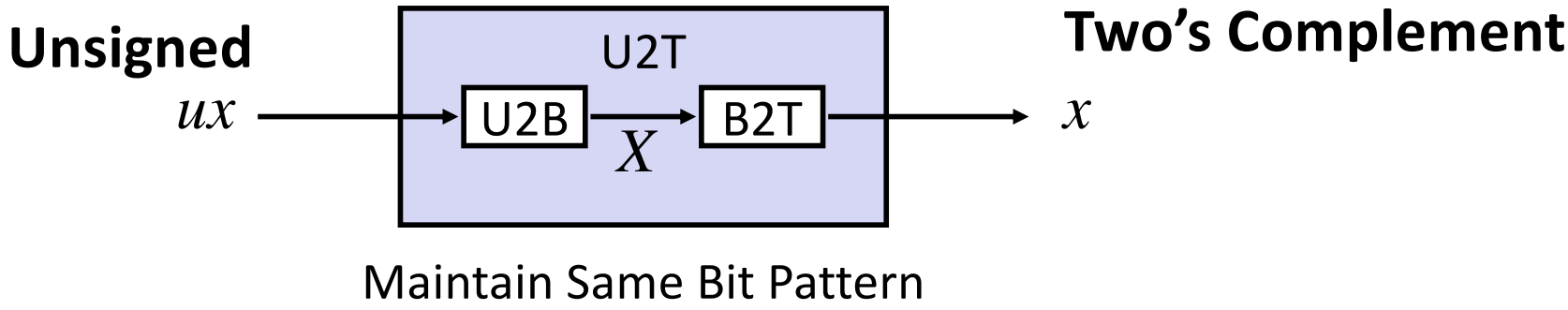
Mapping Between Signed & Unsigned





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

Mapping Signed ↔ Unsigned

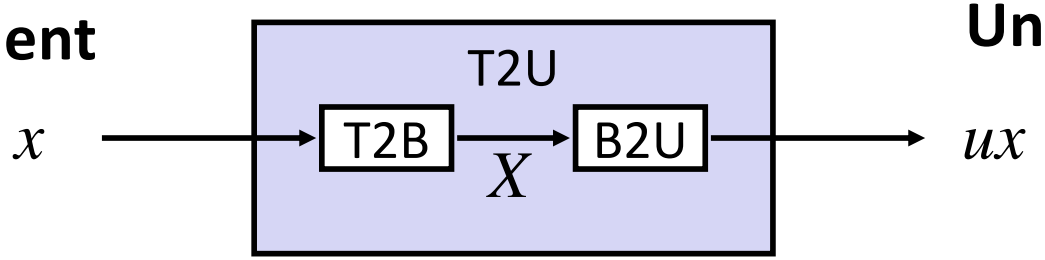
Bits	Signed		Unsigned
0000	0		0
0001	1		1
0010	2		2
0011	3		3
0100	4		4
0101	5	T2U →	5
0110	6	← U2T	6
0111	7		7
1000	-8		8
1001	-7		9
1010	-6		10
1011	-5		11
1100	-4		12
1101	-3		13
1110	-2		14
1111	-1		15

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

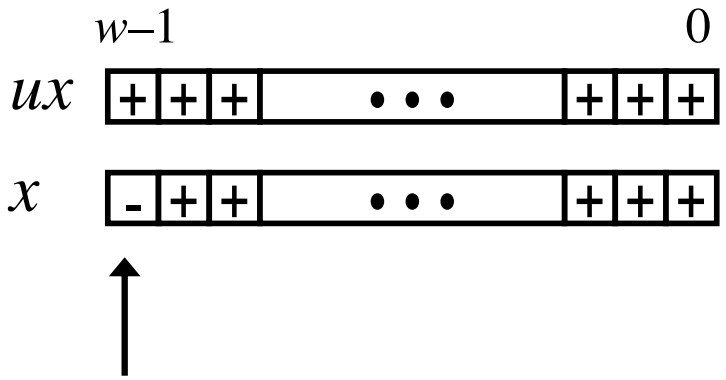
Relation between Signed & Unsigned

Two's Complement



Unsigned

Maintain Same Bit Pattern



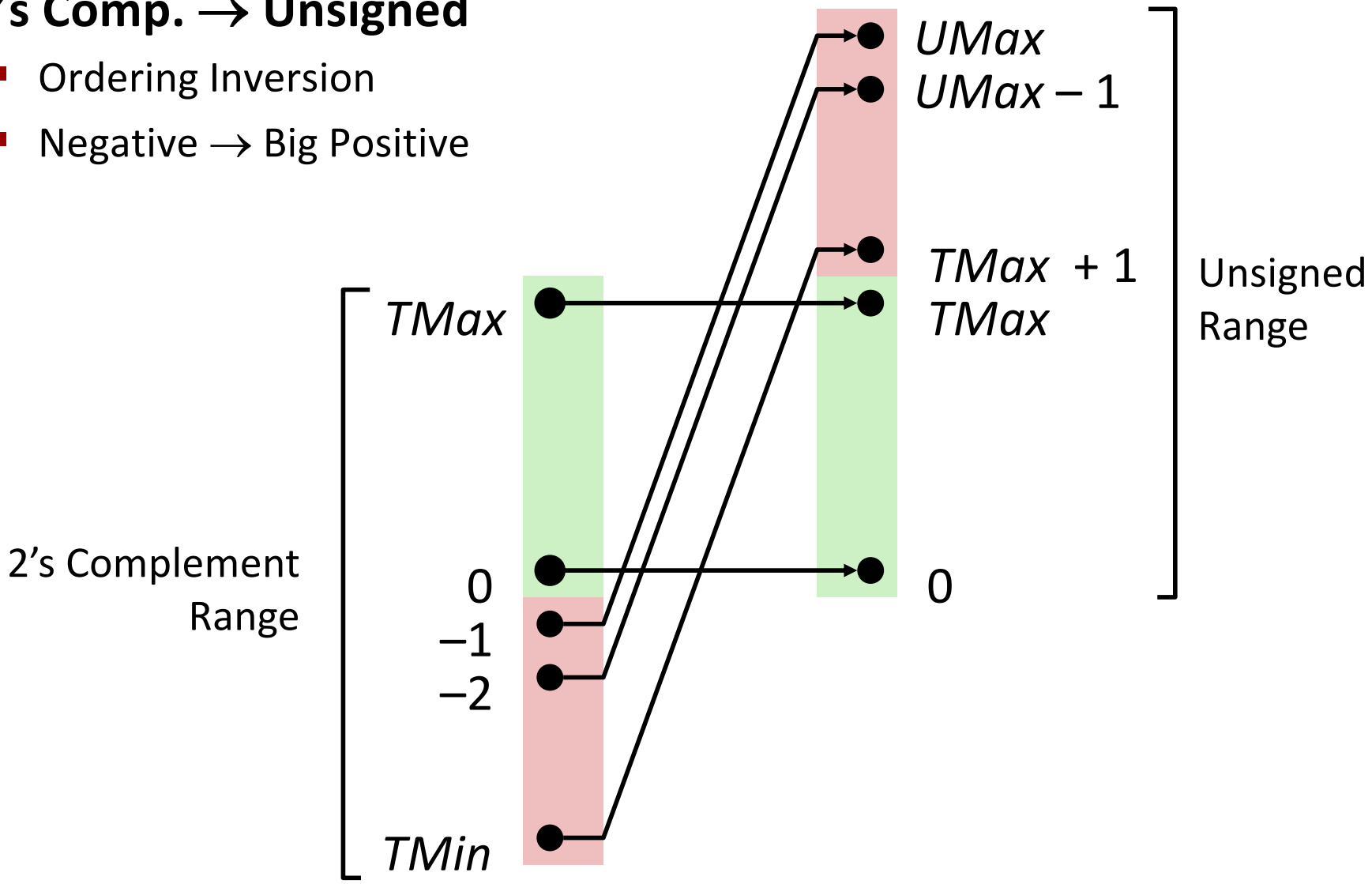
Large negative weight

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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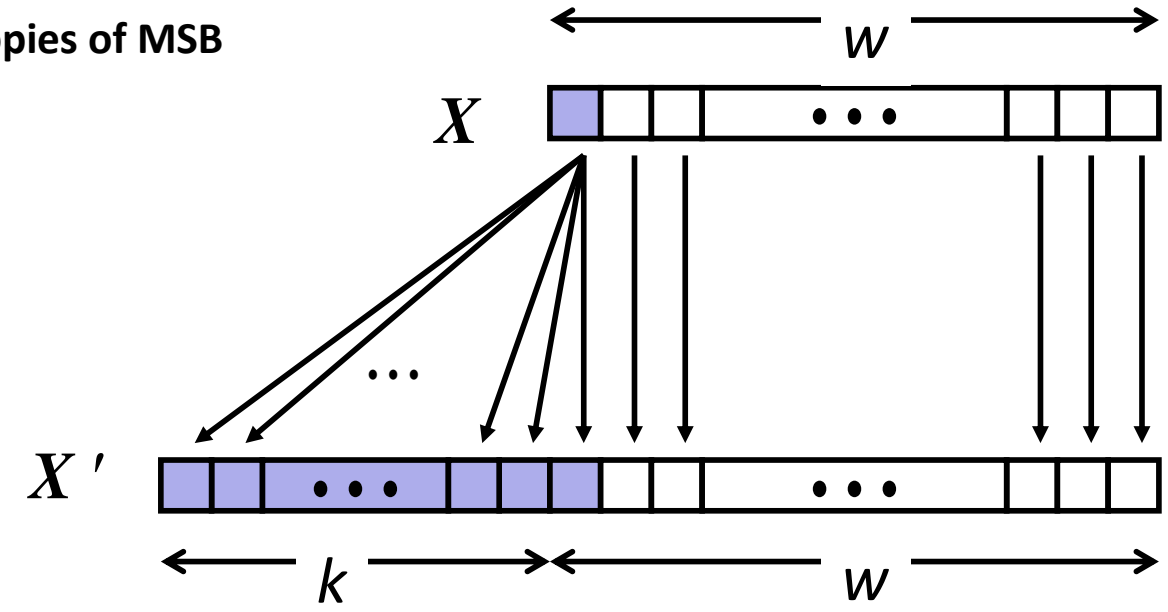
Sign Extension

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



Sign Extension Example

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

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

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

Summary:
Expanding, Truncating: Basic Rules

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

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

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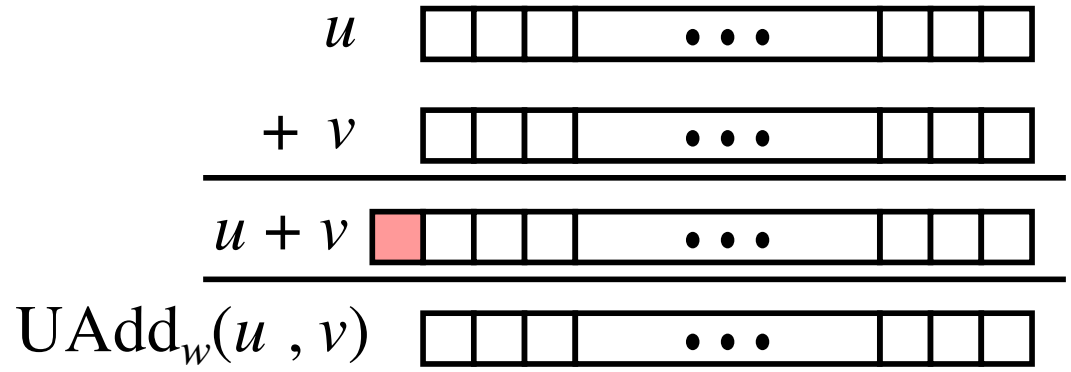
Unsigned Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



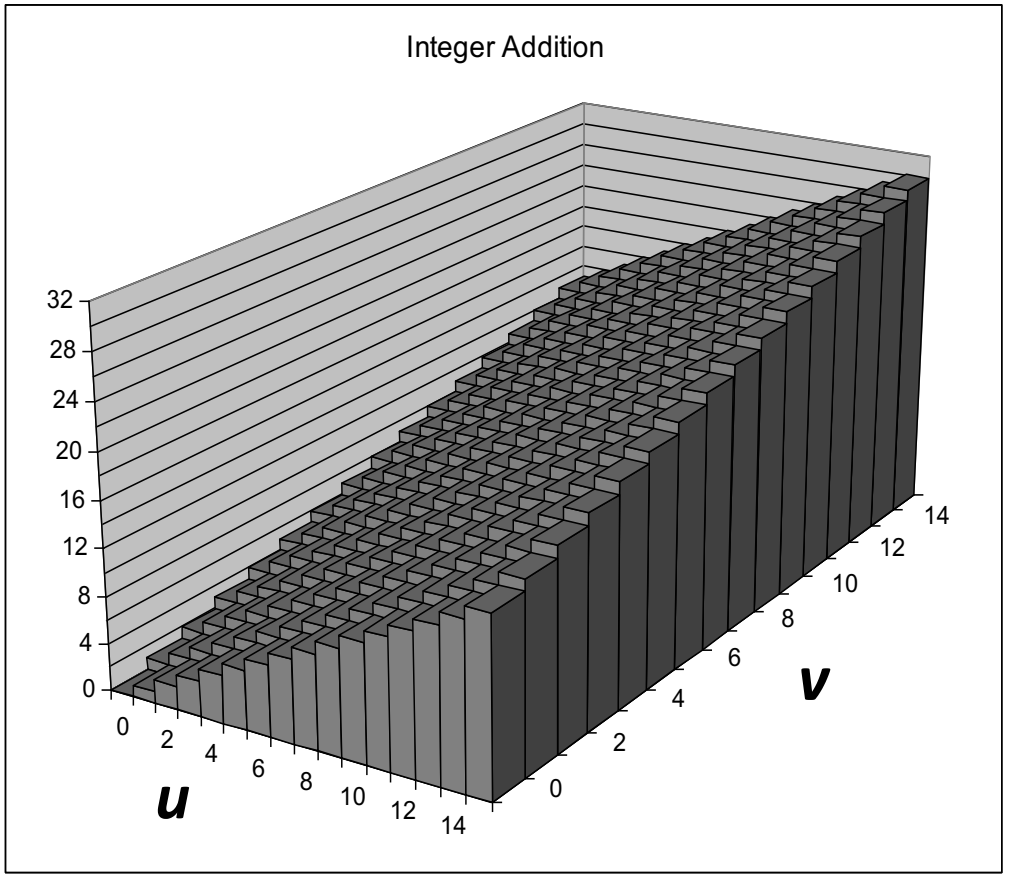
- **Standard Addition Function**
  - Ignores carry output
- **Implements Modular Arithmetic**

