Floating Point

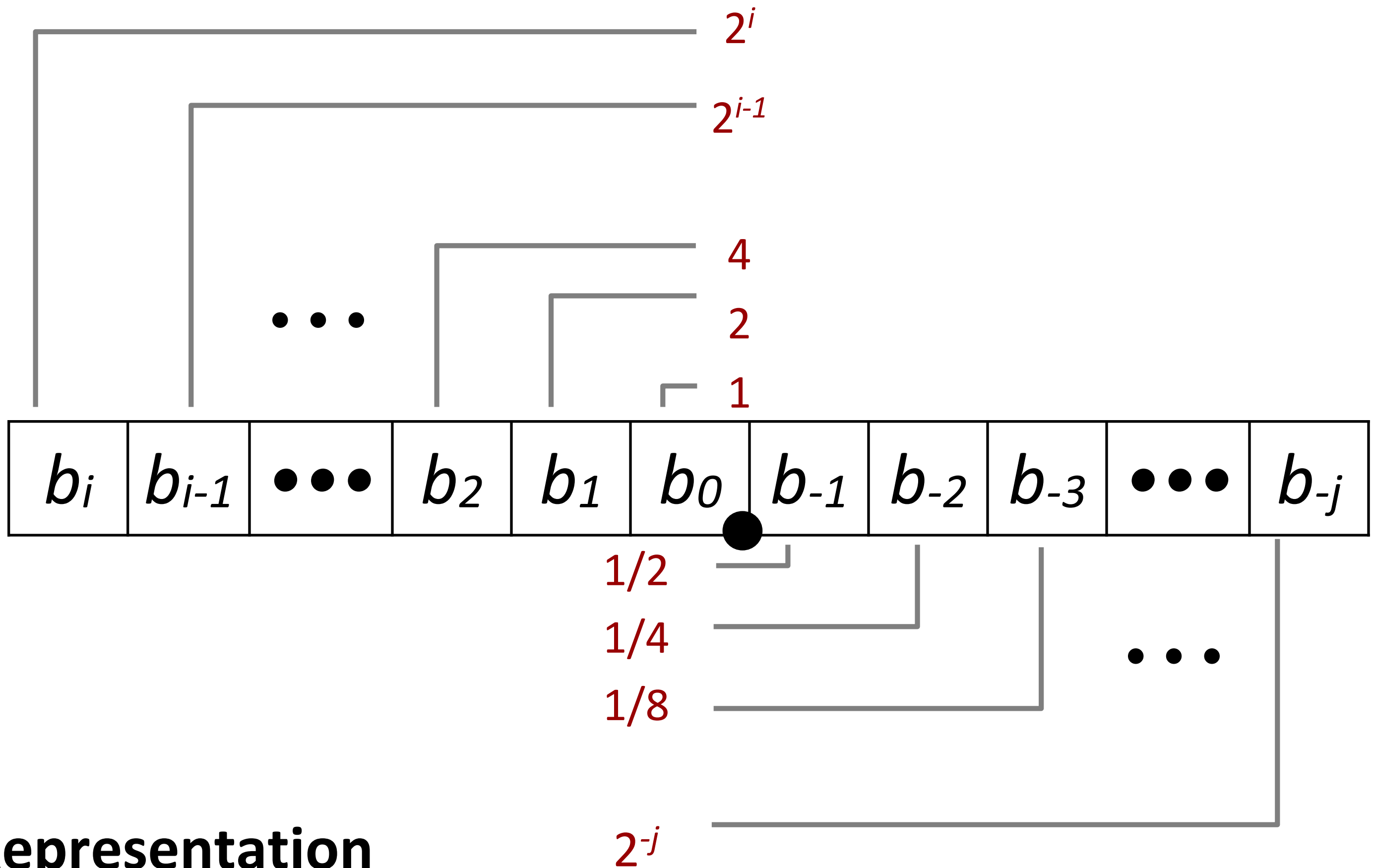
Today: Floating Point

- Background: Fractional binary numbers
- IEEE floating point standard: Definition
- Example and properties
- Rounding, addition, multiplication
- Floating point in C
- Summary

Fractional binary numbers

- **What is 1011.101_2?**

Fractional Binary Numbers



- **Representation**
  - Bits to right of "binary point" represent fractional powers of 2
  - Represents rational number:

$$\sum_{k=-j}^{i} b_k \times 2^k$$

Fractional Binary Numbers: Examples

- **Value** **Representation**

Value	Representation
5 3/4	101.11_2
2 7/8	10.111_2
63/64	0.111111_2

- **Observations**
  - Divide by 2 by shifting right
  - Multiply by 2 by shifting left
  - Numbers of form $0.111111\ldots_2$ are just below 1.0
    - $1/2 + 1/4 + 1/8 + \ldots + 1/2^i + \ldots \rightarrow 1.0$
    - Use notation $1.0 - \varepsilon$

Representable Numbers

- **Limitation**
  - Can only exactly represent numbers of the form $x/2^k$
  - Other rational numbers have repeating bit representations

- **Value** **Representation**
  - 1/3 $0.0101010101[01]\ldots_2$
  - 1/5 $0.001100110011[0011]\ldots_2$
  - 1/10 $0.0001100110011[0011]\ldots_2$

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IEEE Floating Point

- **IEEE Standard 754**
  - Established in 1985 as uniform standard for floating point arithmetic
    - Before that, many idiosyncratic formats
  - Supported by all major CPUs

- **Driven by numerical concerns**
  - Nice standards for rounding, overflow, underflow
  - Hard to make fast in hardware
    - Numerical analysts predominated over hardware designers in defining standard

Floating Point Representation

- **Numerical Form:**

$$(-1)^s\, M\;\; 2^E$$

  - **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

- **Encoding**
  - MSB s is sign bit ***s***
  - exp field encodes ***E*** (but is not equal to E)
  - frac field encodes ***M*** (but is not equal to M)

Precisions

- **Single precision: 32 bits**

s	exp	frac
1	8-bits	23-bits

- **Double precision: 64 bits**

s	exp	frac
1	11-bits	52-bits

- **Extended precision: 80 bits (Intel only)**

s	exp	frac
1	15-bits	63 or 64-bits

Normalized Values

- **Condition: exp ≠ 000…0 and exp ≠ 111…1**

- **Exponent coded as *biased* value: *E* = *Exp* – *Bias***
  - *Exp*: unsigned value exp
  - *Bias* = $2^{k-1} - 1$, where *k* is number of exponent bits
    - Single precision: 127 (Exp: 1…254, E: -126…127)
    - Double precision: 1023 (Exp: 1…2046, E: -1022…1023)

- **Significand coded with implied leading 1: *M* = $1.\mathrm{xxx}\ldots\mathrm{x}_2$**
  - xxx…x: bits of frac
  - Minimum when 000…0 (*M* = 1.0)
  - Maximum when 111…1 (*M* = 2.0 – ε)
  - Get extra leading bit for "free"

Normalized Encoding Example

- **Value:** `Float F = 15213.0;`
  - $15213_{10} = 11101101101101_2$
    $= 1.1101101101101_2 \times 2^{13}$

- **Significand**

  M = $1.\underline{1101101101101}_2$

  `frac=` $\underline{1101101101101}0000000000_2$

- **Exponent**

  E = 13

  $Bias$ = 127

  Exp = 140 = 10001100_2

- **Result:**

s	exp	frac
0	10001100	11011011011010000000000

Denormalized Values

- **Condition:** exp = 000…0

- **Exponent value: $E = -Bias + 1$ (instead of $E = 0 - Bias$)**
- **Significand coded with implied leading 0: $M = 0.xxx…x_2$**
  - **`xxx…x`**: bits of **`frac`**
- **Cases**
  - **`exp`** = 000…0, **`frac`** = 000…0
    - Represents zero value
    - Note distinct values: +0 and –0 (why?)
  - **`exp`** = 000…0, **`frac`** ≠ 000…0
    - Numbers very close to 0.0
    - Lose precision as get smaller
    - Equispaced

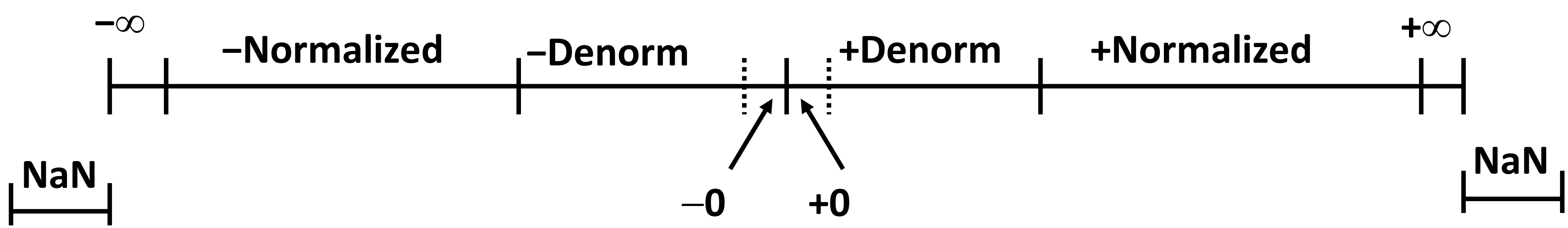
Special Values

- **Condition: `exp` =** 111…1

- **Case: `exp` =** 111…1**, `frac` =** 000…0
  - Represents value ∞ (infinity)
  - Operation that overflows
  - Both positive and negative
  - E.g., 1.0/0.0 = −1.0/−0.0 = +∞, 1.0/−0.0 = −∞

- **Case: `exp` =** 111…1**, `frac` ≠** 000…0
  - Not-a-Number (NaN)
  - Represents case when no numeric value can be determined
  - E.g., sqrt(–1), ∞ − ∞, ∞ × 0

Visualization: Floating Point Encodings



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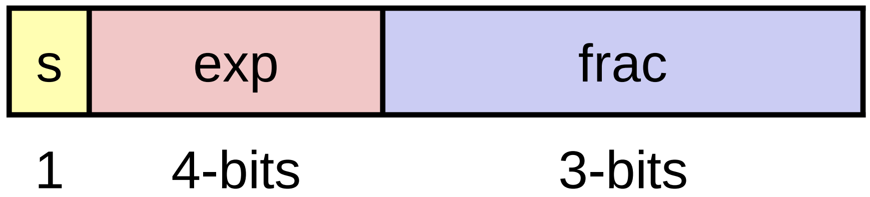
Tiny Floating Point Example



- **8-bit Floating Point Representation**
  - the sign bit is in the most significant bit
  - the next four bits are the exponent, with a bias of 7
  - the last three bits are the **`frac`**

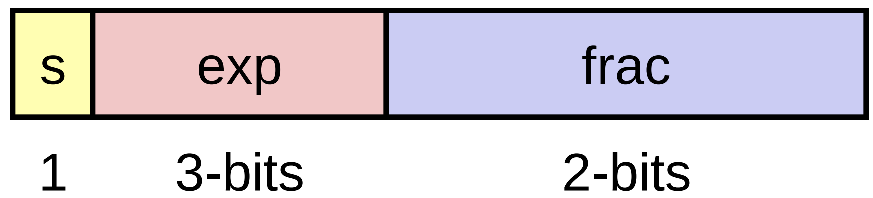
- **Same general form as IEEE Format**
  - normalized, denormalized
  - representation of 0, NaN, infinity

Dynamic Range (Positive Only)

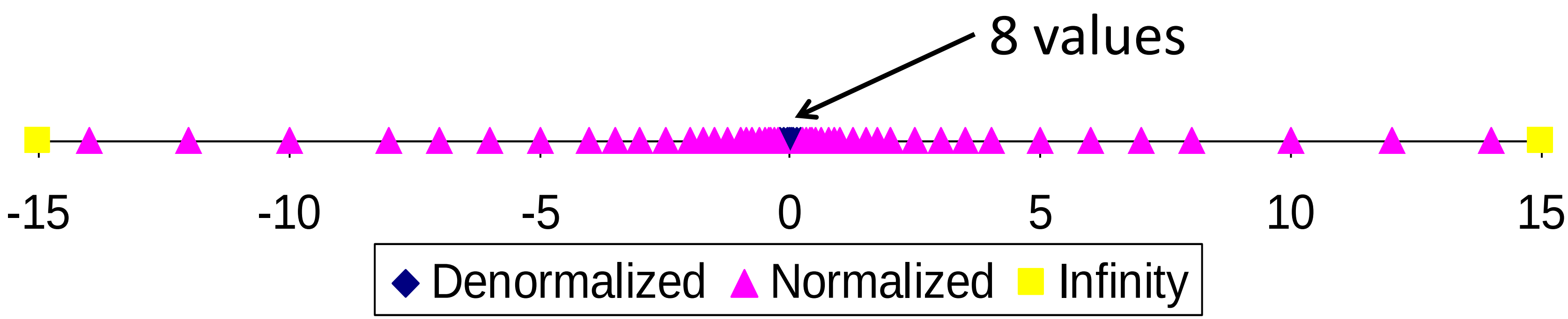
	s	exp	frac	E	Value	
Denormalized numbers	0	0000	000	-6	0	
	0	0000	001	-6	1/8*1/64 = 1/512	closest to zero
	0	0000	010	-6	2/8*1/64 = 2/512	
	…					
	0	0000	110	-6	6/8*1/64 = 6/512	
	0	0000	111	-6	7/8*1/64 = 7/512	largest denorm
Normalized numbers	0	0001	000	-6	8/8*1/64 = 8/512	smallest norm
	0	0001	001	-6	9/8*1/64 = 9/512	
	…					
	0	0110	110	-1	14/8*1/2 = 14/16	
	0	0110	111	-1	15/8*1/2 = 15/16	closest to 1 below
	0	0111	000	0	8/8*1 = 1	
	0	0111	001	0	9/8*1 = 9/8	closest to 1 above
	0	0111	010	0	10/8*1 = 10/8	
	…					
	0	1110	110	7	14/8*128 = 224	
	0	1110	111	7	15/8*128 = 240	largest norm
	0	1111	000	n/a	inf	

Distribution of Values

- **6-bit IEEE-like format**
  - e = 3 exponent bits
  - f = 2 fraction bits
  - Bias is $2^{3-1}-1 = 3$

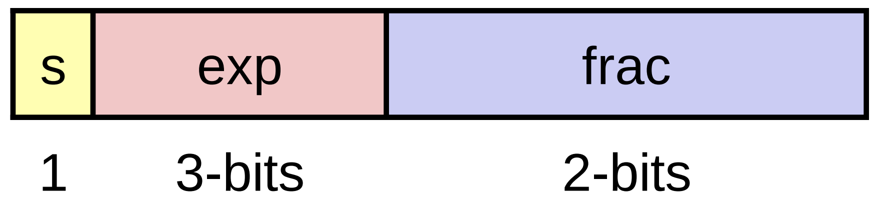


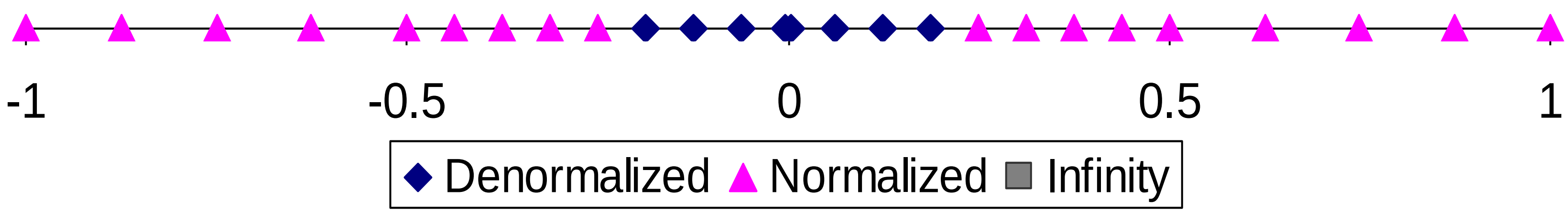
- **Notice how the distribution gets denser toward zero.**



Distribution of Values (close-up view)

- **6-bit IEEE-like format**
  - e = 3 exponent bits
  - f = 2 fraction bits
  - Bias is 3





Interesting Numbers {single,double}

Description	*exp*	*frac*	*Numeric Value*
Zero	**00…00**	**00…00**	**0.0**
Smallest Pos. Denorm.	**00…00**	**00…01**	$2^{-\{23,52\}} \times 2^{-\{126,1022\}}$
Single ≈ 1.4×10^{-45}			
Double ≈ 4.9×10^{-324}			
Largest Denormalized	**00…00**	**11…11**	$(1.0 - \varepsilon) \times 2^{-\{126,1022\}}$
Single ≈ 1.18×10^{-38}			
Double ≈ 2.2×10^{-308}			
Smallest Pos. Normalized	**00…01**	**00…00**	$1.0 \times 2^{-\{126,1022\}}$
Just larger than largest denormalized			
One	**01…11**	**00…00**	**1.0**
Largest Normalized	**11…10**	**11…11**	$(2.0 - \varepsilon) \times 2^{\{127,1023\}}$
Single ≈ 3.4×10^{38}			
Double ≈ 1.8×10^{308}			

Special Properties of Encoding

- **FP Zero Same as Integer Zero**
  - All bits = 0

- **Can (Almost) Use Unsigned Integer Comparison**
  - Must first compare sign bits
  - Must consider −0 = 0
  - NaNs problematic
    - Will be greater than any other values
    - What should comparison yield?
  - Otherwise OK
    - Denorm vs. normalized
    - Normalized vs. infinity

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- **Rounding, addition, multiplication**
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Floating Point Operations: Basic Idea

- $x +_f y = \mathrm{Round}(x + y)$
- $x \times_f y = \mathrm{Round}(x \times y)$
- **Basic idea**
  - First compute exact result
  - Make it fit into desired precision
    - Possibly overflow if exponent too large
    - Possibly round to fit into **`frac`**

Rounding

- **Rounding Modes (illustrate with $ rounding)**

	$1.40	**$1.60**	**$1.50**	**$2.50**	**–$1.50**
Towards zero	$1	$1	$1	$2	–$1
Round down (−∞)	$1	$1	$1	$2	–$2
Round up (+∞)	$2	$2	$2	$3	–$1
Nearest Even (default)	$1	$2	$2	$2	–$2

- **What are the advantages of the modes?**

Closer Look at Round-To-Even

- **Default Rounding Mode**
  - Hard to get any other kind without dropping into assembly
  - All others are statistically biased
    - Sum of set of positive numbers will consistently be over- or under-estimated

- **Applying to Other Decimal Places / Bit Positions**
  - When exactly halfway between two possible values
    - Round so that least significant digit is even
  - E.g., round to nearest hundredth

1.2349999	1.23	(Less than half way)
1.2350001	1.24	(Greater than half way)
1.2350000	1.24	(Half way—round up)
1.2450000	1.24	(Half way—round down)

Rounding Binary Numbers

- **Binary Fractional Numbers**
  - "Even" when least significant bit is 0
  - "Half way" when bits to right of rounding position = $100\ldots_2$

- **Examples**
  - Round to nearest 1/4 (2 bits right of binary point)

Value	Binary	Rounded	Action	Rounded Value
2 3/32	10.00011_2	10.00_2	(<1/2—down)	2
2 3/16	10.00110_2	10.01_2	(>1/2—up)	2 1/4
2 7/8	10.11100_2	11.00_2	(1/2—up)	3
2 5/8	10.10100_2	10.10_2	(1/2—down)	2 1/2

FP Multiplication

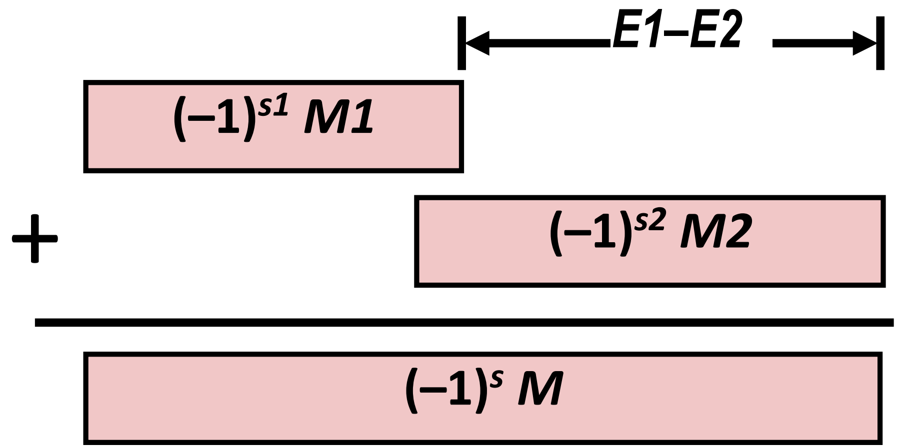
- $(-1)^{s1}\ M1\ \ 2^{E1}\ \ \times\ \ (-1)^{s2}\ M2\ \ 2^{E2}$
- **Exact Result:** $(-1)^{s}\ M\ \ 2^{E}$
  - Sign s: $s1$ ^ $s2$
  - Significand M: $M1 \times M2$
  - Exponent E: $E1 + E2$

- **Fixing**
  - If $M \geq 2$, shift M right, increment E
  - If E out of range, overflow
  - Round M to fit **`frac`** precision

- **Implementation**
  - Biggest chore is multiplying significands

Floating Point Addition

- $(-1)^{s1}\ M1\ \ 2^{E1}\ \ +\ \ (-1)^{s2}\ M2\ \ 2^{E2}$
  - Assume $E1 > E2$
- **Exact Result:** $(-1)^{s}\ M\ \ 2^{E}$
  - Sign *s*, significand *M*:
    - Result of signed align & add
  - Exponent *E*: $E1$



- **Fixing**
  - If $M \geq 2$, shift *M* right, increment *E*
  - if $M < 1$, shift *M* left *k* positions, decrement *E* by *k*
  - Overflow if *E* out of range
  - Round *M* to fit `frac` precision

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Floating Point in C

- **C Guarantees Two Levels**
  - **`float`** single precision
  - **`double`** double precision
- **Conversions/Casting**
  - Casting between **`int`**, **`float`**, and **`double`** changes bit representation
  - **`double`**/**`float`** → **`int`**
    - Truncates fractional part
    - Like rounding toward zero
    - Not defined when out of range or NaN: Generally sets to TMin
  - **`int`** → **`double`**
    - Exact conversion, as long as **`int`** has ≤ 53 bit word size
  - **`int`** → **`float`**
    - Will round according to rounding mode

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Summary

- **IEEE Floating Point has clear mathematical properties**
- **Represents numbers of form M x 2^E**
- **One can reason about operations independent of implementation**
  - As if computed with perfect precision and then rounded
- **Not the same as real arithmetic**
  - Violates associativity/distributivity
  - Makes life difficult for compilers & serious numerical applications programmers

Machine-Level Programming I: Basics

Today: Machine Programming I: Basics

- **History of Intel processors and architectures**
- C, assembly, machine code
- Assembly Basics: Registers, operands, move
- Intro to x86-64

Intel x86 Processors

- **Totally 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 processor. Basis for IBM PC & DOS
- 1MB address space

386	**1985**	**275K**	**16-33**

- First 32 bit processor , referred to as IA32
- Added "flat addressing"
- Capable of running Unix
- 32-bit Linux/gcc uses no instructions introduced in later models

Pentium 4F	**2004**	**125M**	**2800-3800**

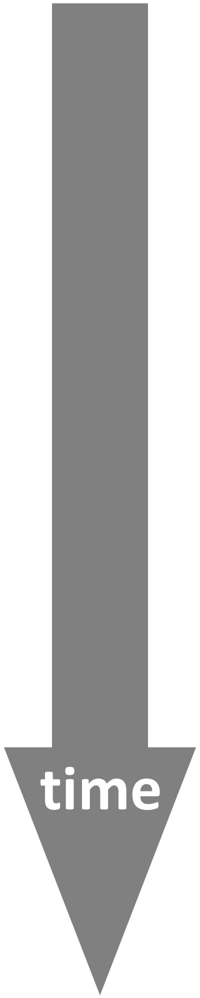
- First 64-bit processor, referred to as x86-64

Core i7	**2008**	**731M**	**2667-3333**

- Our shark machines

Intel x86 Processors: Overview

Architectures	Processors
X86-16	8086
	286
X86-32/IA32	386
	486
	Pentium
MMX	Pentium MMX
SSE	Pentium III
SSE2	Pentium 4
SSE3	Pentium 4E
X86-64 / EM64t	Pentium 4F
	Core 2 Duo
SSE4	Core i7

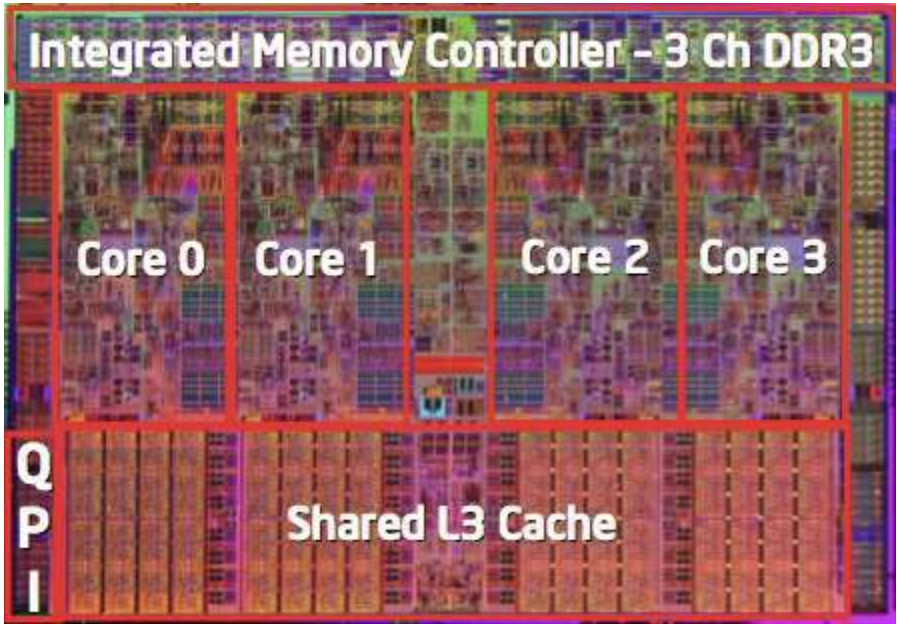


IA: often redefined as latest Intel architecture

Intel x86 Processors, contd.