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

Visualizing (Mathematical) Integer Addition

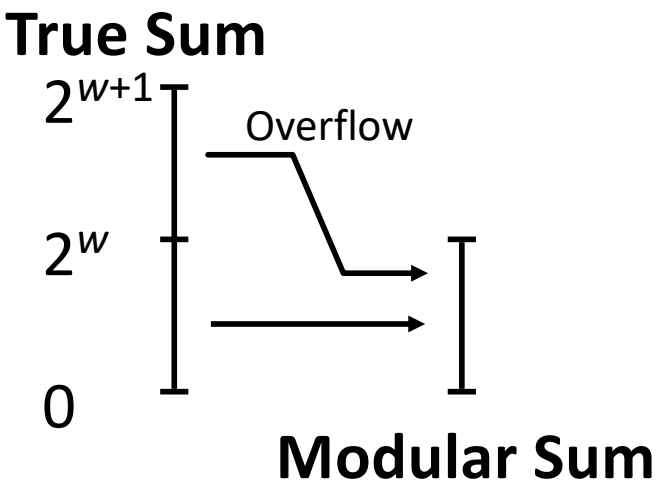
- **Integer Addition**
  - 4-bit integers *u*, *v*
  - Compute true sum $\text{Add}_4(u , v)$
  - Values increase linearly with *u* and *v*
  - Forms planar surface

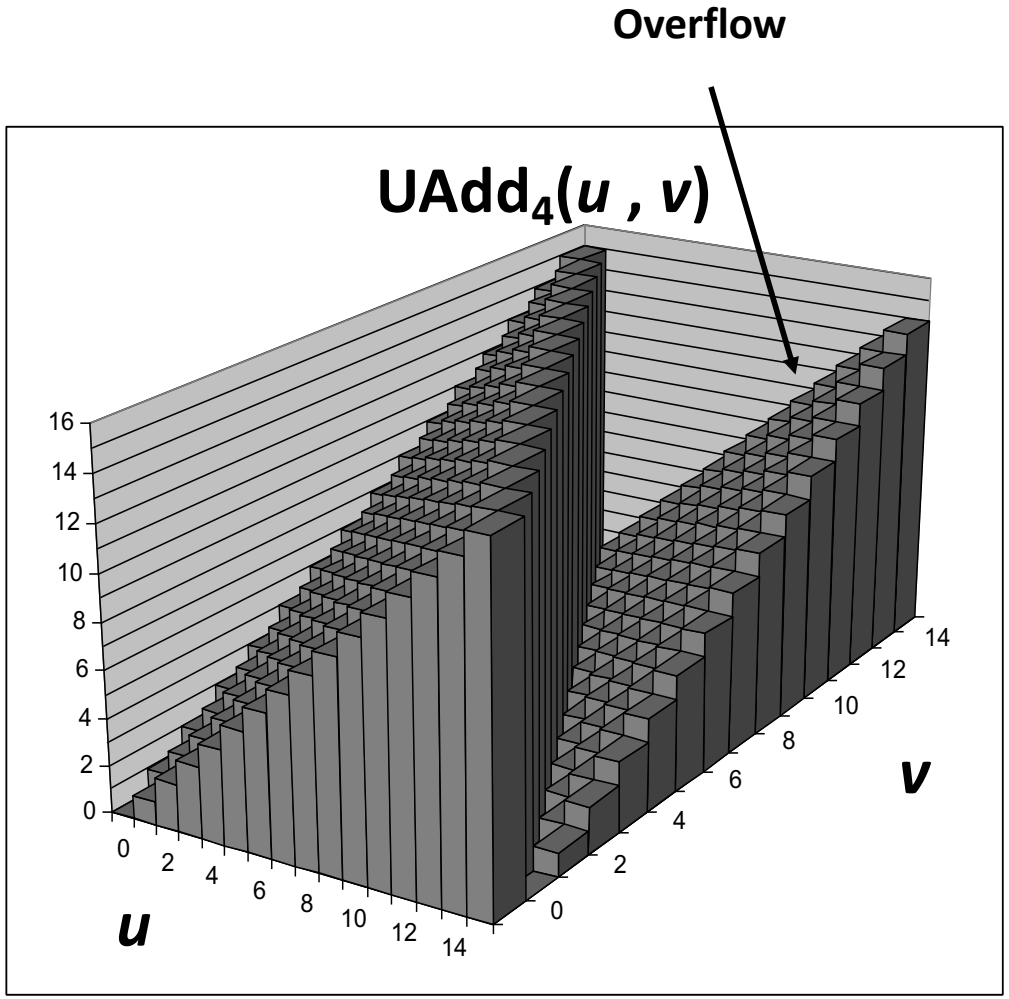
$\text{Add}_4(u , v)$



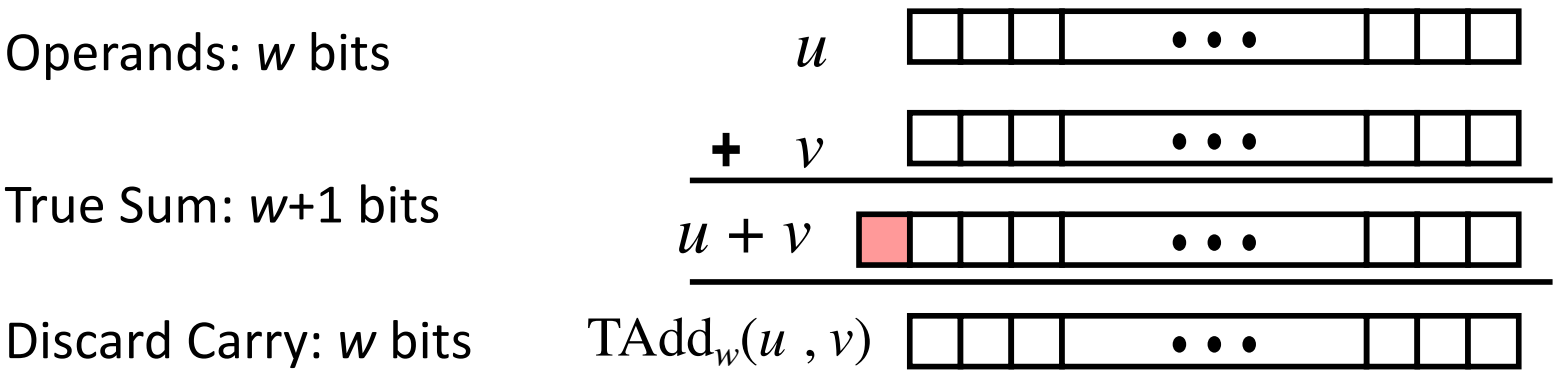
Visualizing Unsigned Addition

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





Two's Complement Addition



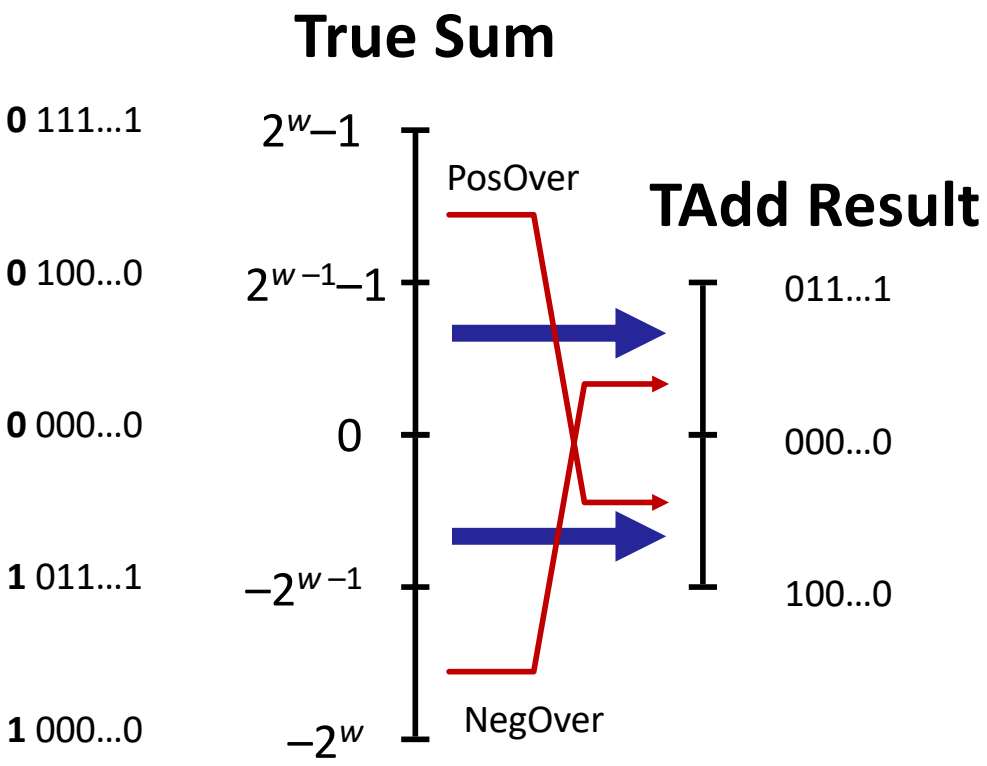
- **TAdd and UAdd have Identical Bit-Level Behavior**
  - Signed vs. unsigned addition in C:

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

  - Will give `s == t`

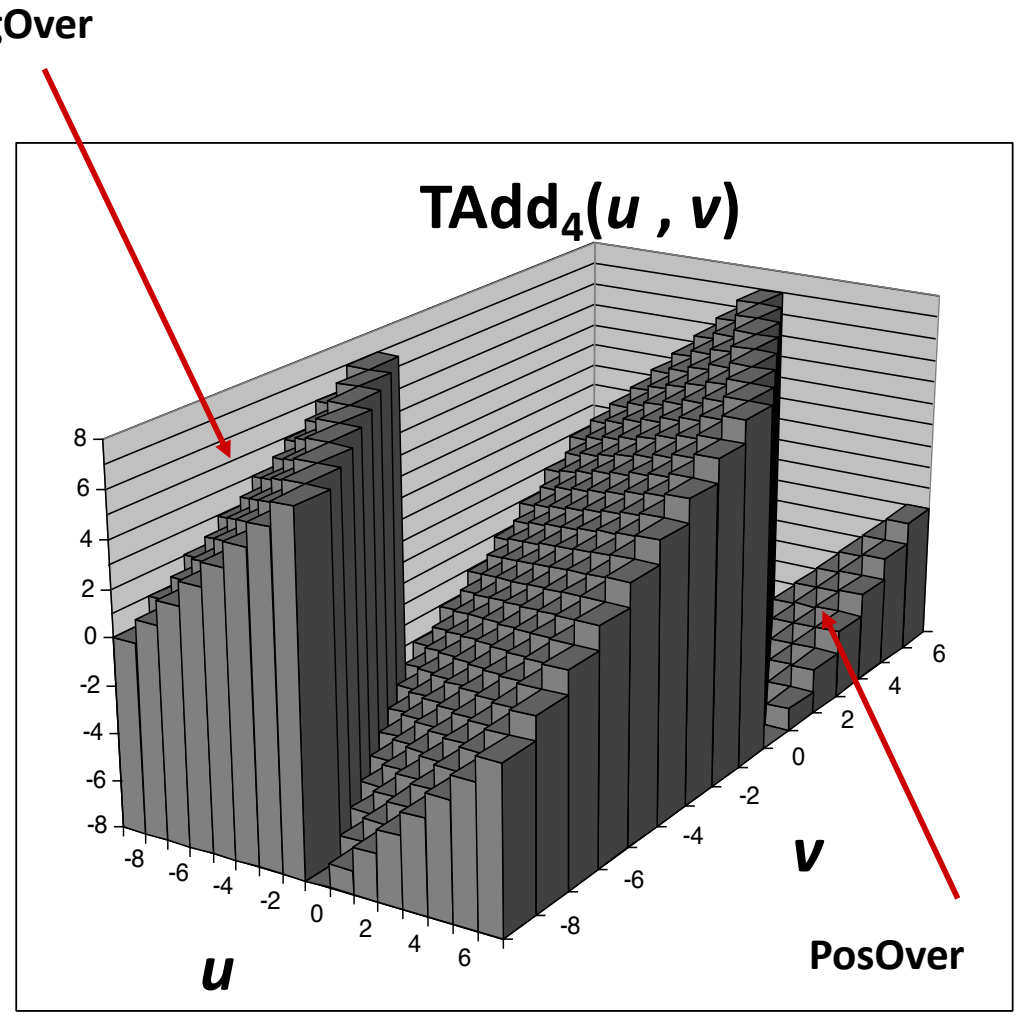
TAdd Overflow

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



Visualizing 2's Complement Addition

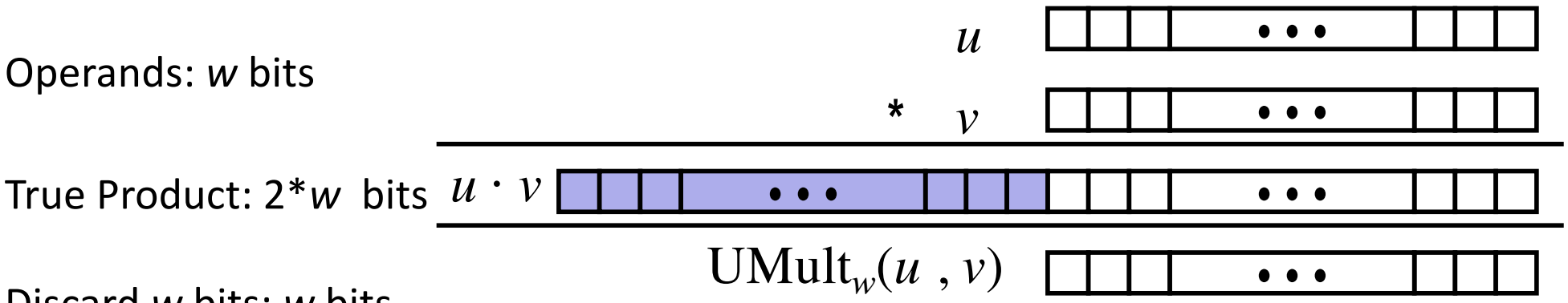
- **Values**
  - 4-bit two's comp.
  - Range from -8 to +7
- **Wraps Around**
  - If sum $\geq 2^{w-1}$
    - Becomes negative
    - At most once
  - If sum $< -2^{w-1}$
    - Becomes positive
    - At most once



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

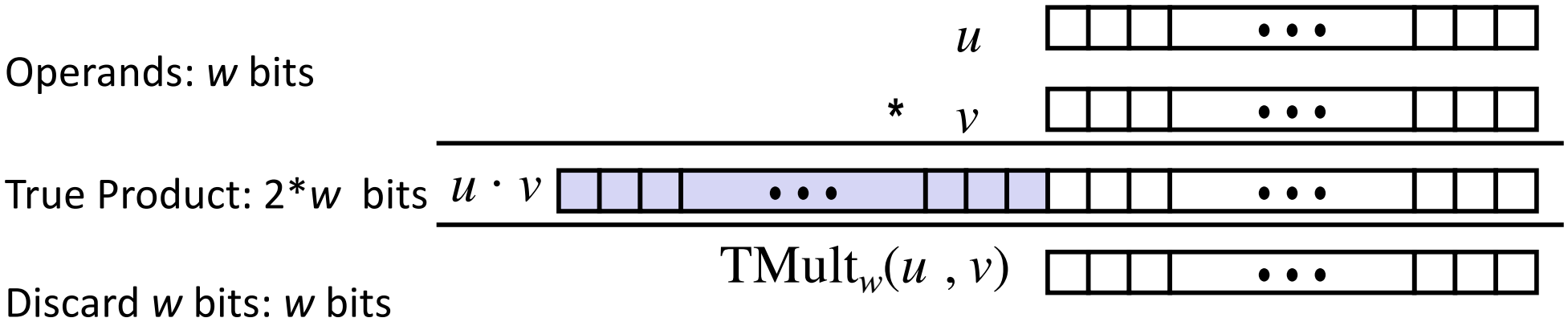
Unsigned Multiplication in C



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

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

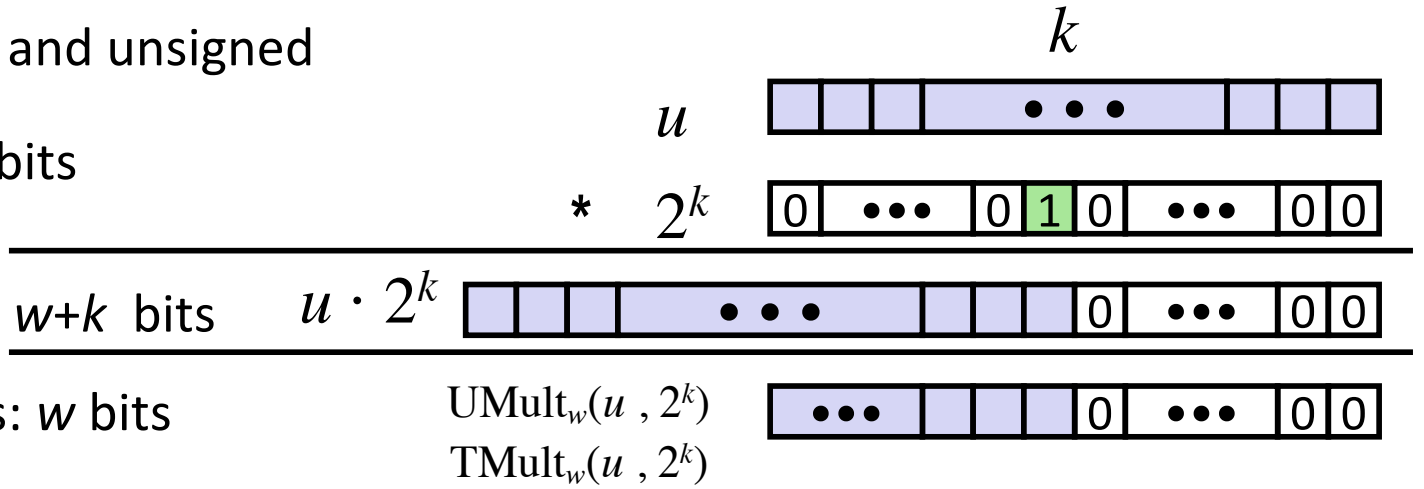
Signed Multiplication in C



- **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

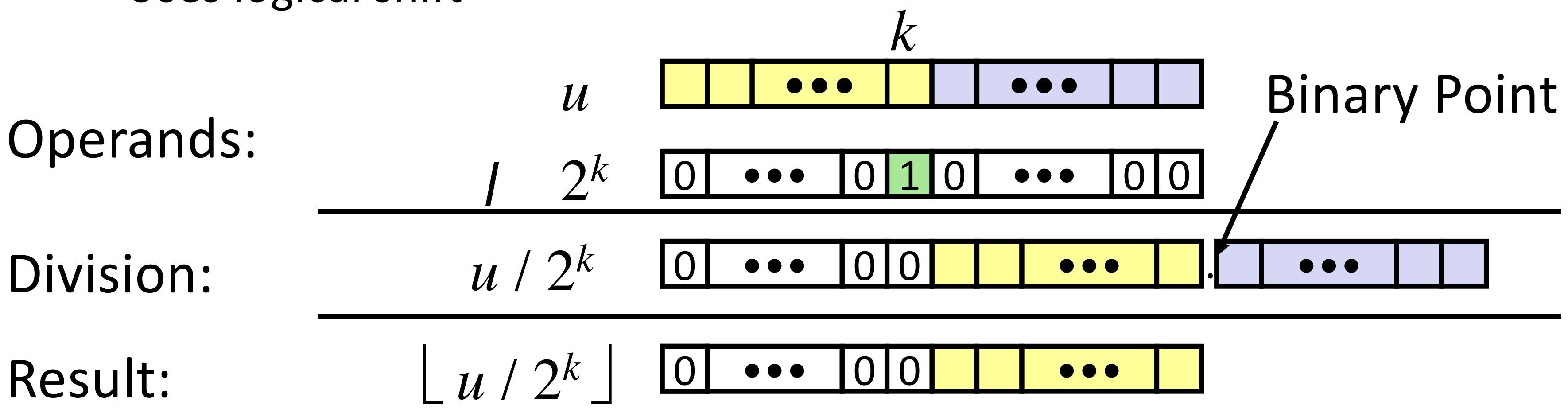
- **Operation**
  - `u << k` gives `u * 2^k`
  - Both signed and unsigned



- **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`

Bits, Bytes, and Integers

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

Arithmetic: Basic Rules

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

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

Why Should I Use Unsigned?

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

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

  - Can be very subtle

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

Counting Down with Unsigned

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

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

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

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

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

Why Should I Use Unsigned? (cont.)

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

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
- **Floating Point**
- Representations in memory, pointers, strings

IEEE Floating-Point Representation

- **Numeric form**
  - $V=(-1)^s \times M \times 2^E$
    - Sign bit ***s*** determines whether number is negative or positive
    - Significand ***M*** normally a fractional value in range [1.0,2.0)
    - Exponent ***E*** weights value by power of two

IEEE Floating-Point Representation

- **Encoding**
  - 

  - **`s`** is sign bit
  - **`exp`** field encodes ***E***
  - **`frac`** field encodes ***M***
- **Sizes**
  - Single precision (32 bits): 8 exp bits, 23 frac bits
  - Double precision (64 bits): 11 exp bits, 52 frac bits

Normalized Values

- **Condition**
  - **`exp` ≠ `000…0` and `exp` ≠ `111…1`**
- **Exponent coded as *biased* value**
  - *E* = *Exp* − *Bias*
    - *Exp* : unsigned value denoted by **`exp`**
    - *Bias* : Bias value
      - Single precision: **127** (*Exp*: 1…254, *E* : -126…127)
      - Double precision: **1023** (*Exp*: 1…2046, *E* : -1022 …1023)
      - In general: *Bias* = $2^{k-1} - 1$, where *k* is the number of exponent bits

Normalized Values

- **Significand coded with implied leading 1**
  - $m = 1.xxx\ldots x_2$
    - `xxx…x`: bits of `frac`
    - Minimum when `000…0` ($M = 1.0$)
    - Maximum when `111…1` ($M = 2.0 - \varepsilon$)
    - Get extra leading bit for "free"

Normalized Encoding Examples

- **Value: 12345 (Hex: 0x3039)**
- **Binary bits: 11000000111001**
- **Fraction representation: $1.1000000111001*2^{13}$**
- **M: 10000001110010000000000**
- **E: 10001100 (140)**
- **Binary Encoding**
  - 0100 0110 0100 0000 1110 0100 0000 0000
  - 4 6 4 0 E 4 0 0

Denormalized Values

- **Condition**
  - **`exp`** = `000…0`
- **Values**
  - Exponent Value: $E = 1 - Bias$
  - Significant Value m = $0.xxx\ldots x_2$
    - `xxx…x`: bits of `frac`

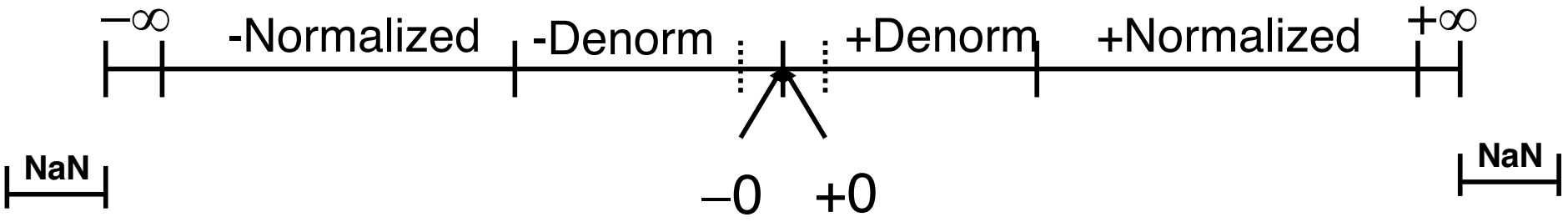
Denormalized Values

- **Cases**
  - **`exp`** = `000…0`, **`frac`** = `000…0`
    - Represents value 0
    - Note that have distinct values +0 and −0
  - **`exp`** = `000…0`, **`frac`** ≠ `000…0`
    - Numbers very close to 0.0
    - Lose precision as get smaller
    - "Gradual underflow"

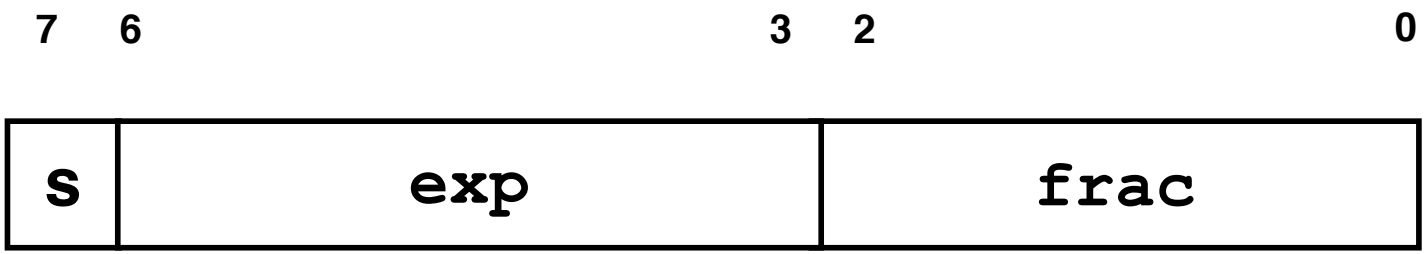
Special Values

- **Condition**
  - s=0, exp = 111…1, frac=000…0 $+\infty$
  - s=1, exp = 111…1, frac=000…0 $-\infty$
  - exp = 111…1 NaN

Summary of Real Number Encodings



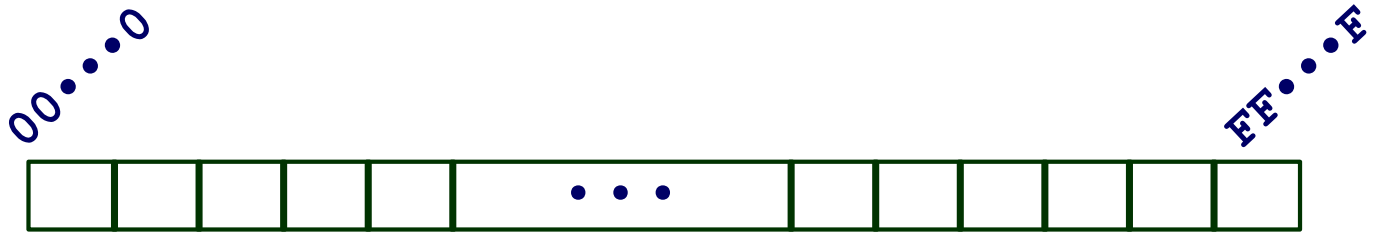
8-bit Floating-Point Representations



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
- Floating Point
- **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

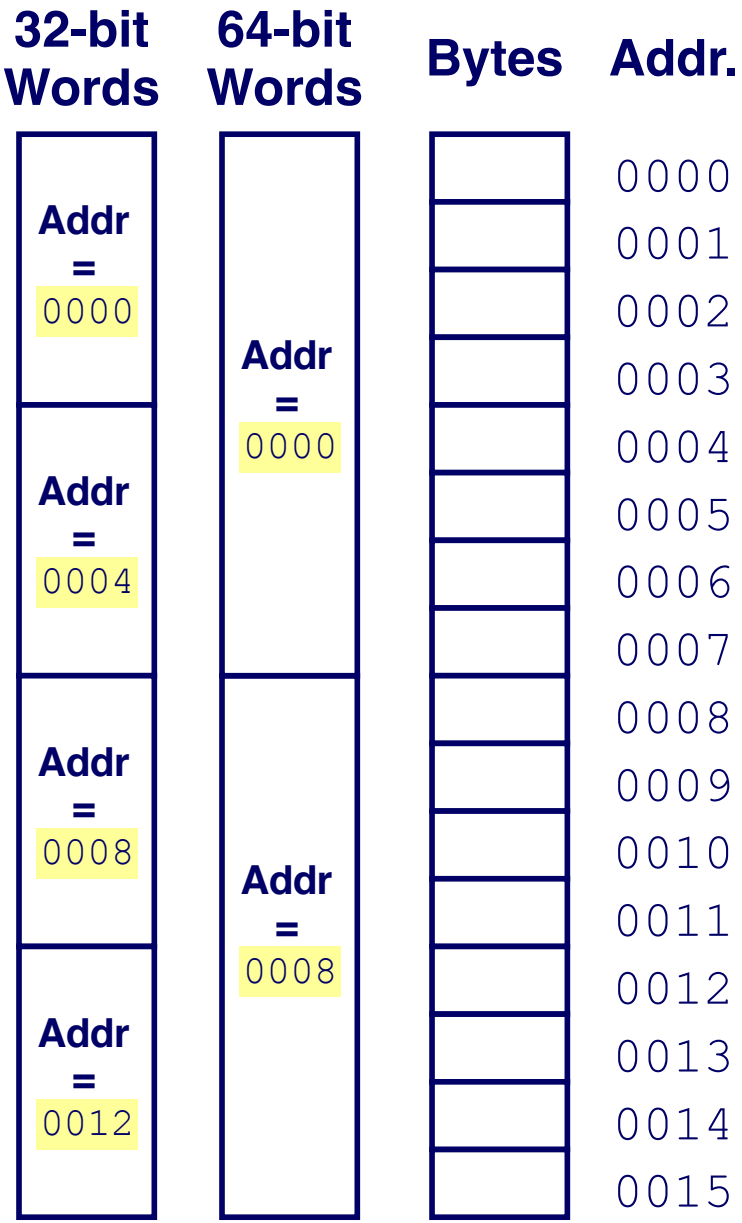
- **Note: system provides private address spaces to each "process"**
  - Think of a process as a program being executed
  - So, a program can clobber its own data, but not that of others