- **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
    - Parallel operations on 1, 2, and 4-byte data, both integer & FP
  - Instructions to enable more efficient conditional operations
- **Linux/GCC Evolution**
  - Two major steps: 1) support 32-bit 386. 2) support 64-bit x86-64

More Information

- Intel processors (Wikipedia)
- Intel microarchitectures

New Species: ia64, then IPF, then Itanium,…

Name	*Date*	*Transistors*
Itanium	**2001**	**10M**

- First shot at 64-bit architecture: first called IA64
- Radically new instruction set designed for high performance
- Can run existing IA32 programs
  - On-board "x86 engine"
- Joint project with Hewlett-Packard

Itanium 2	**2002**	**221M**

- Big performance boost

Itanium 2 Dual-Core	**2006**	**1.7B**

- **Itanium has not taken off in marketplace**
  - Lack of backward compatibility, no good compiler support, Pentium 4 got too good

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

Intel's 64-Bit

- **Intel Attempted Radical Shift from IA32 to IA64**
  - Totally different architecture (Itanium)
  - Executes IA32 code only as legacy
  - Performance disappointing
- **AMD Stepped 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

- **x86-64/EM64T**
  - The emerging standard

- **Presentation**
  - Book presents IA32 in Sections 3.1—3.12
  - Covers x86-64 in 3.13
  - We will cover both simultaneously
  - Some labs will be based on x86-64, others on IA32

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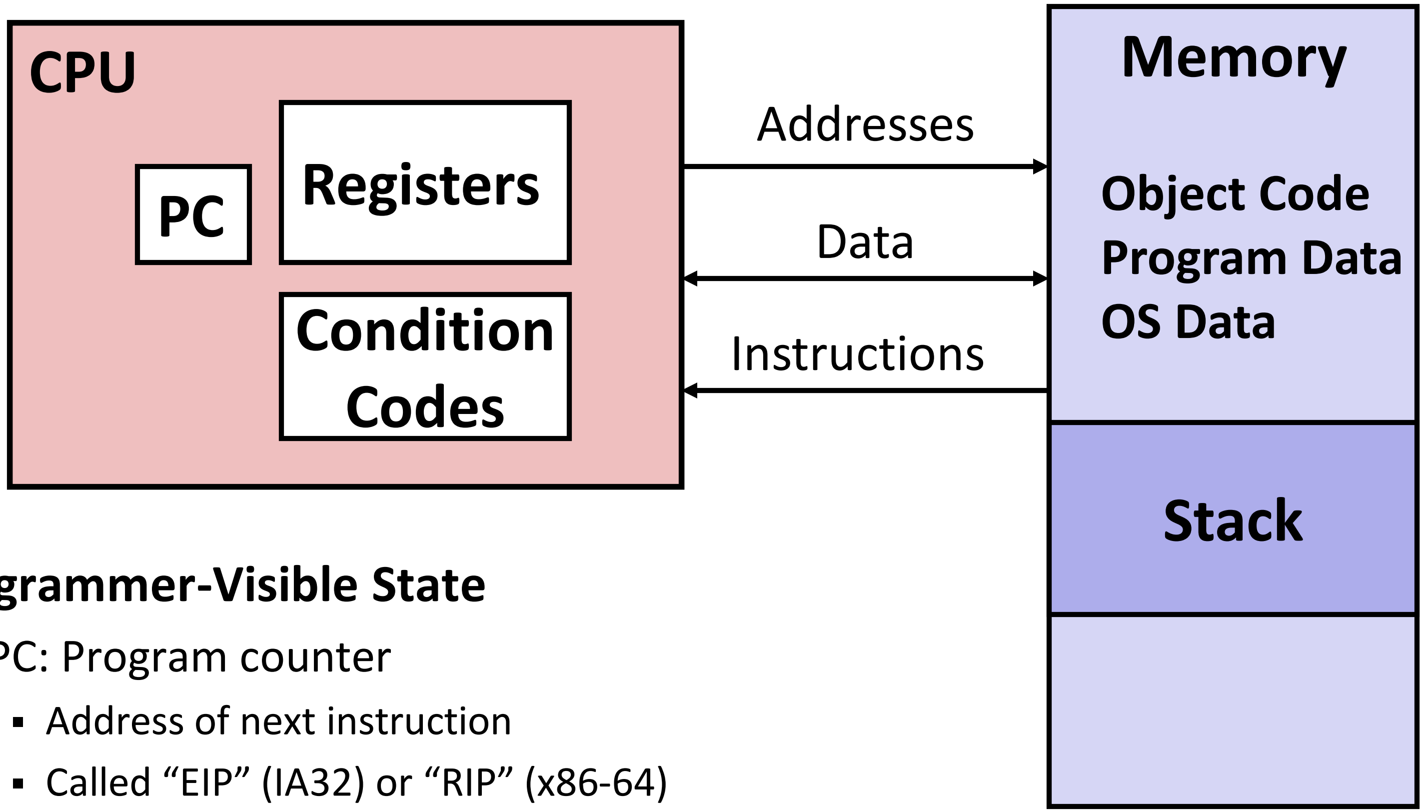
Definitions

- **Architecture: (also instruction set architecture: ISA) The parts of a processor design that one needs to understand to write assembly code.**
  - Examples: instruction set specification, registers.
- **Microarchitecture: Implementation of the architecture.**
  - Examples: cache sizes and core frequency.

- **Example ISAs (Intel): x86, IA, IPF**

Assembly Programmer's View

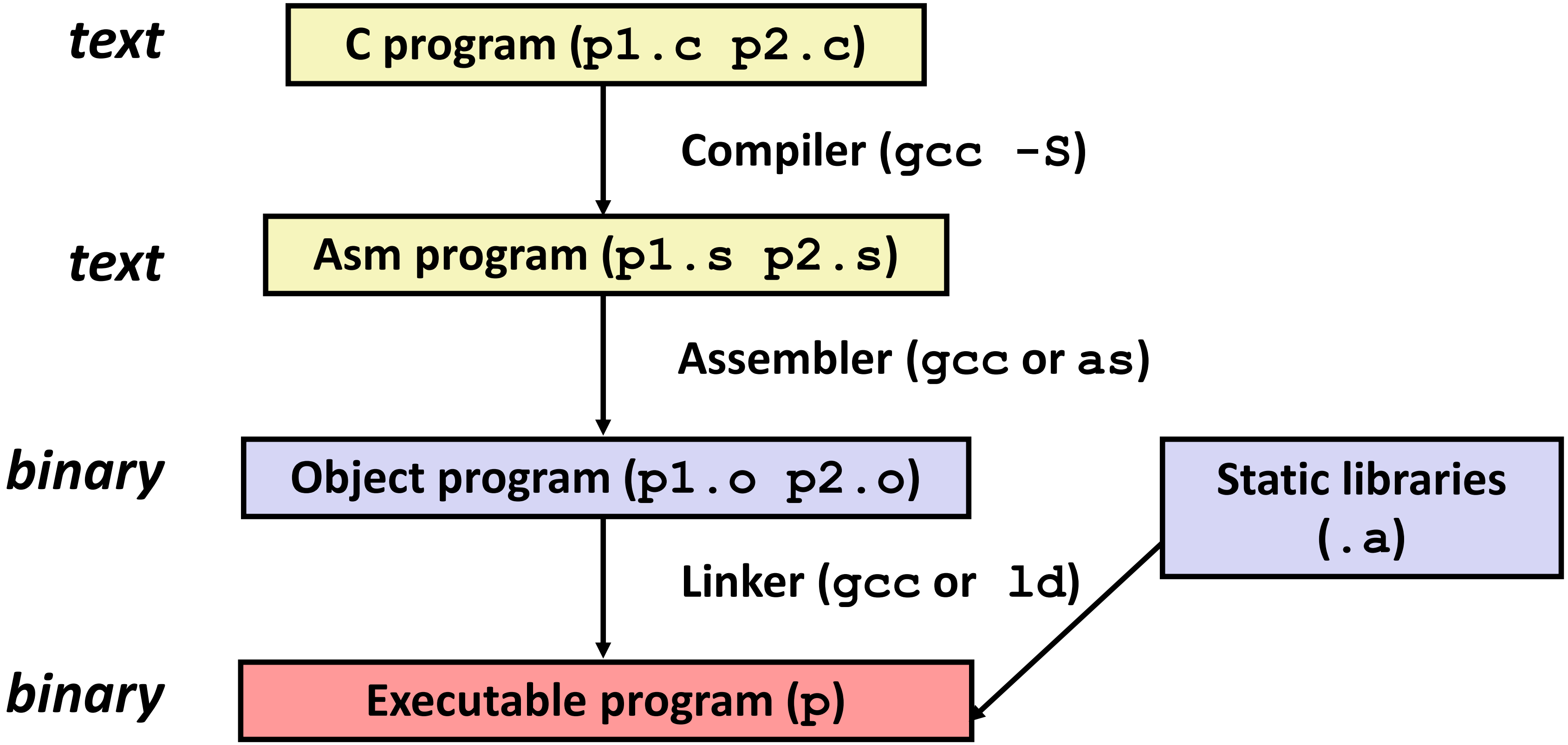


- **Programmer-Visible State**
  - PC: Program counter
    - Address of next instruction
    - Called "EIP" (IA32) or "RIP" (x86-64)
  - Register file
    - Heavily used program data
  - Condition codes
    - Store status information about most recent arithmetic operation
    - Used for conditional branching

- **Memory**
  - Byte addressable array
  - Code, user data, (some) OS data
  - Includes stack used to support procedures

Turning C into Object Code

- Code in files `p1.c p2.c`
- Compile with command: `gcc -O1 p1.c p2.c -o p`
  - Use basic optimizations (`-O1`)
  - Put resulting binary in file `p`



Compiling Into Assembly

C Code

```
int sum(int x, int y)
{
  int t = x+y;
  return t;
}
```

Generated IA32 Assembly

```
sum:
    pushl %ebp
    movl %esp,%ebp
    movl 12(%ebp),%eax
    addl 8(%ebp),%eax
    popl %ebp
    ret
```

Some compilers use instruction "`leave`"

Obtain with command

```
/usr/local/bin/gcc –O1 -S code.c
```

Produces file `code.s`

Assembly Characteristics: Data Types

- **"Integer" data of 1, 2, or 4 bytes**
  - Data values
  - Addresses (untyped pointers)
- **Floating point data of 4, 8, or 10 bytes**
- **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

Code for `sum`

```
0x401040 <sum>:
    0x55
    0x89
    0xe5
    0x8b
    0x45
    0x0c
    0x03
    0x45
    0x08
    0x5d
    0xc3
```

- **Total of 11 bytes**
- **Each instruction 1, 2, or 3 bytes**
- **Starts at address `0x401040`**

- **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

Machine Instruction Example

```
int t = x+y;
```

```
addl 8(%ebp),%eax
```

Similar to expression:

`x += y`

More precisely:

```
int eax;
int *ebp;
eax += ebp[2]
```

```
0x80483ca:   03 45 08
```

- **C Code**
  - Add two signed integers
- **Assembly**
  - Add 2 4-byte integers
    - "Long" words in GCC parlance
    - Same instruction whether signed or unsigned
  - Operands:

`x:`	Register	`%eax`
`y:`	Memory	`M[%ebp+8]`
`t:`	Register	`%eax`

    – Return function value in `%eax`

- **Object Code**
  - 3-byte instruction
  - Stored at address `0x80483ca`

Disassembling Object Code

Disassembled

```
080483c4 <sum>:
 80483c4:   55          push   %ebp
 80483c5:   89 e5       mov    %esp,%ebp
 80483c7:   8b 45 0c    mov    0xc(%ebp),%eax
 80483ca:   03 45 08    add    0x8(%ebp),%eax
 80483cd:   5d          pop    %ebp
 80483ce:   c3          ret
```

- **Disassembler**

  `objdump -d p`

  - 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

```
0x401040:
    0x55
    0x89
    0xe5
    0x8b
    0x45
    0x0c
    0x03
    0x45
    0x08
    0x5d
    0xc3
```

Disassembled

```
Dump of assembler code for function sum:
0x080483c4 <sum+0>:     push   %ebp
0x080483c5 <sum+1>:     mov    %esp,%ebp
0x080483c7 <sum+3>:     mov    0xc(%ebp),%eax
0x080483ca <sum+6>:     add    0x8(%ebp),%eax
0x080483cd <sum+9>:     pop    %ebp
0x080483ce <sum+10>:    ret
```

- **Within gdb Debugger**

  `gdb p`

  `disassemble sum`

  - Disassemble procedure

  `x/11xb sum`

  - Examine the 11 bytes starting at `sum`

What Can be Disassembled?