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 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

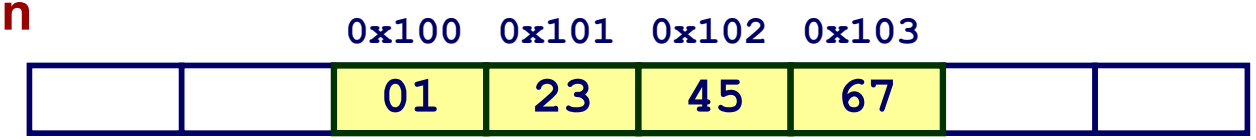
Byte Ordering

- **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

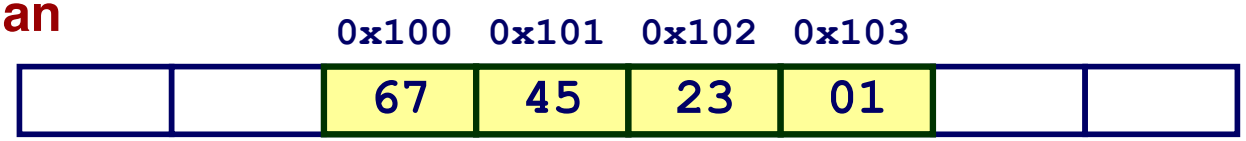
Byte Ordering Example

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

Big Endian



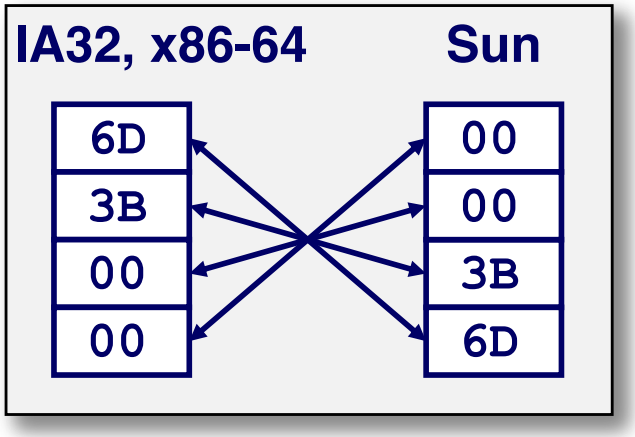
Little Endian



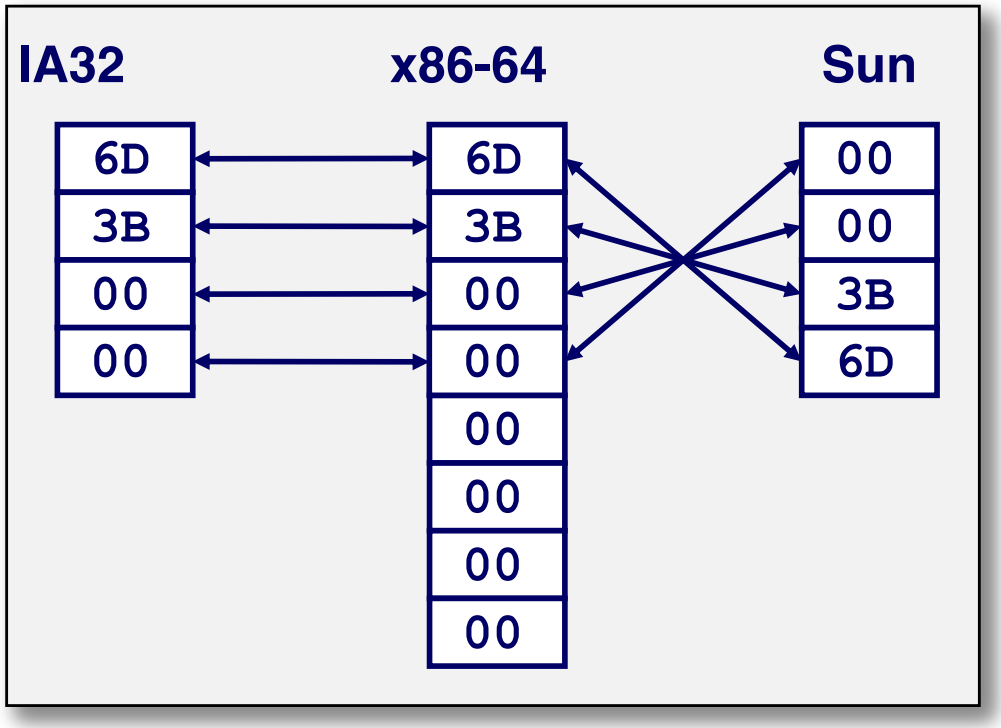
Representing Integers

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

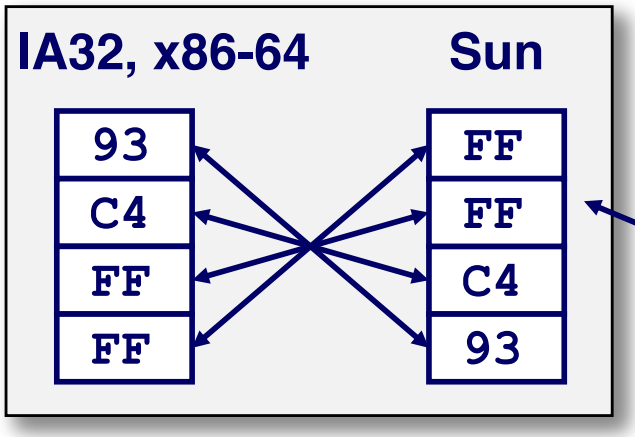
```
int A = 15213;
```




```
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

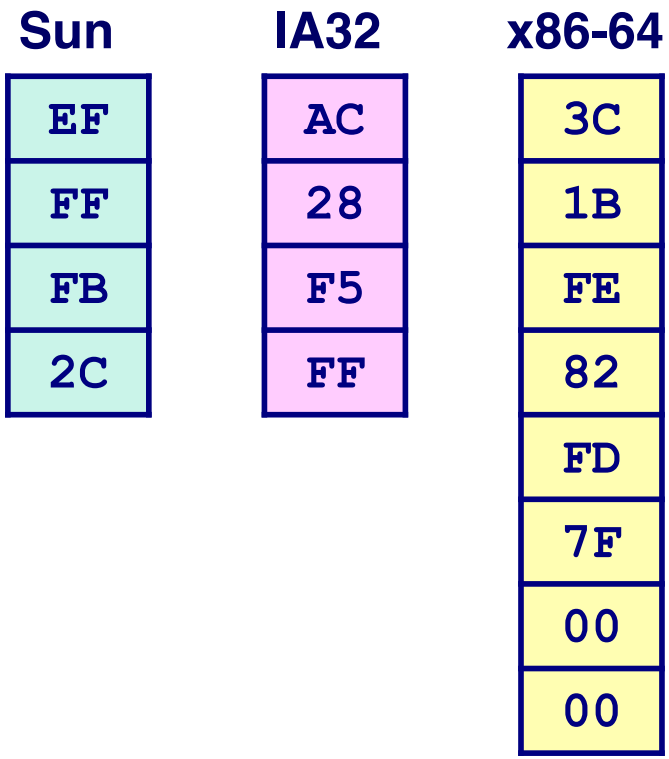
```
int a = 15213;
printf("int a = 15213;\n");
show_bytes((pointer) &a, sizeof(int));
```

Result (Linux x86-64):

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

Representing Pointers

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



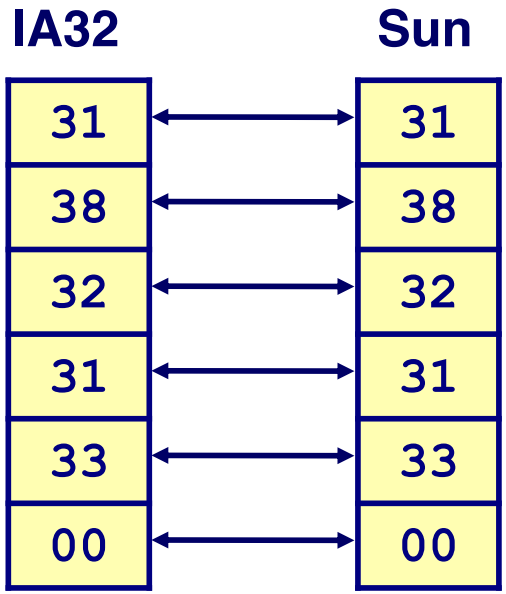
Different compilers & machines assign different locations to objects

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



Integer C Puzzles

Initialization

```
int x = foo();

int y = bar();

unsigned ux = x;