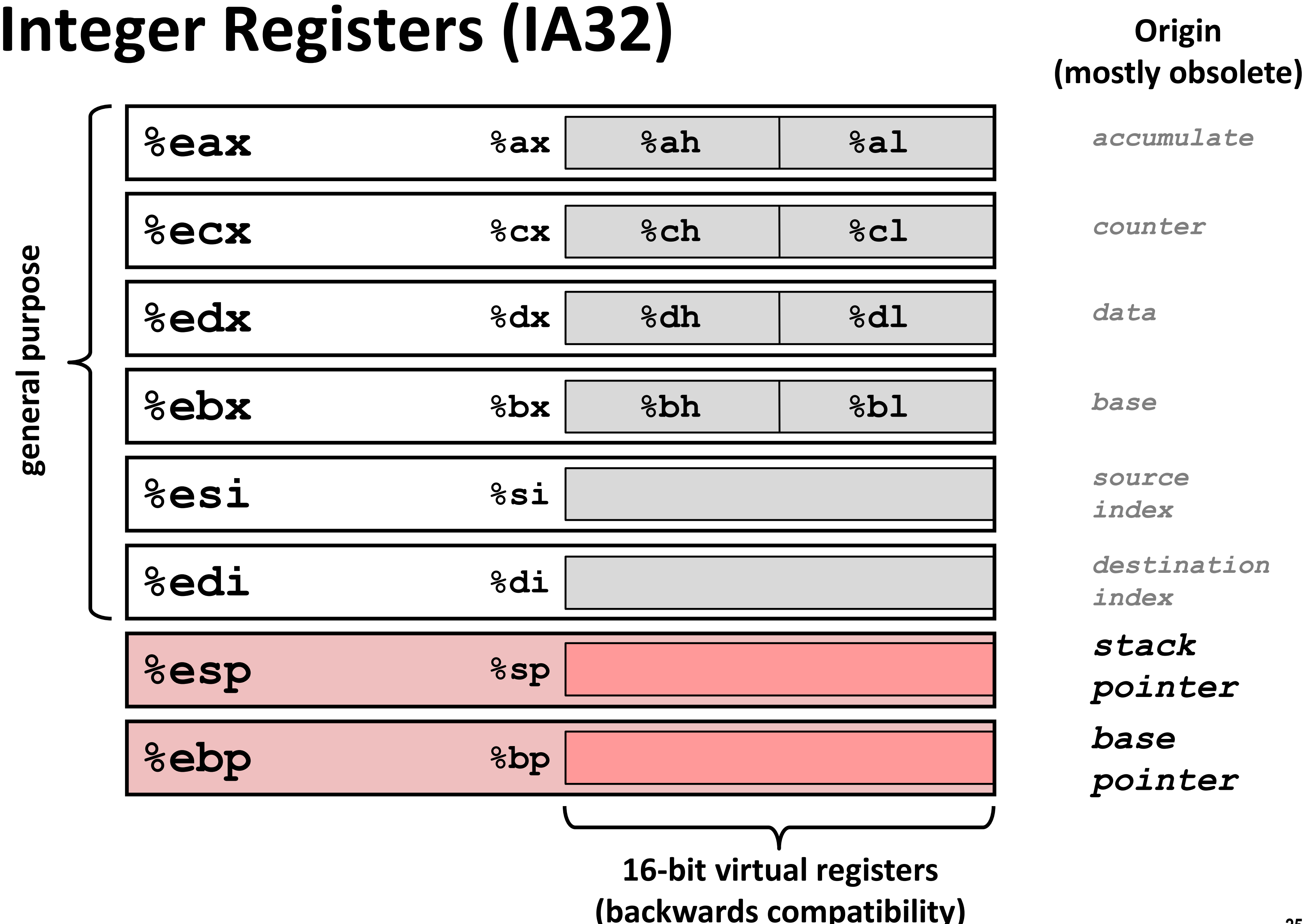
```
% objdump -d WINWORD.EXE

WINWORD.EXE:   file format pei-i386

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

30001000 <.text>:
30001000:  55             push   %ebp
30001001:  8b ec          mov    %esp,%ebp
30001003:  6a ff          push   $0xffffffff
30001005:  68 90 10 00 30 push   $0x30001090
3000100a:  68 91 dc 4c 30 push   $0x304cdc91
```

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

Today: Machine Programming I: Basics

- History of Intel processors and architectures
- C, assembly, machine code
- **Assembly Basics: Registers, operands, move**
- Intro to x86-64

Integer Registers (IA32)



Moving Data: IA32

- **Moving Data**

  `movl` ***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 8 integer registers
    - Example: **`%eax, %edx`**
    - But **`%esp`** and **`%ebp`** reserved for special use
    - Others have special uses for particular instructions
  - ***Memory:*** 4 consecutive bytes of memory at address given by register
    - Simplest example: **`(%eax)`**
    - Various other "address modes"

`%eax`
`%ecx`
`%edx`
`%ebx`
`%esi`
`%edi`
`%esp`
`%ebp`

`movl` Operand Combinations

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

Cannot do memory-memory transfer with a single instruction

Simple Memory Addressing Modes

- **Normal (R) Mem[Reg[R]]**
  - Register R specifies memory address

```
movl (%ecx),%eax
```

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

```
movl 8(%ebp),%edx
```

Using Simple Addressing Modes

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

```
swap:
   pushl %ebp
   movl  %esp,%ebp
   pushl %ebx

   movl  8(%ebp), %edx
   movl  12(%ebp), %ecx
   movl  (%edx), %ebx
   movl  (%ecx), %eax
   movl  %eax, (%edx)
   movl  %ebx, (%ecx)

   popl  %ebx
   popl  %ebp
   ret
```

Set Up

Body

Finish

Using Simple Addressing Modes

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

```
swap:
   pushl %ebp
   movl  %esp,%ebp
   pushl %ebx

   movl  8(%ebp), %edx
   movl  12(%ebp), %ecx
   movl  (%edx), %ebx
   movl  (%ecx), %eax
   movl  %eax, (%edx)
   movl  %ebx, (%ecx)

   popl  %ebx
   popl  %ebp
   ret
```

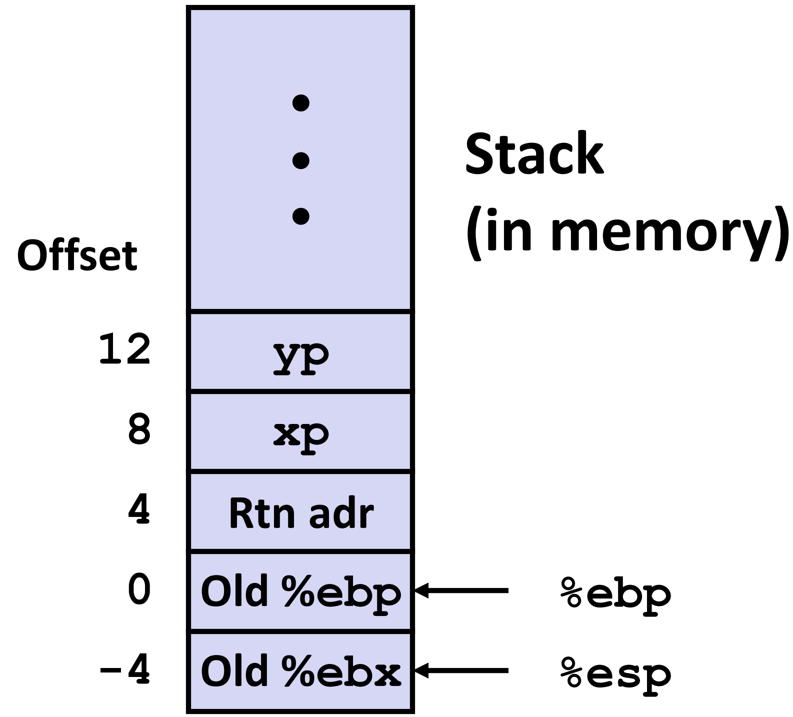
Set Up

Body

Finish

Understanding Swap

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



Register	Value
%edx	xp
%ecx	yp
%ebx	t0
%eax	t1

```
movl  8(%ebp), %edx    # edx = xp
movl  12(%ebp), %ecx   # ecx = yp
movl  (%edx), %ebx     # ebx = *xp (t0)
movl  (%ecx), %eax     # eax = *yp (t1)
movl  %eax, (%edx)     # *xp = t1
movl  %ebx, (%ecx)     # *yp = t0
```

Understanding Swap

%eax	
%edx	
%ecx	
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl   8(%ebp), %edx     # edx = xp
movl   12(%ebp), %ecx    # ecx = yp
movl   (%edx), %ebx      # ebx = *xp (t0)
movl   (%ecx), %eax      # eax = *yp (t1)
movl   %eax, (%edx)      # *xp = t1
movl   %ebx, (%ecx)      # *yp = t0
```

Understanding Swap

Register	Value
%eax	
%edx	0x124
%ecx	
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl  8(%ebp), %edx    # edx = xp
movl  12(%ebp), %ecx   # ecx = yp
movl  (%edx), %ebx     # ebx = *xp (t0)
movl  (%ecx), %eax     # eax = *yp (t1)
movl  %eax, (%edx)     # *xp = t1
movl  %ebx, (%ecx)     # *yp = t0
```

Understanding Swap

Register	Value
%eax	
%edx	0x124
%ecx	0x120
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset	Value	Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl   8(%ebp), %edx     # edx = xp
movl   12(%ebp), %ecx    # ecx = yp
movl   (%edx), %ebx      # ebx = *xp (t0)
movl   (%ecx), %eax      # eax = *yp (t1)
movl   %eax, (%edx)      # *xp = t1
movl   %ebx, (%ecx)      # *yp = t0
```

Understanding Swap

Register	Value
%eax	
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl  8(%ebp), %edx    # edx = xp
movl  12(%ebp), %ecx   # ecx = yp
movl  (%edx), %ebx     # ebx = *xp (t0)
movl  (%ecx), %eax     # eax = *yp (t1)
movl  %eax, (%edx)     # *xp = t1
movl  %ebx, (%ecx)     # *yp = t0
```

Understanding Swap

Register	Value
%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl  8(%ebp), %edx    # edx = xp
movl  12(%ebp), %ecx   # ecx = yp
movl  (%edx), %ebx     # ebx = *xp (t0)
movl  (%ecx), %eax     # eax = *yp (t1)
movl  %eax, (%edx)     # *xp = t1
movl  %ebx, (%ecx)     # *yp = t0
```

Understanding Swap

%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		456	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
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	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl   8(%ebp), %edx     # edx = xp
movl   12(%ebp), %ecx    # ecx = yp
movl   (%edx), %ebx      # ebx = *xp (t0)
movl   (%ecx), %eax      # eax = *yp (t1)
movl   %eax, (%edx)      # *xp = t1
movl   %ebx, (%ecx)      # *yp = t0
```

Understanding Swap

Register	Value
%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		456	0x124
		123	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl   8(%ebp), %edx     # edx = xp
movl   12(%ebp), %ecx    # ecx = yp
movl   (%edx), %ebx      # ebx = *xp (t0)
movl   (%ecx), %eax      # eax = *yp (t1)
movl   %eax, (%edx)      # *xp = t1
movl   %ebx, (%ecx)      # *yp = t0
```

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 8 integer registers
  - Ri: Index register: Any, except for **`%esp`**
    - Unlikely you'd use **`%ebp`**, either
  - 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]]**

Today: Machine Programming I: Basics

- History of Intel processors and architectures
- C, assembly, machine code
- Assembly Basics: Registers, operands, move
- **Intro to x86-64**

Data Representations: IA32 + x86-64

- **Sizes of C Objects (in Bytes)**

C Data Type	*Generic 32-bit*	*Intel IA32*	*x86-64*
unsigned	4	4	4
int	4	4	4
long int	4	4	8
char	1	1	1
short	2	2	2
float	4	4	4
double	8	8	8
long double	8	10/12	16
char *	4	4	8

  – *Or any other pointer*

x86-64 Integer Registers

`%rax`	`%eax`	`%r8`	`%r8d`
`%rbx`	`%ebx`	`%r9`	`%r9d`
`%rcx`	`%ecx`	`%r10`	`%r10d`
`%rdx`	`%edx`	`%r11`	`%r11d`
`%rsi`	`%esi`	`%r12`	`%r12d`
`%rdi`	`%edi`	`%r13`	`%r13d`
`%rsp`	`%esp`	`%r14`	`%r14d`
`%rbp`	`%ebp`	`%r15`	`%r15d`

- Extend existing registers. Add 8 new ones.
- Make **`%ebp`/`%rbp`** general purpose

Instructions

- **Long word `l` (4 Bytes) ↔ Quad word `q` (8 Bytes)**

- **New instructions:**
  - **`movl` → `movq`**
  - **`addl` → `addq`**
  - **`sall` → `salq`**
  - etc.

- **32-bit instructions that generate 32-bit results**
  - Set higher order bits of destination register to 0
  - Example: **`addl`**

32-bit code for swap

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