unsigned uy = y;
```

- `x < 0` □□ `((x*2) < 0)`
- `ux >= 0`
- `x & 7 == 7` □□ `(x<<30) < 0`
- `ux > -1`
- `x > y` □□ `-x < -y`
- `x * x >= 0`
- `x > 0 && y > 0` □□ `x + y > 0`
- `x >= 0` □□ `-x <= 0`
- `x <= 0` □□ `-x >= 0`
- `(x|-x)>>31 == -1`
- `ux >> 3 == ux/8`
- `x >> 3 == x/8`
- `x & (x-1) != 0`

Machine-Level Programming I: Basics

Machine Programming I: Basics

- **History of Intel processors and architectures**
- C, assembly, machine code
- Assembly Basics: Registers, operands, move
- Arithmetic & logical operations

Intel x86 Processors

- **Dominate laptop/desktop/server market**

- **Evolutionary design**
  - Backwards compatible up until 8086, introduced in 1978
  - Added more features as time goes on

- **Complex instruction set computer (CISC)**
  - Many different instructions with many different formats
    - But, only small subset encountered with Linux programs
  - Hard to match performance of Reduced Instruction Set Computers (RISC)
  - But, Intel has done just that!
    - In terms of speed. Less so for low power.

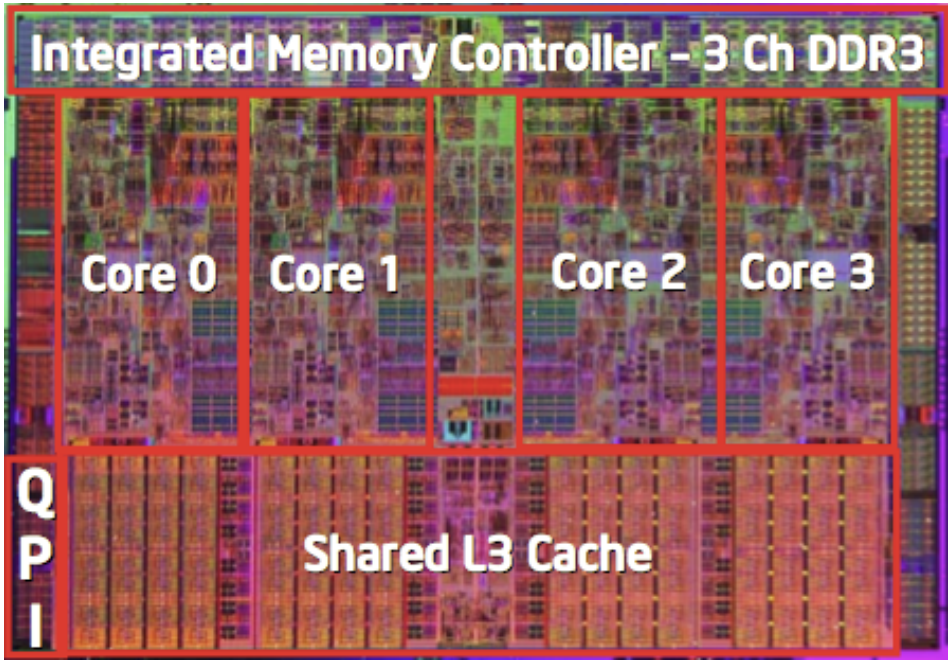
Intel x86 Evolution: Milestones

Name	*Date*	*Transistors*	*MHz*
8086	**1978**	**29K**	**5-10**
▪ First 16-bit Intel processor. Basis for IBM PC & DOS			
▪ 1MB address space			
386	**1985**	**275K**	**16-33**
▪ First 32 bit Intel processor , referred to as IA32			
▪ Added “flat addressing”, capable of running Unix			
Pentium 4E	**2004**	**125M**	**2800-3800**
▪ First 64-bit Intel x86 processor, referred to as x86-64			
Core 2	**2006**	**291M**	**1060-3500**
▪ First multi-core Intel processor			
Core i7	**2008**	**731M**	**1700-3900**
▪ Four cores (our shark machines)			

Intel x86 Processors, cont.

- **Machine Evolution**

386	1985	0.3M
Pentium	1993	3.1M
Pentium/MMX	1997	4.5M
PentiumPro	1995	6.5M
Pentium III	1999	8.2M
Pentium 4	2001	42M
Core 2 Duo	2006	291M
Core i7	2008	731M



- **Added Features**
  - Instructions to support multimedia operations
  - Instructions to enable more efficient conditional operations
  - Transition from 32 bits to 64 bits
  - More cores

2015 State of the Art

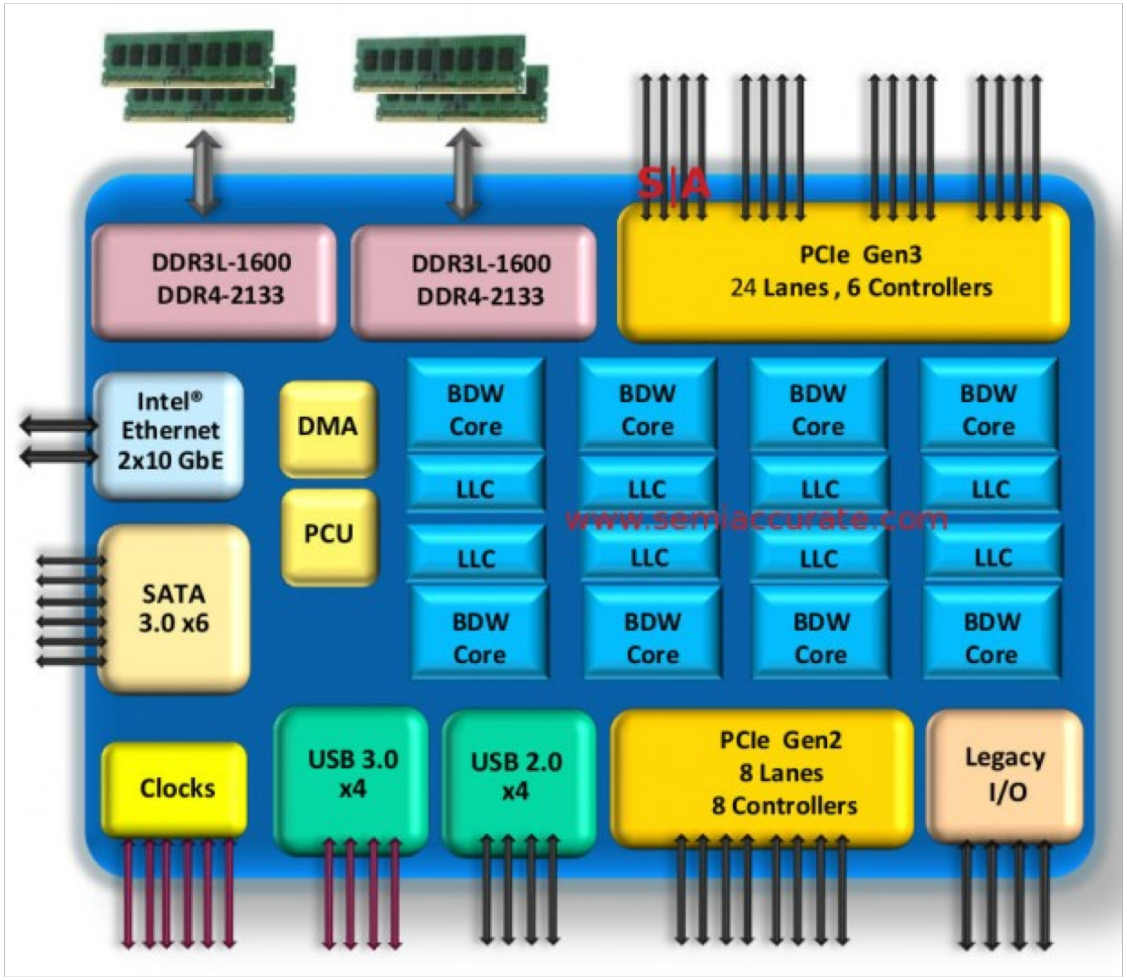
- Core i7 Broadwell 2015

Desktop Model

- 4 cores
- Integrated graphics
- 3.3-3.8 GHz
- 65W

Server Model

- 8 cores
- Integrated I/O
- 2-2.6 GHz
- 45W



x86 Clones: Advanced Micro Devices (AMD)

- **Historically**
  - AMD has followed just behind Intel
  - A little bit slower, a lot cheaper
- **Then**
  - Recruited top circuit designers from Digital Equipment Corp. and other downward trending companies
  - Built Opteron: tough competitor to Pentium 4
  - Developed x86-64, their own extension to 64 bits
- **Recent Years**
  - Intel got its act together
    - Leads the world in semiconductor technology
  - AMD has fallen behind
    - Relies on external semiconductor manufacturer

Intel's 64-Bit History

- **2001: Intel Attempts Radical Shift from IA32 to IA64**
  - Totally different architecture (Itanium)
  - Executes IA32 code only as legacy
  - Performance disappointing
- **2003: AMD Steps in with Evolutionary Solution**
  - x86-64 (now called "AMD64")
- **Intel Felt Obligated to Focus on IA64**
  - Hard to admit mistake or that AMD is better
- **2004: Intel Announces EM64T extension to IA32**
  - Extended Memory 64-bit Technology
  - Almost identical to x86-64!
- **All but low-end x86 processors support x86-64**
  - But, lots of code still runs in 32-bit mode

Our Coverage

- **IA32**
  - The traditional x86
  - For 15/18-213: RIP, Summer 2015

- **x86-64**
  - The standard
  - `shark> gcc hello.c`
  - `shark> gcc -m64 hello.c`

- **Presentation**
  - Book covers x86-64
  - Web aside on IA32
  - We will only cover x86-64

Machine Programming I: Basics

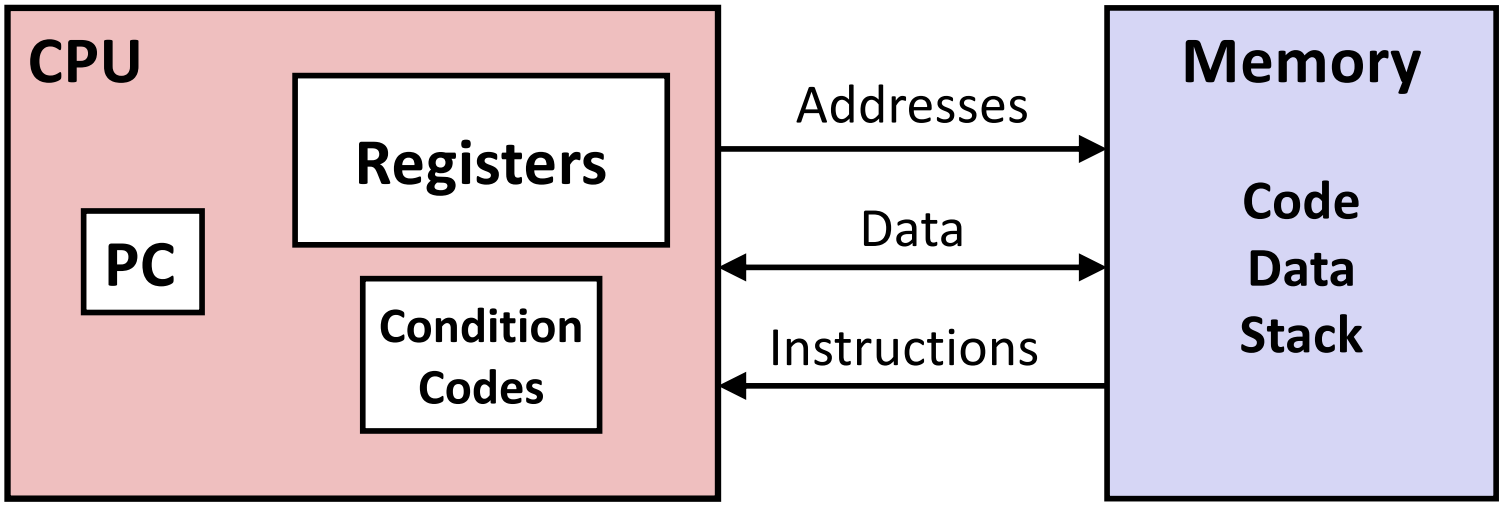
- History of Intel processors and architectures
- **C, assembly, machine code**
- Assembly Basics: Registers, operands, move
- Arithmetic & logical operations

Definitions

- **Architecture: (also ISA: instruction set architecture) The parts of a processor design that one needs to understand or write assembly/machine code.**
  - Examples: instruction set specification, registers.
- **Microarchitecture: Implementation of the architecture.**
  - Examples: cache sizes and core frequency.
- **Code Forms:**
  - Machine Code: The byte-level programs that a processor executes
  - Assembly Code: A text representation of machine code

- **Example ISAs:**
  - Intel: x86, IA32, Itanium, x86-64
  - ARM: Used in almost all mobile phones

Assembly/Machine Code View

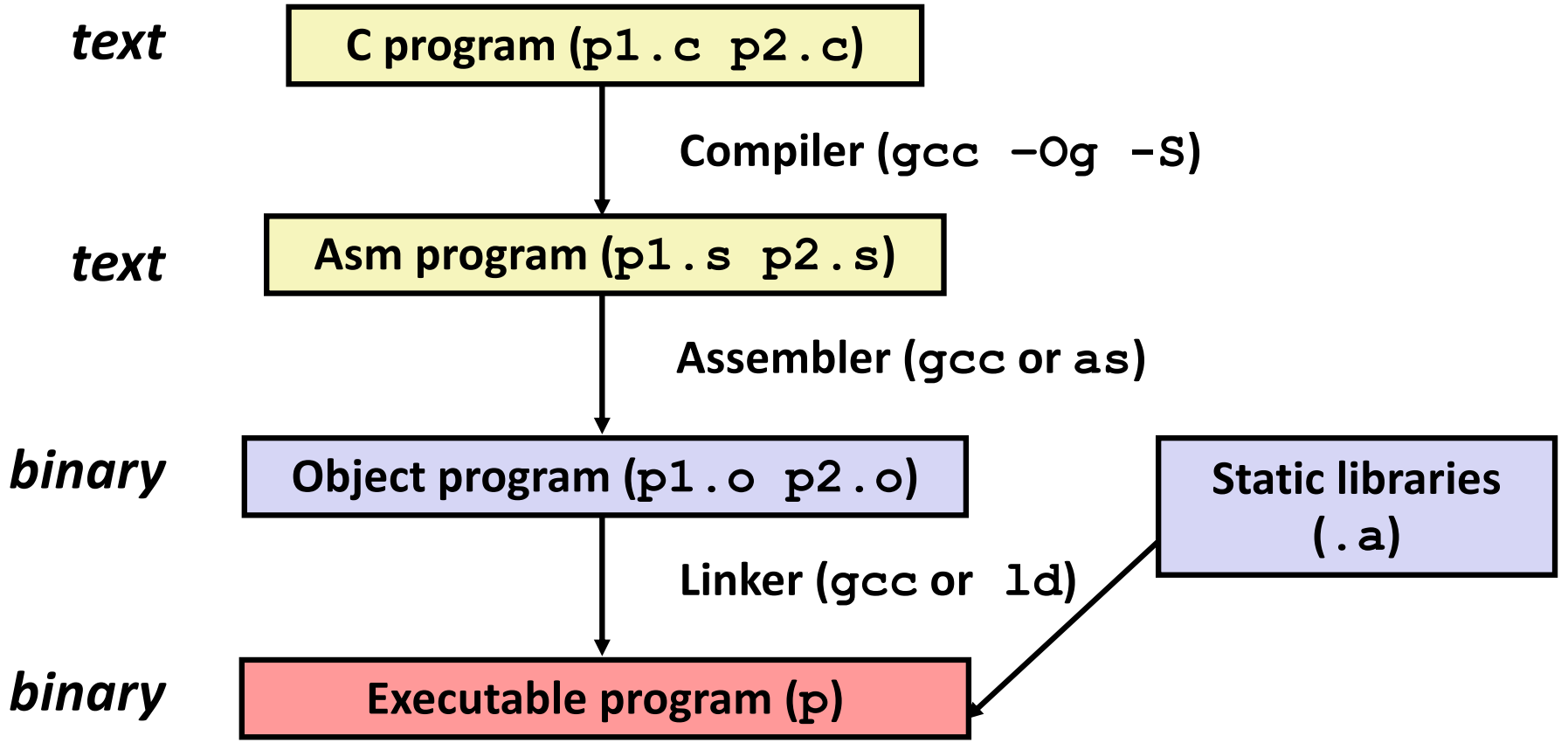


Programmer-Visible State

- **PC: Program counter**
  - Address of next instruction
  - Called "RIP" (x86-64)
- **Register file**
  - Heavily used program data
- **Condition codes**
  - Store status information about most recent arithmetic or logical operation
  - Used for conditional branching
- **Memory**
  - Byte addressable array
  - Code and user data
  - Stack to support procedures

Turning C into Object Code

- Code in files `p1.c p2.c`
- Compile with command: `gcc –Og p1.c p2.c -o p`
  - Use basic optimizations (`–Og`) [New to recent versions of GCC]
  - Put resulting binary in file `p`



Compiling Into Assembly

C Code (sum.c)

```
long plus(long x, long y);

void sumstore(long x, long y,
              long *dest)
{
    long t = plus(x, y);
    *dest = t;
}
```

Generated x86-64 Assembly

```
sumstore:
    pushq   %rbx
    movq    %rdx, %rbx
    call    plus
    movq    %rax, (%rbx)
    popq    %rbx
    ret
```

Obtain with command

```
gcc –Og –S sum.c
```

Produces file `sum.s`

***Warning*: Will get very different results on different machines (Andrew Linux, Mac OS-X, …) due to different versions of gcc and different compiler settings.**

Assembly Characteristics: Data Types

- **“Integer” data of 1, 2, 4, or 8 bytes**
  - Data values
  - Addresses (untyped pointers)
- **Floating point data of 4, 8, or 10 bytes**
- **Code: Byte sequences encoding series of instructions**
- **No aggregate types such as arrays or structures**
  - Just contiguously allocated bytes in memory

Assembly Characteristics: Operations

- **Perform arithmetic function on register or memory data**
- **Transfer data between memory and register**
  - Load data from memory into register
  - Store register data into memory
- **Transfer control**
  - Unconditional jumps to/from procedures
  - Conditional branches

Object Code

- **Assembler**
  - Translates `.s` into `.o`
  - Binary encoding of each instruction
  - Nearly-complete image of executable code
  - Missing linkages between code in different files
- **Linker**
  - Resolves references between files
  - Combines with static run-time libraries
    - E.g., code for **`malloc`**, **`printf`**
  - Some libraries are *dynamically linked*
    - Linking occurs when program begins execution

Code for `sumstore`

```
0x0400595:
    0x53
    0x48
    0x89
    0xd3
    0xe8
    0xf2
    0xff
    0xff
    0xff
    0x48
    0x89
    0x03
    0x5b
    0xc3
```

- **Total of 14 bytes**
- **Each instruction 1, 3, or 5 bytes**
- **Starts at address `0x0400595`**

Machine Instruction Example

- **C Code**

```
*dest = t;
```

  - Store value **t** where designated by **dest**

- **Assembly**

```
movq %rax, (%rbx)
```

  - Move 8-byte value to memory
    - Quad words in x86-64 parlance
  - Operands:

    t: Register **%rax**

    dest: Register **%rbx**

    ***dest:** Memory **M[%rbx]**

- **Object Code**

```
0x40059e:  48 89 03
```

  - 3-byte instruction
  - Stored at address **0x40059e**

Disassembling Object Code

Disassembled

```
0000000000400595 <sumstore>:
  400595:  53                   push   %rbx
  400596:  48 89 d3             mov    %rdx,%rbx
  400599:  e8 f2 ff ff ff       callq  400590 <plus>
  40059e:  48 89 03             mov    %rax,(%rbx)
  4005a1:  5b                   pop    %rbx
  4005a2:  c3                   retq
```

- **Disassembler**

  `objdump -d sum`

  - Useful tool for examining object code
  - Analyzes bit pattern of series of instructions
  - Produces approximate rendition of assembly code
  - Can be run on either `a.out` (complete executable) or `.o` file

Alternate Disassembly

Object

```
0x0400595:
    0x53
    0x48
    0x89
    0xd3
    0xe8
    0xf2
    0xff
    0xff
    0xff
    0x48
    0x89
    0x03
    0x5b
    0xc3
```

Disassembled

```
Dump of assembler code for function sumstore:
 0x0000000000400595 <+0>: push   %rbx
 0x0000000000400596 <+1>: mov    %rdx,%rbx
 0x0000000000400599 <+4>: callq  0x400590 <plus>
 0x000000000040059e <+9>: mov    %rax,(%rbx)
 0x00000000004005a1 <+12>:pop    %rbx
 0x00000000004005a2 <+13>:retq
```

- **Within gdb Debugger**

  `gdb sum`

  `disassemble sumstore`

  - Disassemble procedure

  `x/14xb sumstore`

  - Examine the 14 bytes starting at `sumstore`

What Can be Disassembled?