```
swap:
  pushl %ebp
  movl  %esp,%ebp
  pushl %ebx

  movl   8(%ebp), %edx
  movl   12(%ebp), %ecx
  movl   (%edx), %ebx
  movl   (%ecx), %eax
  movl   %eax, (%edx)
  movl   %ebx, (%ecx)

  popl   %ebx
  popl   %ebp
  ret
```

Set Up

Body

Finish

64-bit code for swap

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

```
swap:
                                  Set Up

    movl   (%rdi), %edx
    movl   (%rsi), %eax           Body
    movl   %eax, (%rdi)
    movl   %edx, (%rsi)

    ret                           Finish
```

- **Operands passed in registers (why useful?)**
  - First (**`xp`**) in **`%rdi`**, second (**`yp`**) in **`%rsi`**
  - 64-bit pointers
- **No stack operations required**
- **32-bit data**
  - Data held in registers **`%eax`** and **`%edx`**
  - **`movl`** operation

64-bit code for long int swap

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

```
swap_l:
                                  Set Up
   movq    (%rdi), %rdx
   movq    (%rsi), %rax           Body
   movq    %rax, (%rdi)
   movq    %rdx, (%rsi)

   ret                            Finish
```

- **64-bit data**
  - Data held in registers `%rax` and `%rdx`
  - `movq` operation
    - "q" stands for quad-word

Machine Programming I: Summary

- **History of Intel processors and architectures**
  - Evolutionary design leads to many quirks and artifacts
- **C, assembly, machine code**
  - Compiler must transform statements, expressions, procedures into low-level instruction sequences
- **Assembly Basics: Registers, operands, move**
  - The x86 move instructions cover wide range of data movement forms
- **Intro to x86-64**
  - A major departure from the style of code seen in IA32

Machine-Level Programming II: Arithmetic & Control

Today

- **Complete addressing mode, address computation (leal)**
- Arithmetic operations
- Control: Condition codes
- Conditional branches
- While loops

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 8 integer registers
  - Ri: Index register: Any, except for `%esp`
    - Unlikely you'd use `%ebp`, either
  - 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 Instruction

- `leal` ***Src,Dest***
  - *Src* is address mode expression
  - Set *Dest* 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**

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

Converted to ASM by compiler:

```
leal (%eax,%eax,2), %eax   ;t <- x+x*2
sall $2, %eax              ;return t<<2
```

Today

- Complete addressing mode, address computation (leal)
- **Arithmetic operations**
- Control: Condition codes
- Conditional branches
- While loops

Some Arithmetic Operations

- **Two Operand Instructions:**

Format		*Computation*	
`addl`	*Src,Dest*	Dest = Dest + Src	
`subl`	*Src,Dest*	Dest = Dest – Src	
`imull`	*Src,Dest*	Dest = Dest * Src	
`sall`	*Src,Dest*	Dest = Dest << Src	*Also called shll*
`sarl`	*Src,Dest*	Dest = Dest >> Src	*Arithmetic*
`shrl`	*Src,Dest*	Dest = Dest >> Src	*Logical*
`xorl`	*Src,Dest*	Dest = Dest ^ Src	
`andl`	*Src,Dest*	Dest = Dest & Src	
`orl`	*Src,Dest*	Dest = Dest | Src	

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

Some Arithmetic Operations

- **One Operand Instructions**

`incl`	*Dest*	*Dest = Dest + 1*
`decl`	*Dest*	*Dest = Dest – 1*
`negl`	*Dest*	*Dest = – Dest*
`notl`	*Dest*	*Dest = ~Dest*

- **See book for more instructions**

Arithmetic Expression Example

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

```
arith:
  pushl  %ebp
  movl   %esp, %ebp

  movl   8(%ebp), %ecx
  movl   12(%ebp), %edx
  leal   (%edx,%edx,2), %eax
  sall   $4, %eax
  leal   4(%ecx,%eax), %eax
  addl   %ecx, %edx
  addl   16(%ebp), %edx
  imull  %edx, %eax

  popl   %ebp
  ret
```

Set Up

Body

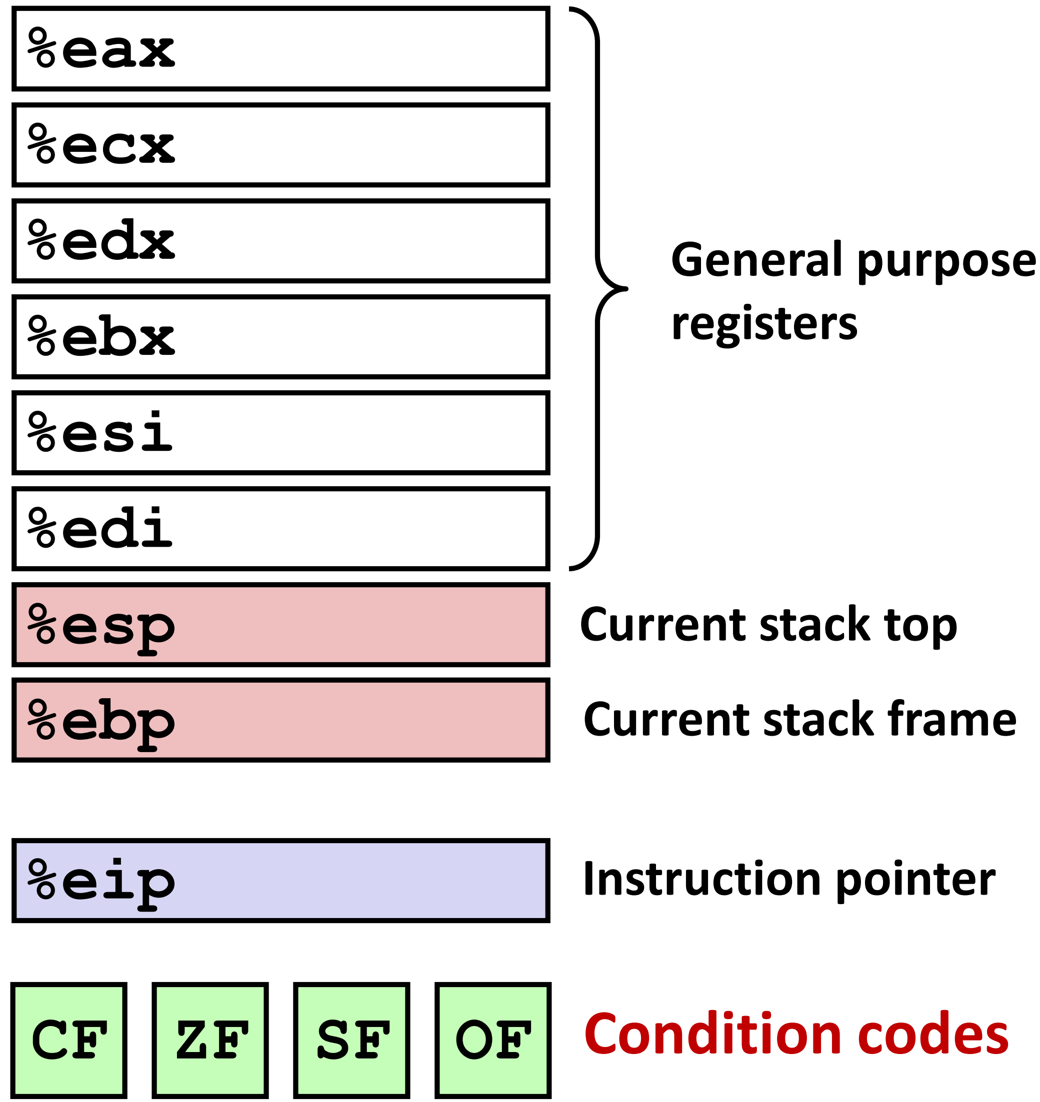
Finish

Today

- Complete addressing mode, address computation (leal)
- Arithmetic operations
- Control: Condition codes
- Conditional branches
- Loops

Processor State (IA32, Partial)

- **Information about currently executing program**
  - Temporary data
    (**`%eax`**, …)
  - Location of runtime stack
    (**`%ebp`**,**`%esp`**)
  - Location of current code control point
    (**`%eip`**, …)
  - 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: **`addl/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 `lea` instruction**
- **Full documentation (IA32), link on course website**

Condition Codes (Explicit Setting: Compare)

- **Explicit Setting by Compare Instruction**
  - **`cmpl/cmpq`** *Src2*, *Src1*
  - **`cmpl 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**
  - **`testl`/`testq`** *Src2*, *Src1*
    `testl 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 single byte based on combinations of condition codes

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)

Reading Condition Codes (Cont.)

- **SetX Instructions:**
  - Set single byte based on combination of condition codes
- **One of 8 addressable byte registers**
  - Does not alter remaining 3 bytes
  - Typically use **`movzbl`** to finish job

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

Body

```
movl 12(%ebp),%eax    # eax = y
cmpl %eax,8(%ebp)     # Compare x : y
setg %al              # al = x > y
movzbl %al,%eax       # Zero rest of %eax
```

%eax	%ah	%al
%ecx	%ch	%cl
%edx	%dh	%dl
%ebx	%bh	%bl
%esi		
%edi		
%esp		
%ebp		

Reading Condition Codes: x86-64

- **SetX Instructions:**
  - Set single byte based on combination of condition codes
  - Does not alter remaining 3 bytes

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

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

Bodies

```
cmpl %esi, %edi
setg %al
movzbl %al, %eax
```

```
cmpq %rsi, %rdi
setg %al
movzbl %al, %eax
```

Is `%rax` zero?

Yes: 32-bit instructions set high order 32 bits to 0!

Today

- Complete addressing mode, address computation (leal)
- Arithmetic operations
- x86-64
- Control: Condition codes
- **Conditional branches & Moves**
- Loops

Jumping

- **jX Instructions**
  - Jump to different part of code depending on condition codes

jX	Condition	Description
`jmp`	`1`	Unconditional
`je`	`ZF`	Equal / Zero
`jne`	`~ZF`	Not Equal / Not Zero
`js`	`SF`	Negative
`jns`	`~SF`	Nonnegative
`jg`	`~(SF^OF)&~ZF`	Greater (Signed)
`jge`	`~(SF^OF)`	Greater or Equal (Signed)
`jl`	`(SF^OF)`	Less (Signed)
`jle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`ja`	`~CF&~ZF`	Above (unsigned)
`jb`	`CF`	Below (unsigned)

Conditional Branch Example

```
int absdiff(int x, int y)
{
    int result;
    if (x > y) {
      result = x-y;
    } else {
      result = y-x;
    }
    return result;
}
```

```
absdiff:
    pushl   %ebp                Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx
    movl    12(%ebp), %eax
    cmpl    %eax, %edx          Body1
    jle     .L6
    subl    %eax, %edx
    movl    %edx, %eax          Body2a
    jmp .L7
.L6:
    subl %edx, %eax             Body2b
.L7:
    popl %ebp
    ret                         Finish
```

Conditional Branch Example (Cont.)