```
% objdump -d WINWORD.EXE

WINWORD.EXE:   file format pei-i386

No symbols in "WINWORD.EXE".
Disassembly of section .text:

30001000 <.text>:
30001000:
30001001:
30001003:
30001005:
3000100a:
```

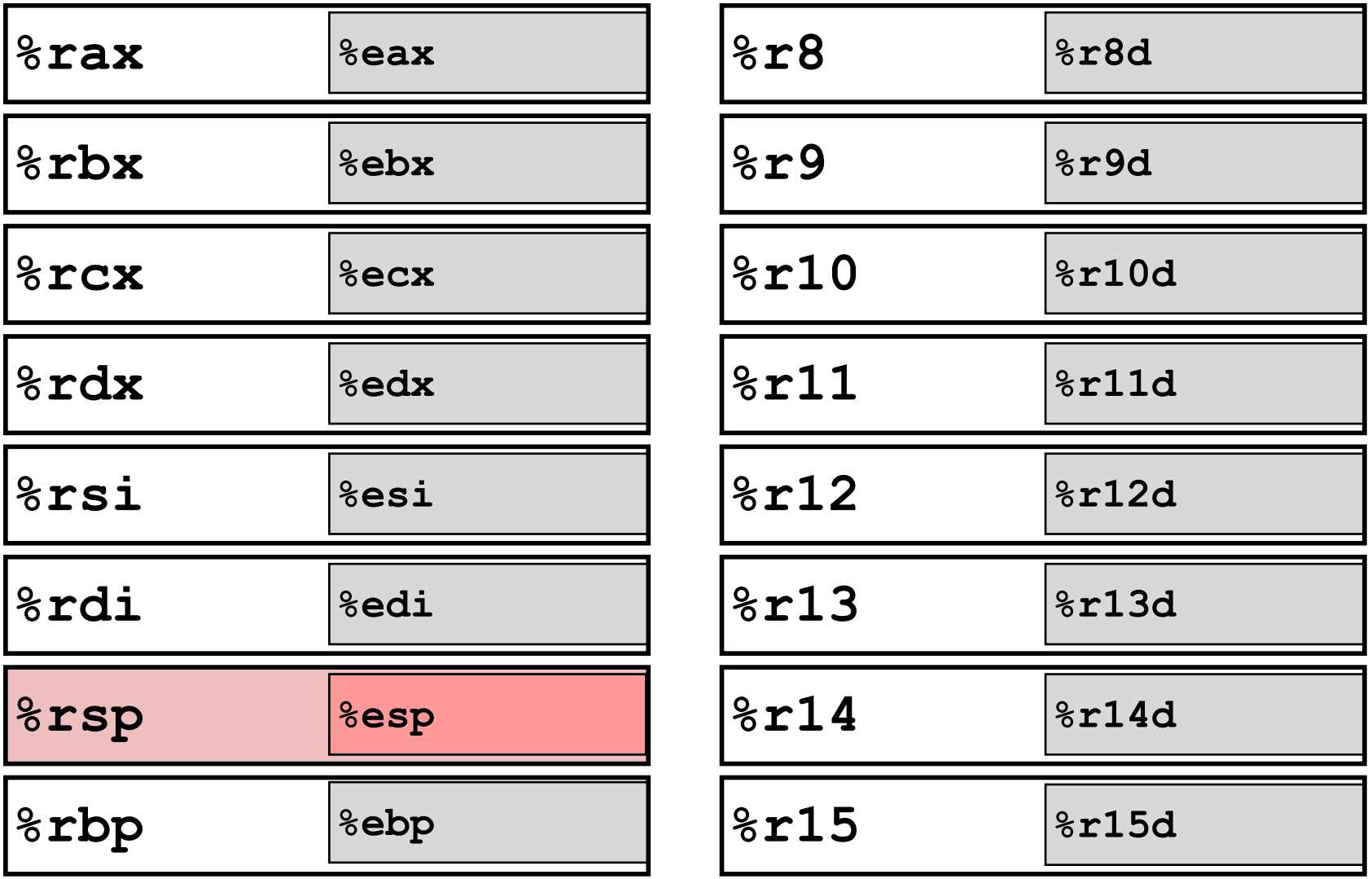
Reverse engineering forbidden by
Microsoft End User License Agreement

- Anything that can be interpreted as executable code
- Disassembler examines bytes and reconstructs assembly source

Machine Programming I: Basics

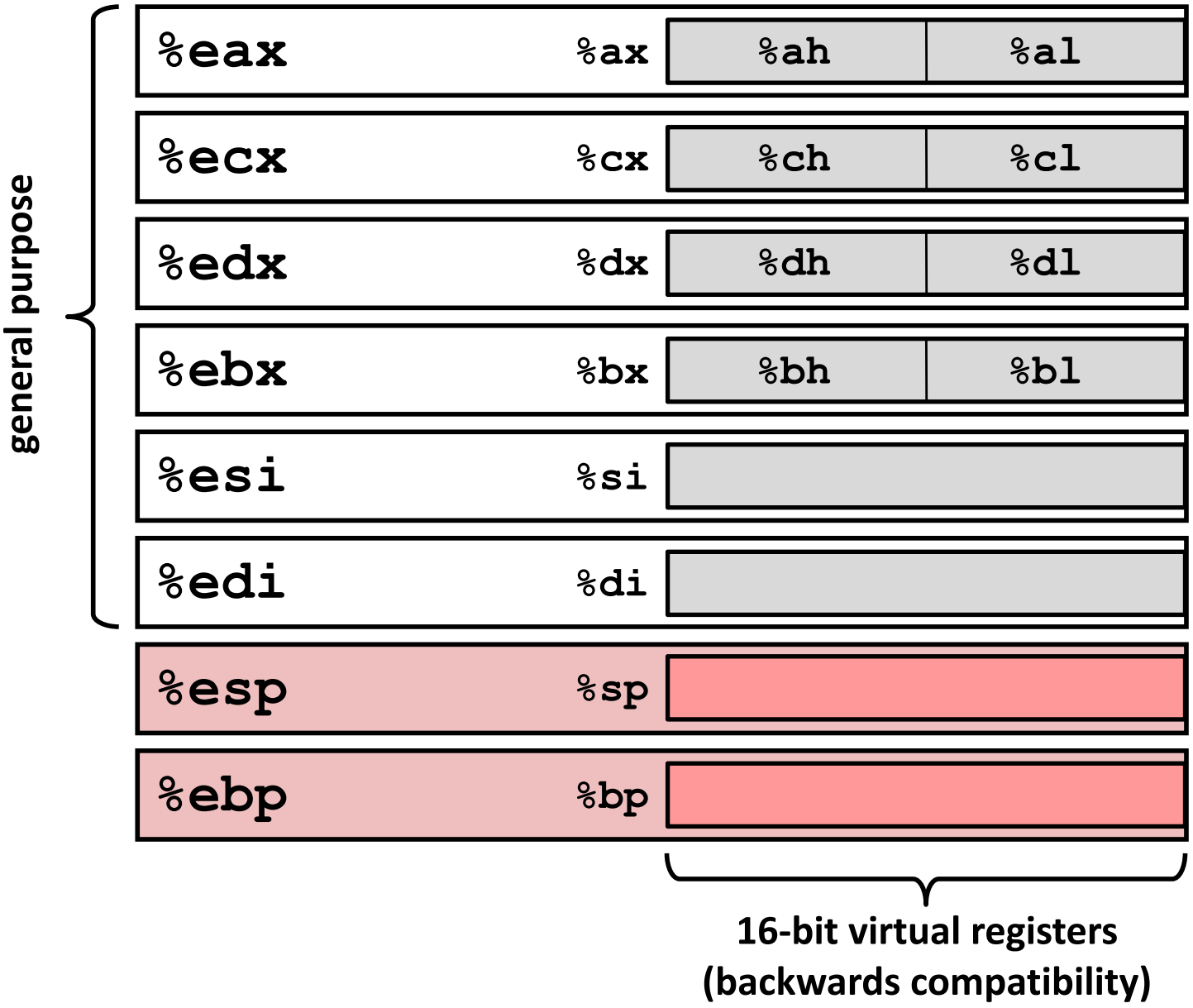
- History of Intel processors and architectures
- C, assembly, machine code
- **Assembly Basics: Registers, operands, move**
- Arithmetic & logical operations

x86-64 Integer Registers



- Can reference low-order 4 bytes (also low-order 1 & 2 bytes)

Some History: IA32 Registers

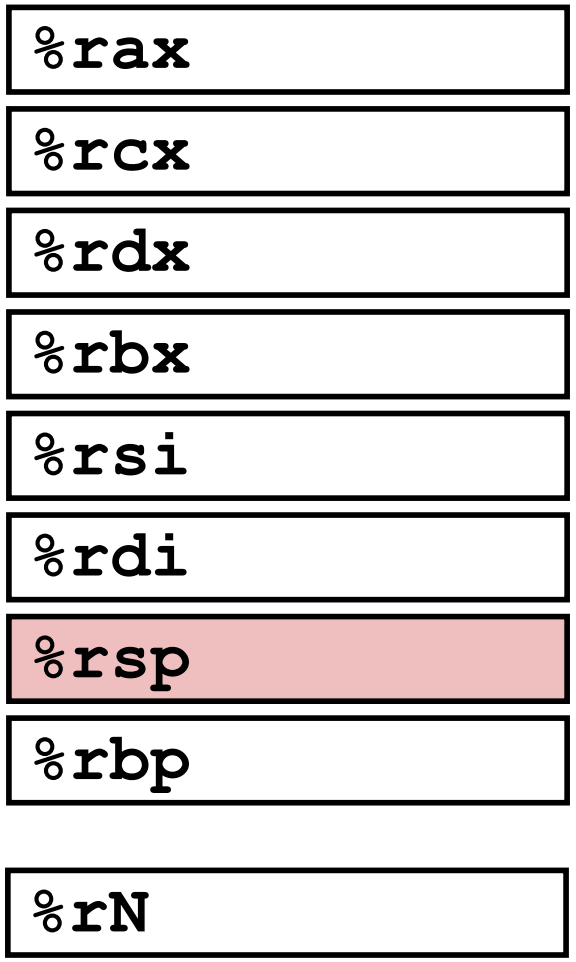


Moving Data

- **Moving Data**

  `movq` ***Source*, *Dest*:**

- **Operand Types**
  - ***Immediate:*** Constant integer data
    - Example: **`$0x400, $-533`**
    - Like C constant, but prefixed with **`'$'`**
    - Encoded with 1, 2, or 4 bytes
  - ***Register:*** One of 16 integer registers
    - Example: **`%rax`**, **`%r13`**
    - But **`%rsp`** reserved for special use
    - Others have special uses for particular instructions
  - ***Memory:*** 8 consecutive bytes of memory at address given by register
    - Simplest example: **`(%rax)`**
    - Various other "address modes"



`movq` Operand Combinations

Cannot do memory-memory transfer with a single instruction

	Source	Dest	Src,Dest	C Analog
`movq`	*Imm*	*Reg*	`movq $0x4,%rax`	`temp = 0x4;`
		Mem	`movq $-147,(%rax)`	`*p = -147;`
	Reg	*Reg*	`movq %rax,%rdx`	`temp2 = temp1;`
		Mem	`movq %rax,(%rdx)`	`*p = temp;`
	Mem	*Reg*	`movq (%rax),%rdx`	`temp = *p;`

Simple Memory Addressing Modes

- **Normal (R) Mem[Reg[R]]**
  - Register R specifies memory address
  - Aha! Pointer dereferencing in C

```
movq (%rcx),%rax
```

- **Displacement D(R) Mem[Reg[R]+D]**
  - Register R specifies start of memory region
  - Constant displacement D specifies offset

```
movq 8(%rbp),%rdx
```

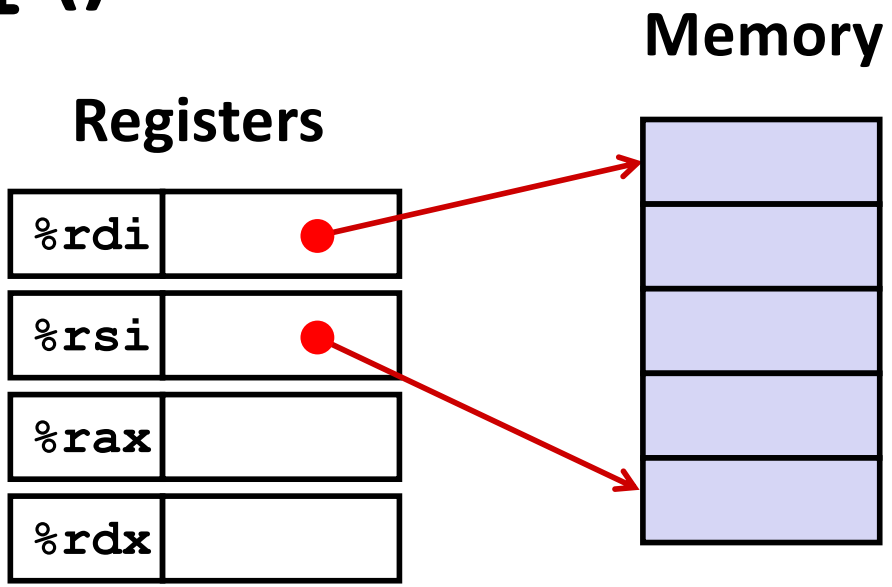
Example of Simple Addressing Modes