```
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
  goto Exit;
Else:
  result = y-x;
Exit:
  return result;
}
```

- **C allows "goto" as means of transferring control**
  - Closer to machine-level programming style
- **Generally considered bad coding style**

```
absdiff:
    pushl   %ebp             } Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx    } Body1
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L6
    subl    %eax, %edx       } Body2a
    movl    %edx, %eax
    jmp .L7
.L6:
    subl %edx, %eax          } Body2b
.L7:
    popl %ebp                } Finish
    ret
```

Using Conditional Moves

- **Conditional Move Instructions**
  - Instruction supports:

    if (Test) Dest ← Src
  - Supported in post-1995 x86 processors
  - GCC does not always use them
    - Wants to preserve compatibility with ancient processors
    - Enabled for x86-64
    - Use switch `-march=686` for IA32
- **Why?**
  - Branches are very disruptive to instruction flow through pipelines
  - Conditional move do not require control transfer

C Code

```
val = Test
    ? Then_Expr
    : Else_Expr;
```

Goto Version

```
  tval = Then_Expr;
  result = Else_Expr;
  t = Test;
  if (t) result = tval;
  return result;
```

Conditional Move Example: x86-64

```
int absdiff(int x, int y) {
    int result;
    if (x > y) {
        result = x-y;
    } else {
        result = y-x;
    }
    return result;
}
```

x in %edi

y in %esi

```
absdiff:
  movl    %edi, %edx
  subl    %esi, %edx   # tval = x-y
  movl    %esi, %eax
  subl    %edi, %eax   # result = y-x
  cmpl    %esi, %edi   # Compare x:y
  cmovg   %edx, %eax   # If >, result = tval
  ret
```

Today

- Complete addressing mode, address computation (leal)
- Arithmetic operations
- x86-64
- Control: Condition codes
- Conditional branches and moves
- **Loops**

"Do-While" Loop Example

C Code

```
int pcount_do(unsigned x)
{
  int result = 0;
  do {
    result += x & 0x1;
    x >>= 1;
  } while (x);
  return result;
}
```

Goto Version

```
int pcount_do(unsigned x)
{
  int result = 0;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
  return result;
}
```

- Count number of 1's in argument x ("popcount")
- Use conditional branch to either continue looping or to exit loop

"Do-While" Loop Compilation

Goto Version

```
int pcount_do(unsigned x)  {
  int result = 0;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
  return result;
}
```

- Registers:

%edx	x
%ecx	result

```
  movl   $0, %ecx      #   result = 0
.L2:     # loop:
  movl   %edx, %eax
  andl   $1, %eax      #   t = x & 1
  addl   %eax, %ecx    #   result += t
  shrl   %edx          #   x >>= 1
  jne    .L2           #   If !0, goto loop
```

General "Do-While" Translation

C Code

```
do
   Body
   while (Test);
```

Goto Version

```
loop:
   Body
   if (Test)
      goto loop
```

- **Body:** {
  Statement$_1$;
  Statement$_2$;
  …
  Statement$_n$;
  }

- **Test returns integer**
  - = 0 interpreted as false
  - ≠ 0 interpreted as true

"While" Loop Example

C Code

```
int pcount_while(unsigned x) {
  int result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Goto Version

```
int pcount_do(unsigned x)  {
  int result = 0;
  if (!x) goto done;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
done:
  return result;
}
```

- Is this code equivalent to the do-while version?

General "While" Translation

While version

```
while (Test)
  Body
```

Do-While Version

```
  if (!Test)
    goto done;
  do
    Body
    while(Test);
done:
```

Goto Version

```
  if (!Test)
    goto done;
loop:
  Body
  if (Test)
    goto loop;
done:
```

“For” Loop Example

C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

- Is this code equivalent to other versions?

"For" Loop Form

General Form

```
for (Init; Test; Update )

    Body
```

```
for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned mask = 1 << i;
  result += (x & mask) != 0;
}
```

"For" Loop → While Loop

For Version

```
for (Init; Test; Update )
    Body
```

While Version

```
Init;
while (Test ) {
    Body
    Update;
}
```

"For" Loop → … → Goto

For Version

```
for (Init; Test; Update )
    Body
```

While Version

```
Init;
while (Test ) {
    Body
    Update;
}
```

```
  Init;
  if (!Test)
    goto done;
  do
    Body
    Update
  while(Test) ;
done:
```

```
  Init;
  if (!Test)
    goto done;
loop:
  Body
  Update
  if (Test)
    goto loop;
done:
```

"For" Loop Conversion Example

C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

Goto Version

```
int pcount_for_gt(unsigned x) {
  int i;
  int result = 0;
  i = 0;                        Init
  if (!(i < WSIZE))             ! Test
    goto done;
 loop:
  {                             Body
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  i++;  Update
  if (i < WSIZE)  Test
    goto loop;
 done:
  return result;
}
```

- Initial test can be optimized away

Summary

- **Today**
  - Complete addressing mode, address computation (leal)
  - Arithmetic operations
  - Control: Condition codes
  - Conditional branches & conditional moves
  - Loops
- **Next Time**
  - Switch statements
  - Stack
  - Call / return
  - Procedure call discipline

Machine-Level Programming III: Switch Statements and IA32 Procedures

Today

- **Switch statements**
- **IA 32 Procedures**
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

```
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

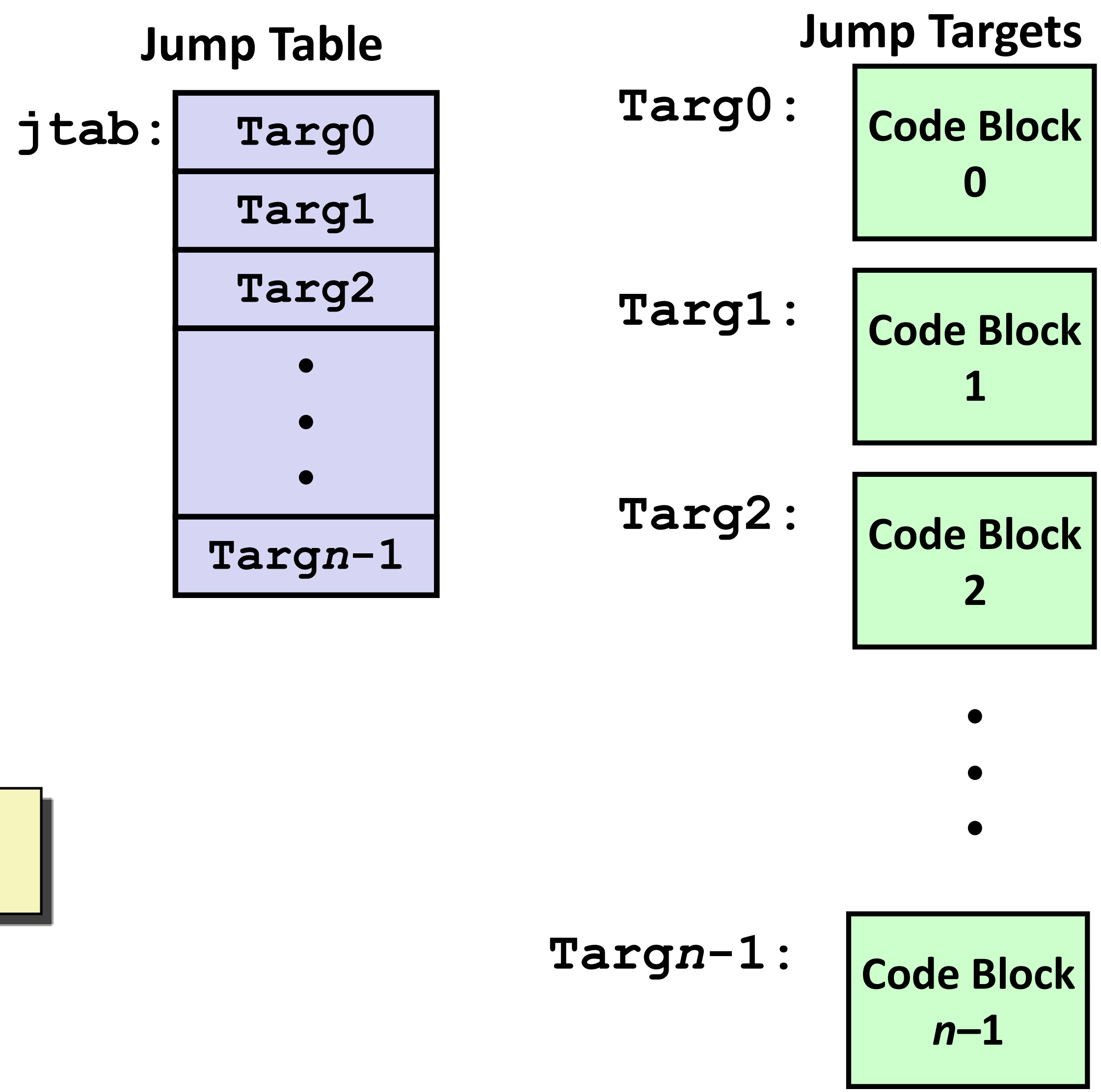
Switch Statement Example

- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

Jump Table Structure

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```



Approximate Translation

```
target = JTab[x];
goto *target;
```

Switch Statement Example (IA32)

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch(x) {
      . . .
    }
    return w;
}
```

Jump table

```
.section    .rodata
  .align 4
.L7:
  .long     .L2 # x = 0
  .long     .L3 # x = 1
  .long     .L4 # x = 2
  .long     .L5 # x = 3
  .long     .L2 # x = 4
  .long     .L6 # x = 5
  .long     .L6 # x = 6
```

Setup:

```
switch_eg:
  pushl  %ebp              # Setup
  movl   %esp, %ebp        # Setup
  movl   8(%ebp), %eax     # eax = x
  cmpl   $6, %eax          # Compare x:6
  ja     .L2               # If unsigned > goto default
  jmp    *.L7(,%eax,4)     # Goto *JTab[x]
```

Indirect jump

Assembly Setup Explanation

- **Table Structure**
  - Each target requires 4 bytes
  - Base address at **.L7**

- **Jumping**
  - **Direct: jmp .L2**
  - Jump target is denoted by label **.L2**

  - **Indirect: jmp *.L7(,%eax,4)**
  - Start of jump table: **.L7**
  - Must scale by factor of 4 (labels have 32-bits = 4 Bytes on IA32)
  - Fetch target from effective Address **.L7 + eax*4**
    - Only for $0 \le \mathbf{x} \le 6$

Jump table

```
.section    .rodata
  .align 4
.L7:
  .long     .L2 # x = 0
  .long     .L3 # x = 1
  .long     .L4 # x = 2
  .long     .L5 # x = 3
  .long     .L2 # x = 4
  .long     .L6 # x = 5
  .long     .L6 # x = 6
```

x86-64 Switch Implementation

- Same general idea, adapted to 64-bit code
- Table entries 64 bits (pointers)
- Cases use revised code

```
switch(x) {
case 1:       // .L3
    w = y*z;
    break;
  . . .
}
```

```
.L3:
  movq    %rdx, %rax
  imulq   %rsi, %rax
  ret
```

Jump Table

```
  .section  .rodata
  .align 8
.L7:
  .quad     .L2     # x = 0
  .quad     .L3     # x = 1
  .quad     .L4     # x = 2
  .quad     .L5     # x = 3
  .quad     .L2     # x = 4
  .quad     .L6     # X = 5
  .quad     .L6     # x = 6
```

IA32 Object Code

- **Setup**
  - Label `.L2` becomes address `0x8048422`
  - Label `.L7` becomes address `0x8048660`

Assembly Code

```
switch_eg:
  . . .
  ja      .L2            # If unsigned > goto default
  jmp     *.L7(,%eax,4)  # Goto *JTab[x]
```

Disassembled Object Code

```
08048410 <switch_eg>:
 . . .
 8048419:77 07                  ja     8048422 <switch_eg+0x12>
 804841b:ff 24 85 60 86 04 08   jmp    *0x8048660(,%eax,4)
```

Summarizing

- **C Control**
  - if-then-else
  - do-while
  - while, for
  - switch
- **Assembler Control**
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler generates code sequence to implement more complex control
- **Standard Techniques**
  - Loops converted to do-while form
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees

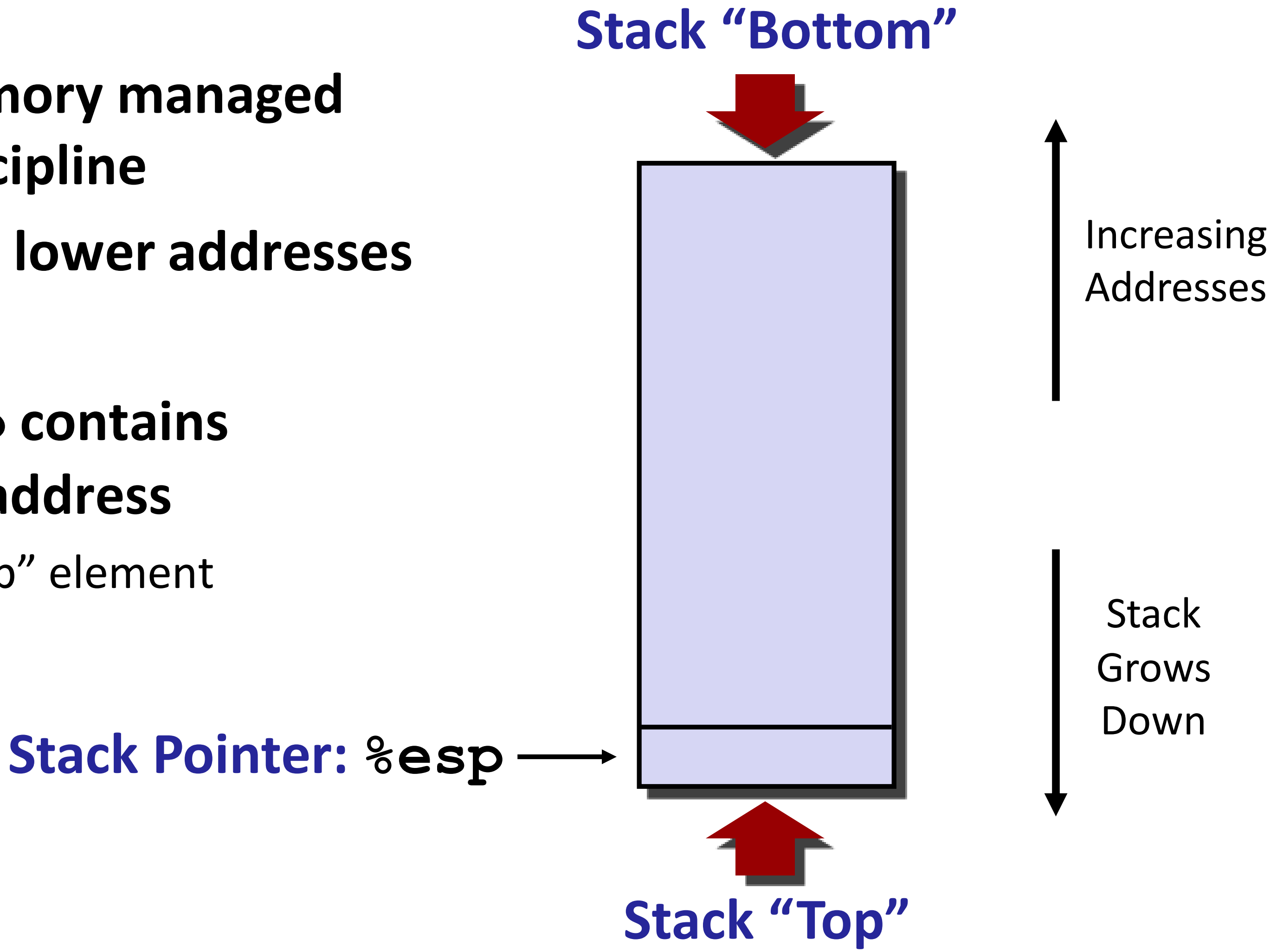
Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

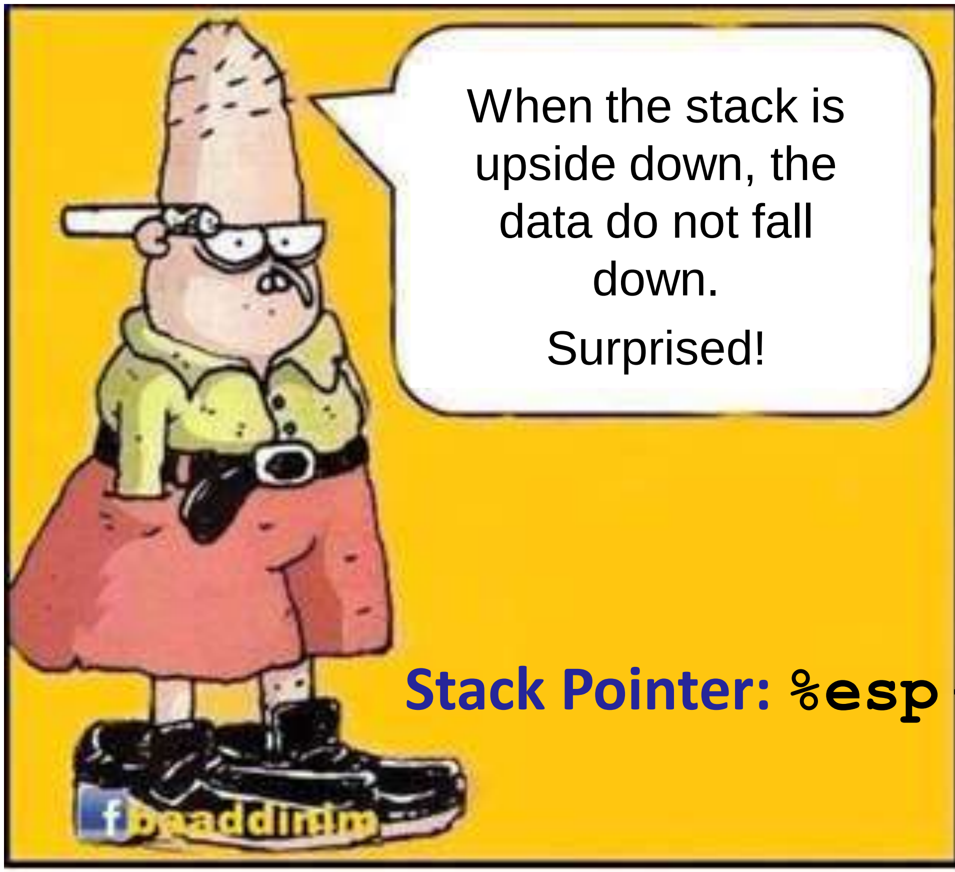
IA32 Stack

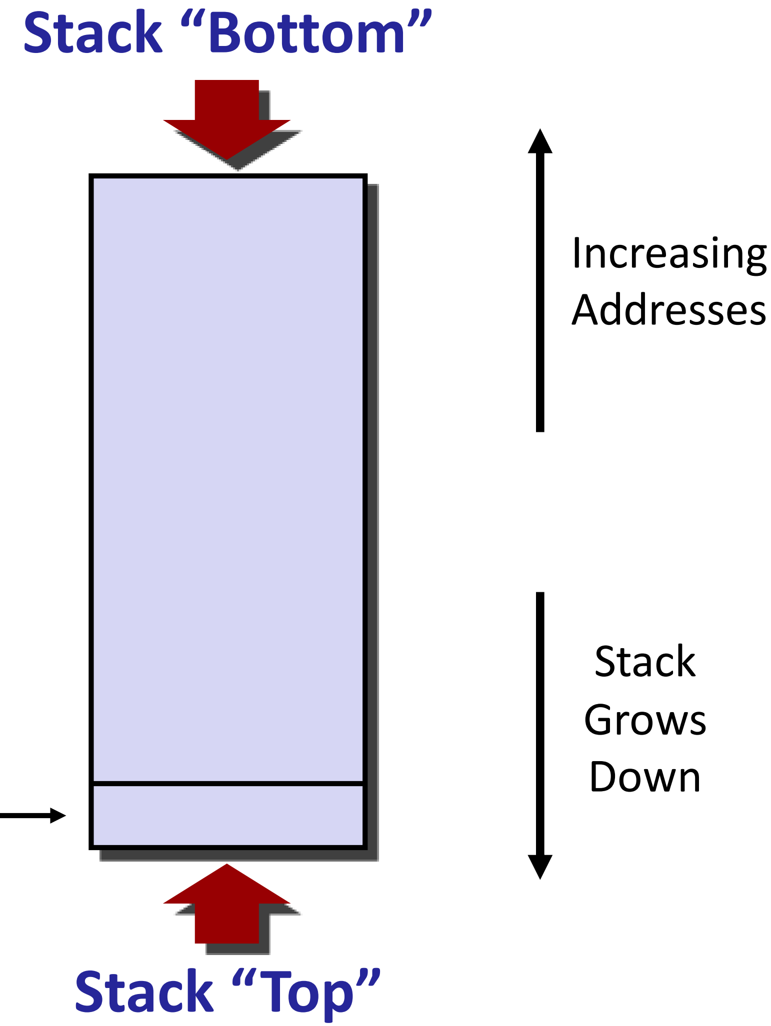
- Region of memory managed with stack discipline
- Grows toward lower addresses

- Register `%esp` contains lowest stack address
  - address of "top" element



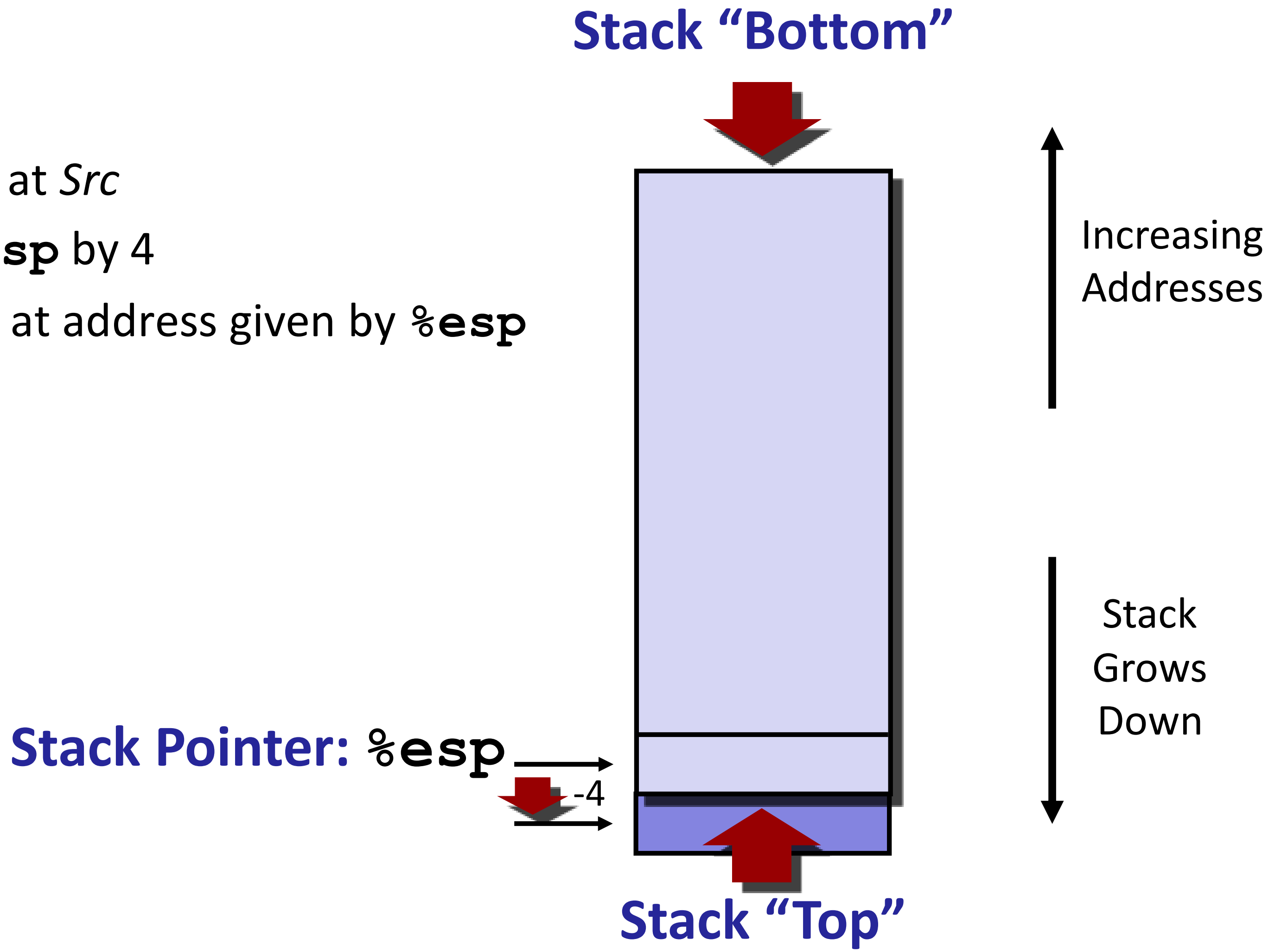
IA32 Stack


When the stack is upside down, the data do not fall down.
Surprised!