```
void swap
    (long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
    movq    (%rdi), %rax
    movq    (%rsi), %rdx
    movq    %rdx, (%rdi)
    movq    %rax, (%rsi)
    ret
```

Understanding Swap()

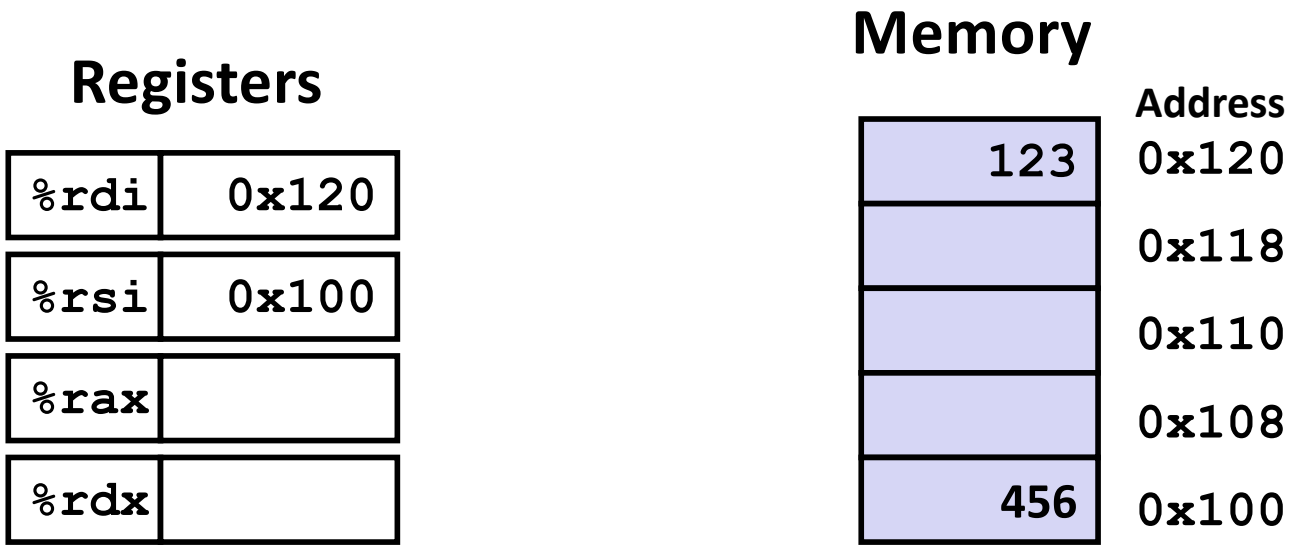
```
void swap
    (long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```



Register	Value
%rdi	xp
%rsi	yp
%rax	t0
%rdx	t1

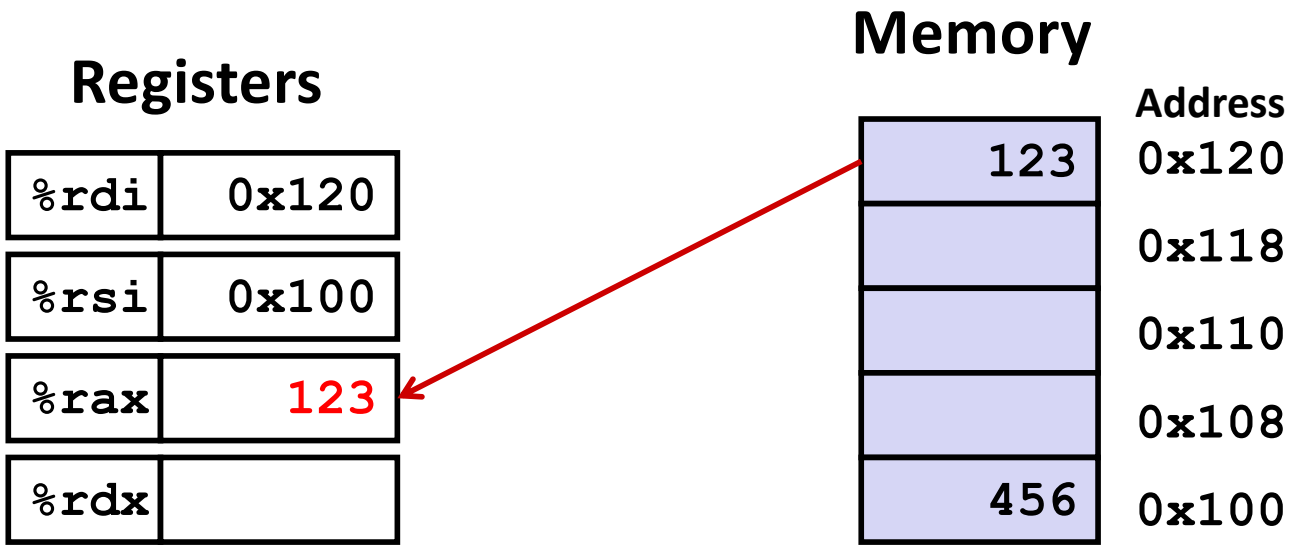
```
swap:
    movq    (%rdi), %rax  # t0 = *xp
    movq    (%rsi), %rdx  # t1 = *yp
    movq    %rdx, (%rdi)  # *xp = t1
    movq    %rax, (%rsi)  # *yp = t0
    ret
```

Understanding Swap()



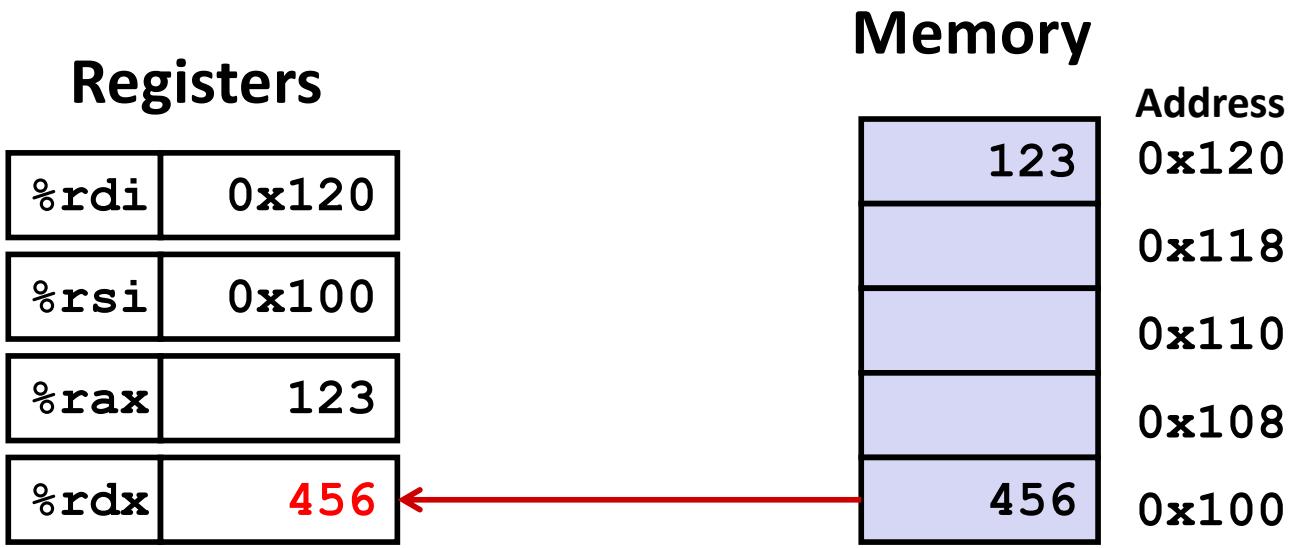

```
swap:
    movq    (%rdi), %rax  # t0 = *xp
    movq    (%rsi), %rdx  # t1 = *yp
    movq    %rdx, (%rdi)  # *xp = t1
    movq    %rax, (%rsi)  # *yp = t0
    ret
```

Understanding Swap()



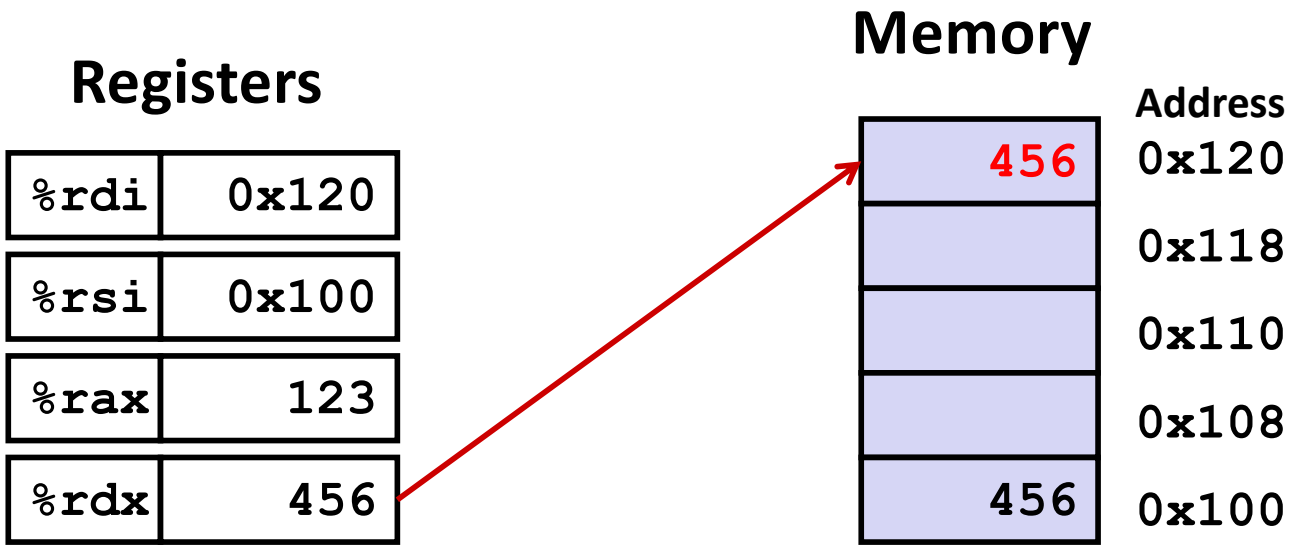

```
swap:
    movq    (%rdi), %rax  # t0 = *xp
    movq    (%rsi), %rdx  # t1 = *yp
    movq    %rdx, (%rdi)  # *xp = t1
    movq    %rax, (%rsi)  # *yp = t0
    ret
```

Understanding Swap()



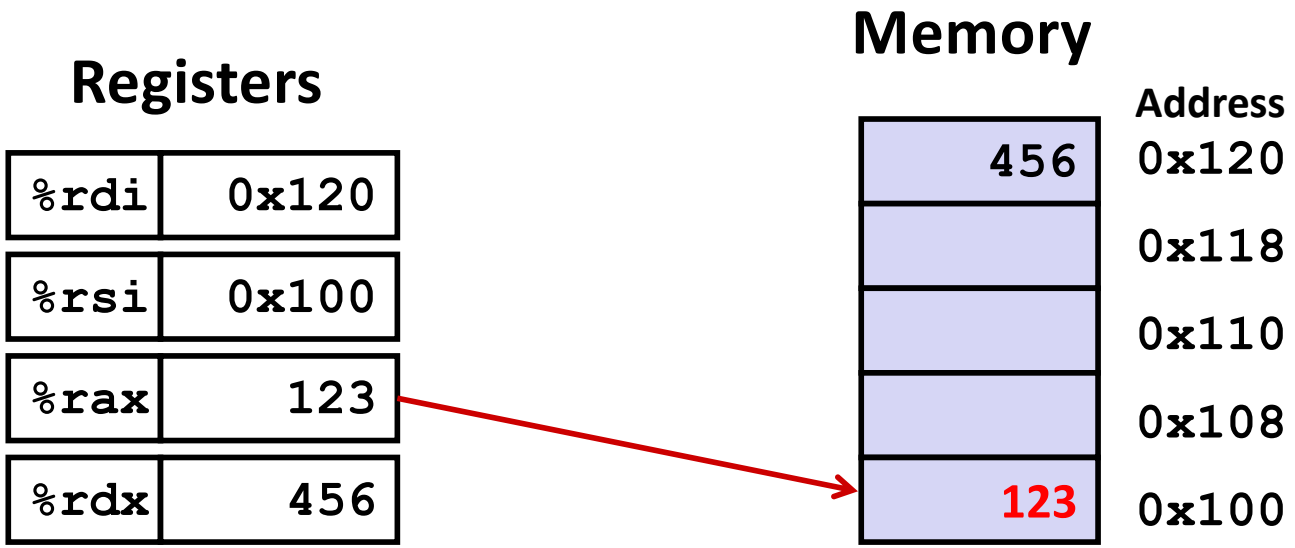

```
swap:
    movq    (%rdi), %rax  # t0 = *xp
    movq    (%rsi), %rdx  # t1 = *yp
    movq    %rdx, (%rdi)  # *xp = t1
    movq    %rax, (%rsi)  # *yp = t0
    ret
```

Understanding Swap()




```
swap:
    movq    (%rdi), %rax  # t0 = *xp
    movq    (%rsi), %rdx  # t1 = *yp
    movq    %rdx, (%rdi)  # *xp = t1
    movq    %rax, (%rsi)  # *yp = t0
    ret
```

Understanding Swap()




```
swap:
    movq    (%rdi), %rax  # t0 = *xp
    movq    (%rsi), %rdx  # t1 = *yp
    movq    %rdx, (%rdi)  # *xp = t1
    movq    %rax, (%rsi)  # *yp = t0
    ret
```

Simple Memory Addressing Modes

- **Normal (R) Mem[Reg[R]]**
  - Register R specifies memory address
  - Aha! Pointer dereferencing in C

```
movq (%rcx),%rax
```

- **Displacement D(R) Mem[Reg[R]+D]**
  - Register R specifies start of memory region
  - Constant displacement D specifies offset

```
movq 8(%rbp),%rdx
```

Complete Memory Addressing Modes

- **Most General Form**

  D(Rb,Ri,S) **Mem[Reg[Rb]+S*Reg[Ri]+ D]**

  - D: Constant "displacement" 1, 2, or 4 bytes
  - Rb: Base register: Any of 16 integer registers
  - Ri: Index register: Any, except for `%rsp`
  - S: Scale: 1, 2, 4, or 8 (*why these numbers?*)

- **Special Cases**

  (Rb,Ri) **Mem[Reg[Rb]+Reg[Ri]]**

  D(Rb,Ri) **Mem[Reg[Rb]+Reg[Ri]+D]**

  (Rb,Ri,S) **Mem[Reg[Rb]+S*Reg[Ri]]**

Address Computation Examples

`%rdx`	`0xf000`
`%rcx`	`0x0100`

Expression	Address Computation	Address
`0x8(%rdx)`	`0xf000 + 0x8`	`0xf008`
`(%rdx,%rcx)`	`0xf000 + 0x100`	`0xf100`
`(%rdx,%rcx,4)`	`0xf000 + 4*0x100`	`0xf400`
`0x80(,%rdx,2)`	`2*0xf000 + 0x80`	`0x1e080`

Machine Programming I: Basics

- History of Intel processors and architectures
- C, assembly, machine code
- Assembly Basics: Registers, operands, move
- **Arithmetic & logical operations**

Address Computation Instruction

- **`leaq` Src, Dst**
  - Src is address mode expression
  - Set Dst to address denoted by expression

- **Uses**
  - Computing addresses without a memory reference
    - E.g., translation of `p = &x[i];`
  - Computing arithmetic expressions of the form x + k*y
    - k = 1, 2, 4, or 8

- **Example**

```
long m12(long x)
{
  return x*12;
}
```

Converted to ASM by compiler:

```
leaq (%rdi,%rdi,2), %rax # t <- x+x*2
salq $2, %rax            # return t<<2
```

Some Arithmetic Operations

- **Two Operand Instructions:**

Format	Computation		
`addq`	Src,Dest	Dest = Dest + Src	
`subq`	Src,Dest	Dest = Dest – Src	
`imulq`	Src,Dest	Dest = Dest * Src	
`salq`	Src,Dest	Dest = Dest << Src	Also called shlq
`sarq`	Src,Dest	Dest = Dest >> Src	Arithmetic
`shrq`	Src,Dest	Dest = Dest >> Src	Logical
`xorq`	Src,Dest	Dest = Dest ^ Src	
`andq`	Src,Dest	Dest = Dest & Src	
`orq`	Src,Dest	Dest = Dest | Src	

- **Watch out for argument order!**
- **No distinction between signed and unsigned int (why?)**

Some Arithmetic Operations

- **One Operand Instructions**

`incq`	Dest	Dest = Dest + 1
`decq`	Dest	Dest = Dest – 1
`negq`	Dest	Dest = – Dest
`notq`	Dest	Dest = ~Dest

- **See book for more instructions**

Arithmetic Expression Example

```
long arith
(long x, long y, long z)
{
  long t1 = x+y;
  long t2 = z+t1;
  long t3 = x+4;
  long t4 = y * 48;
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

```
arith:
   leaq    (%rdi,%rsi), %rax
   addq    %rdx, %rax
   leaq    (%rsi,%rsi,2), %rdx
   salq    $4, %rdx
   leaq    4(%rdi,%rdx), %rcx
   imulq   %rcx, %rax
   ret
```

Interesting Instructions

- **`leaq`**: address computation
- **`salq`**: shift
- **`imulq`**: multiplication
  - But, only used once

Understanding Arithmetic Expression Example

```
long arith
(long x, long y, long z)
{
  long t1 = x+y;
  long t2 = z+t1;
  long t3 = x+4;
  long t4 = y * 48;
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

```
arith:
   leaq    (%rdi,%rsi), %rax    # t1
   addq    %rdx, %rax           # t2
   leaq    (%rsi,%rsi,2), %rdx
   salq    $4, %rdx             # t4
   leaq    4(%rdi,%rdx), %rcx   # t5
   imulq   %rcx, %rax           # rval
   ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	t1, t2, rval
%rdx	t4
%rcx	t5

Machine Programming I: Summary

- **History of Intel processors and architectures**
  - Evolutionary design leads to many quirks and artifacts
- **C, assembly, machine code**
  - New forms of visible state: program counter, registers, ...
  - Compiler must transform statements, expressions, procedures into low-level instruction sequences
- **Assembly Basics: Registers, operands, move**
  - The x86-64 move instructions cover wide range of data movement forms
- **Arithmetic**
  - C compiler will figure out different instruction combinations to carry out computation

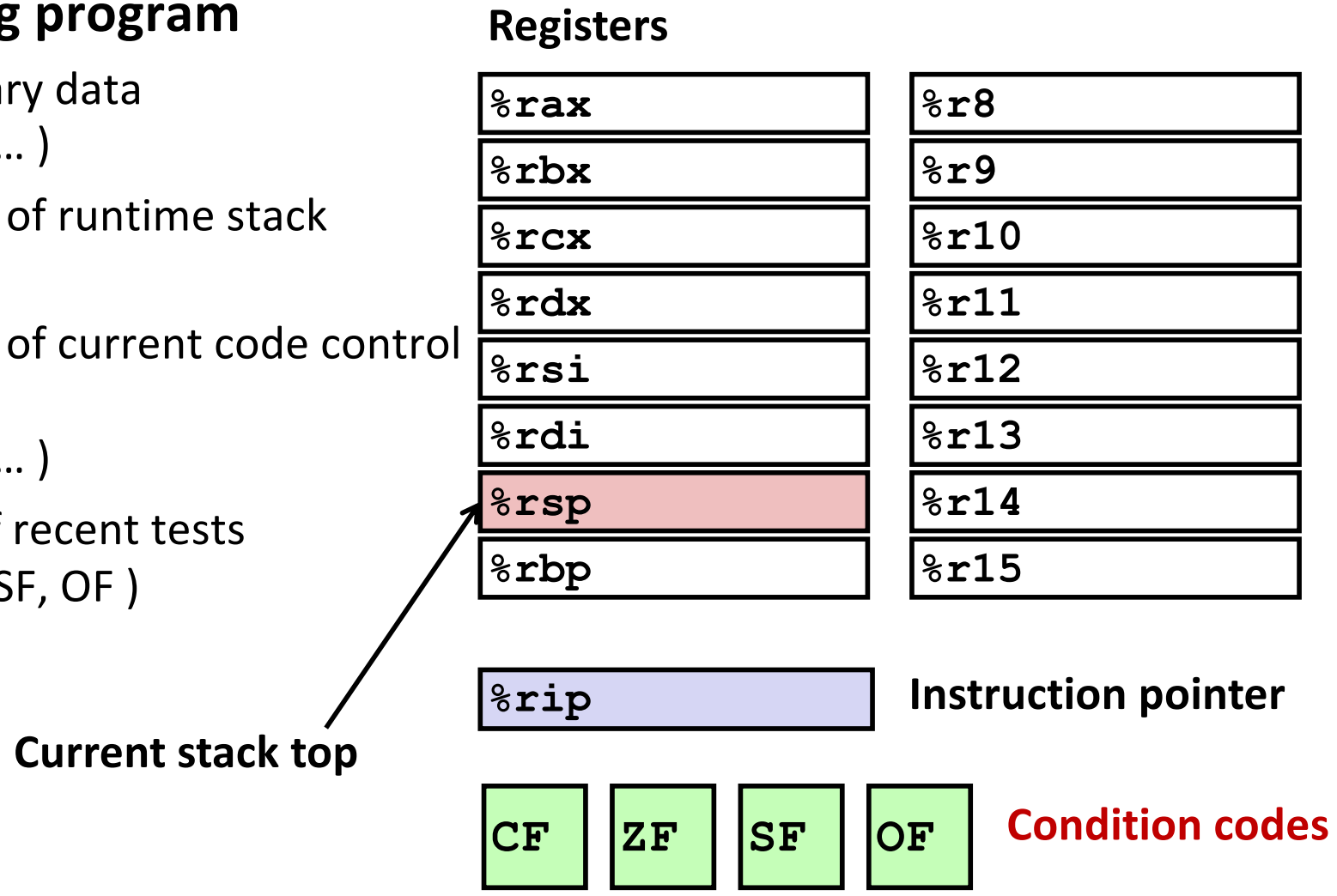
Machine-Level Programming II: Control

Control

- **Control: Condition codes**
- Conditional branches
- Loops
- Switch Statements

Processor State (x86-64, Partial)

- **Information about currently executing program**
  - Temporary data (**`%rax`**, …)
  - Location of runtime stack (**`%rsp`**)
  - Location of current code control point (**`%rip`**, …)
  - Status of recent tests (CF, ZF, SF, OF)



Condition Codes (Implicit Setting)

- **Single bit registers**
  - CF Carry Flag (for unsigned) SF Sign Flag (for signed)
  - ZF Zero Flag OF Overflow Flag (for signed)

- **Implicitly set (think of it as side effect) by arithmetic operations**

  Example: **`addq`** Src,Dest ↔ **`t = a+b`**

  CF set if carry out from most significant bit (unsigned overflow)

  ZF set if **`t == 0`**

  SF set if **`t < 0`** (as signed)

  OF set if two's-complement (signed) overflow

```
(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)
```

- **Not set by `leaq` instruction**

Condition Codes (Explicit Setting: Compare)

- **Explicit Setting by Compare Instruction**
  - **`cmpq`** Src2, Src1
  - **`cmpq b,a`** like computing **`a-b`** without setting destination

  - CF set if carry out from most significant bit (used for unsigned comparisons)
  - ZF set if **`a == b`**
  - SF set if **`(a-b) < 0`** (as signed)
  - OF set if two's-complement (signed) overflow

```
(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)
```

Condition Codes (Explicit Setting: Test)

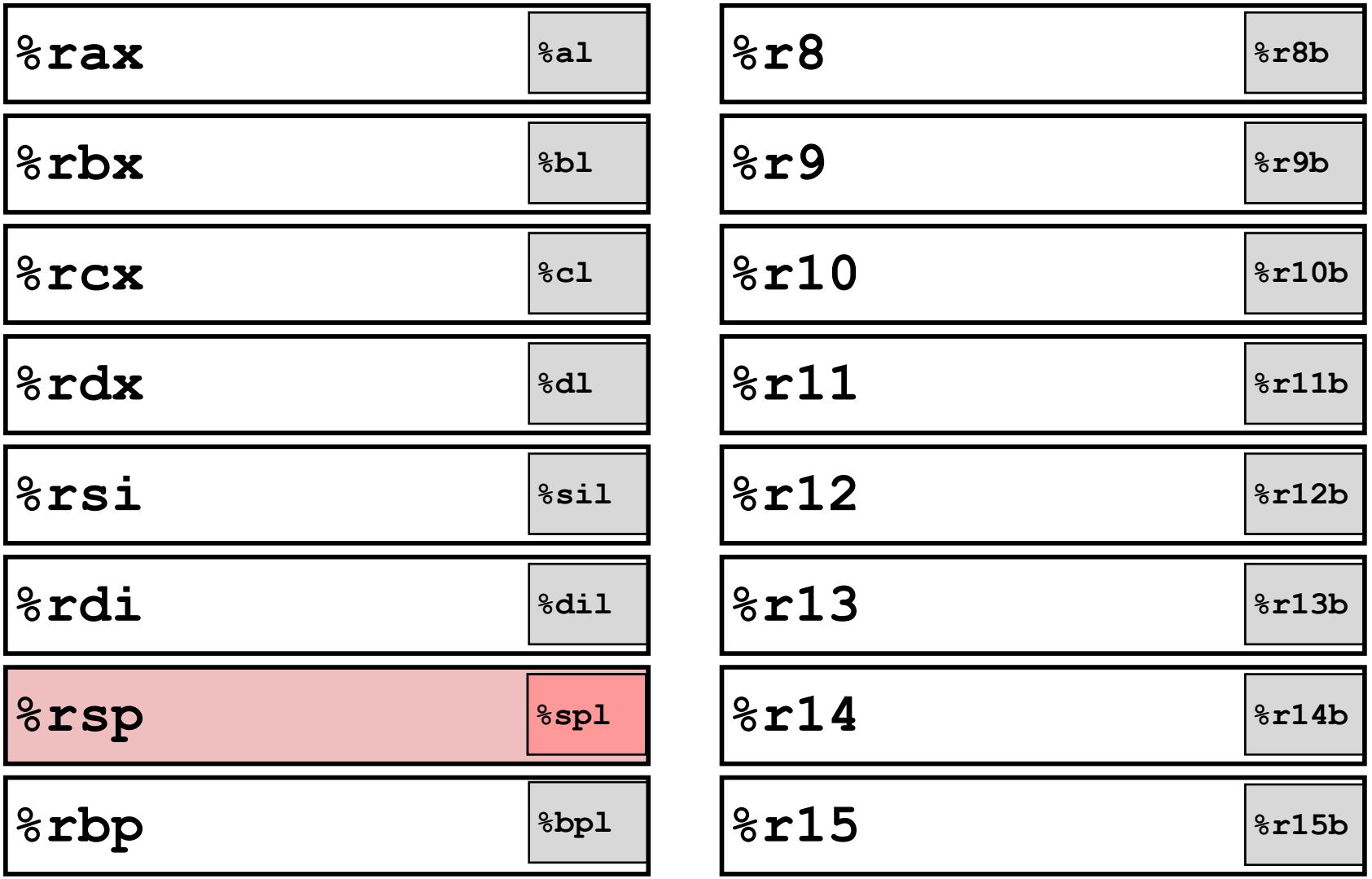
- **Explicit Setting by Test instruction**
  - **`testq`** Src2, Src1
    - **`testq b,a`** like computing **`a&b`** without setting destination
  - Sets condition codes based on value of Src1 & Src2
  - Useful to have one of the operands be a mask
  - ZF set when **`a&b == 0`**
  - SF set when **`a&b < 0`**

Reading Condition Codes

- **SetX Instructions**
  - Set low-order byte of destination to 0 or 1 based on combinations of condition codes
  - Does not alter remaining 7 bytes

SetX	Condition	Description
`sete`	`ZF`	Equal / Zero
`setne`	`~ZF`	Not Equal / Not Zero
`sets`	`SF`	Negative
`setns`	`~SF`	Nonnegative
`setg`	`~(SF^OF)&~ZF`	Greater (Signed)
`setge`	`~(SF^OF)`	Greater or Equal (Signed)
`setl`	`(SF^OF)`	Less (Signed)
`setle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`seta`	`~CF&~ZF`	Above (unsigned)
`setb`	`CF`	Below (unsigned)

x86-64 Integer Registers



- Can reference low-order byte

Reading Condition Codes (Cont.)

- **SetX Instructions:**
  - Set single byte based on combination of condition codes
- **One of addressable byte registers**
  - Does not alter remaining bytes
  - Typically use **`movzbl`** to finish job
    - 32-bit instructions also set upper 32 bits to

```
int gt (long x, long y)
{
  return x > y;
}
```

Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rax`	Return value

```
cmpq    %rsi, %rdi    # Compare x:y
setg    %al           # Set when >
movzbl  %al, %eax     # Zero rest of %eax
ret
```