Stack "Bottom"
Increasing Addresses
Stack Grows Down
Stack Pointer: %esp
Stack "Top"

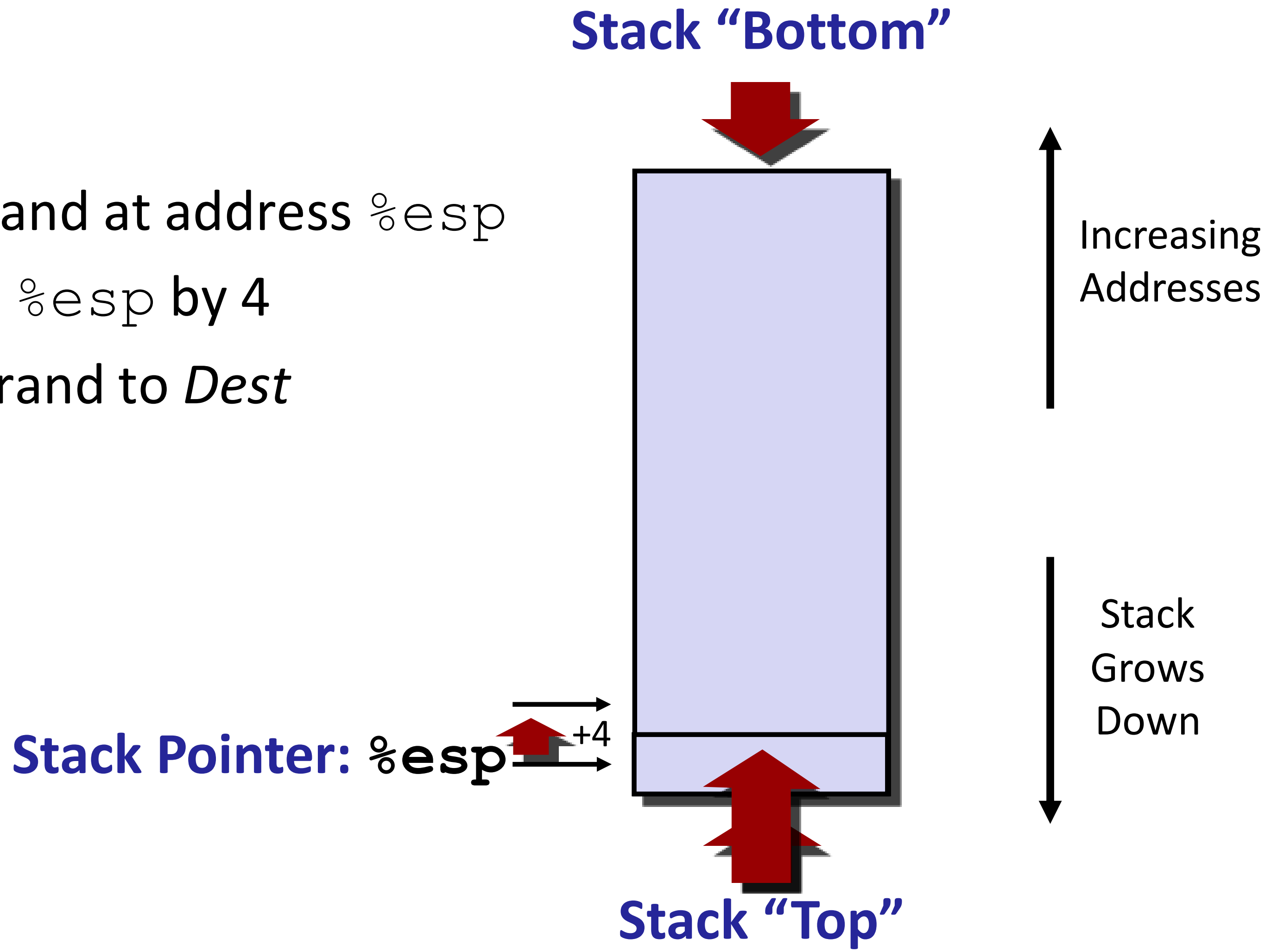
IA32 Stack: Push

- **`pushl`** ***Src***
  - Fetch operand at *Src*
  - Decrement **`%esp`** by 4
  - Write operand at address given by **`%esp`**



IA32 Stack: Pop

- **`popl`** *Dest*
  - Read operand at address `%esp`
  - Increment `%esp` by 4
  - Write operand to *Dest*



Procedure Control Flow

- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to ***label***
- **Return address:**
  - Address of the next instruction right after call
  - Example from disassembly

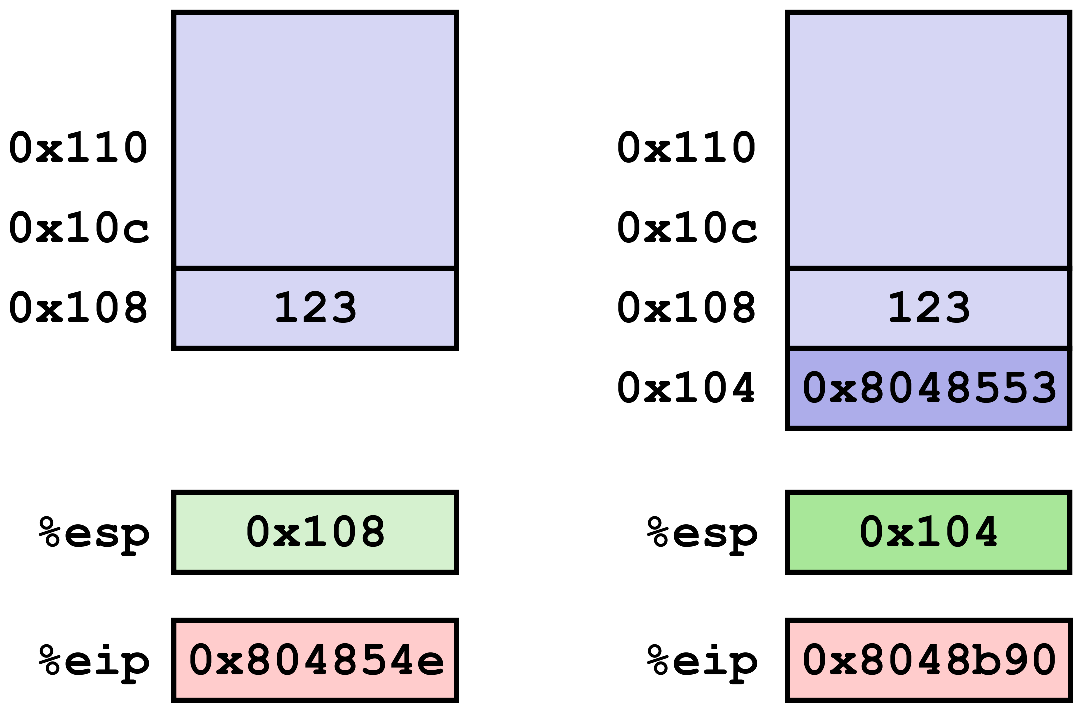
```
804854e:   e8 3d 06 00 00       call    8048b90 <main>
8048553:   50                   pushl   %eax
```

  - Return address = `0x8048553`
- **Procedure return: `ret`**
  - Pop address from stack
  - Jump to address

Procedure Call Example

```
804854e:      e8 3d 06 00 00      call    8048b90 <main>
8048553:      50                  pushl   %eax
```

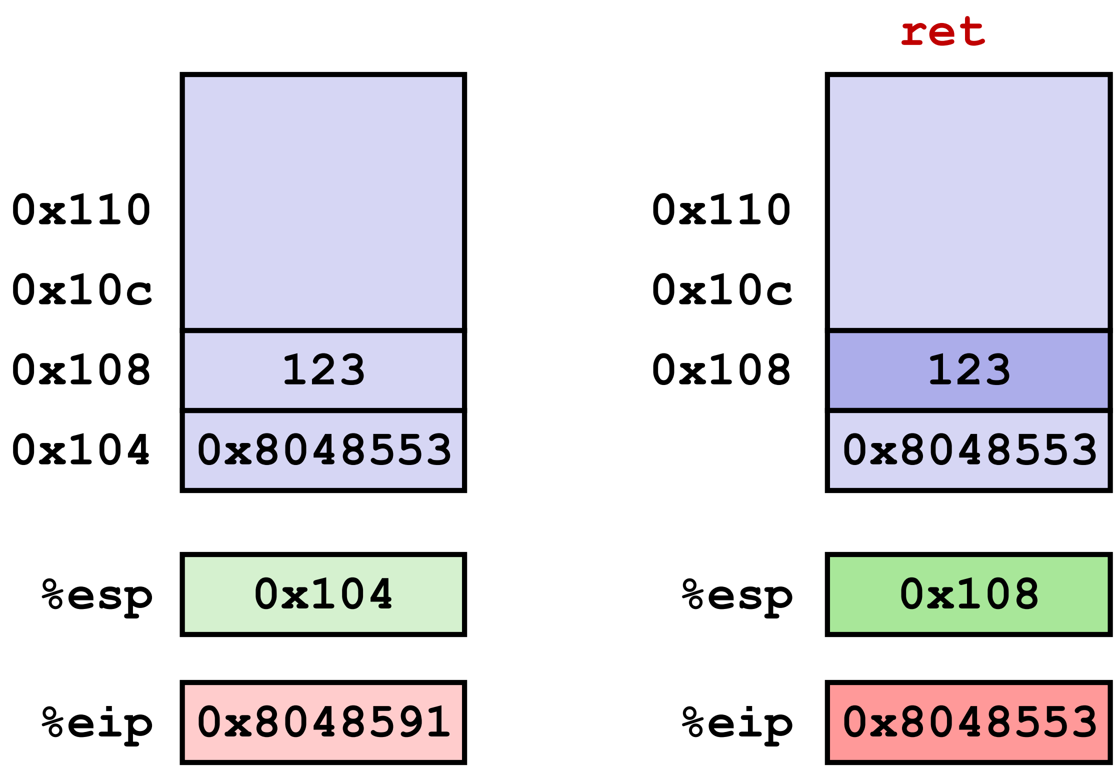
call 8048b90



%eip: program counter

Procedure Return Example

```
8048591:     c3                    ret
```



`%eip`: program counter

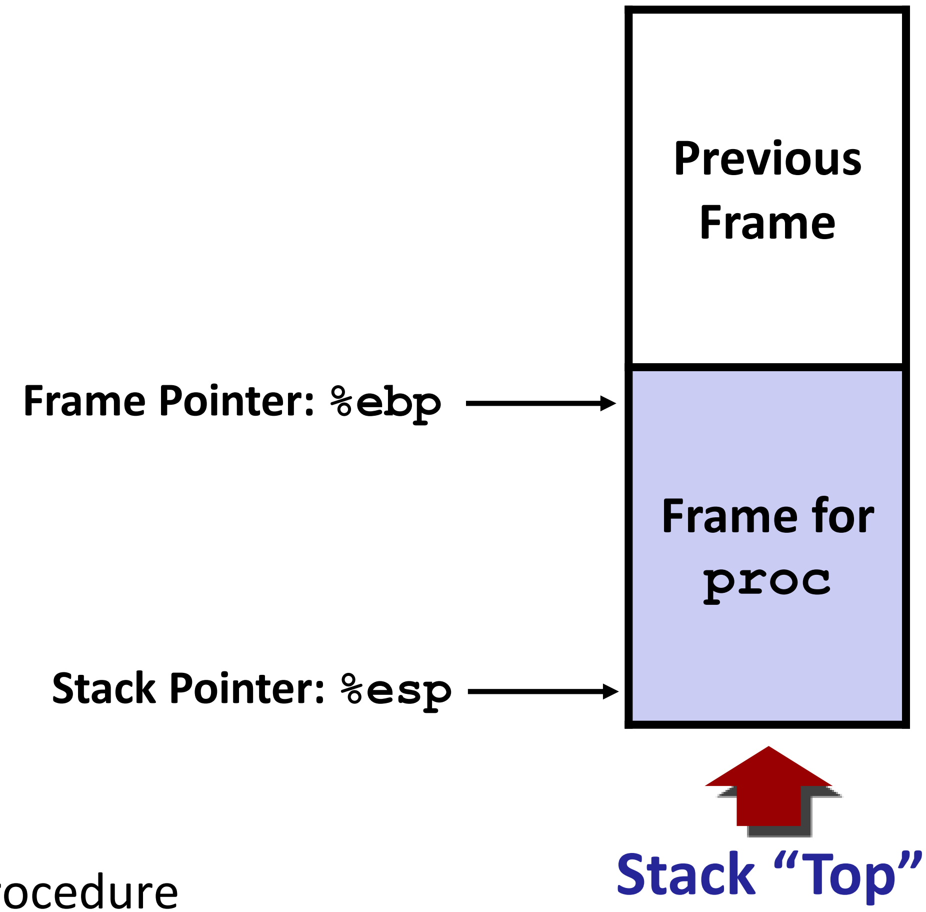
Stack-Based Languages

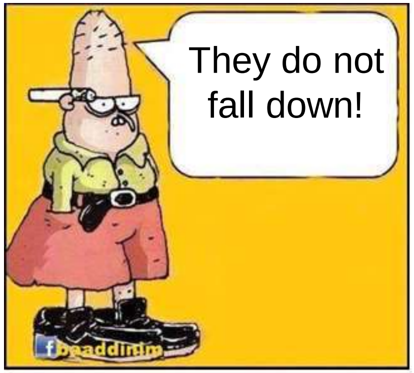
- **Languages that support recursion**
  - e.g., C, Pascal, Java
  - Code must be "*Reentrant*"
    - Multiple simultaneous instantiations of single procedure
  - Need some place to store state of each instantiation
    - Arguments
    - Local variables
    - Return pointer
- **Stack discipline**
  - State for given procedure needed for limited time
    - From when called to when return
  - Callee returns before caller does
- **Stack allocated in *Frames***
  - state for single procedure instantiation

Stack Frames

- **Contents**
  - Local variables
  - Return information
  - Temporary space

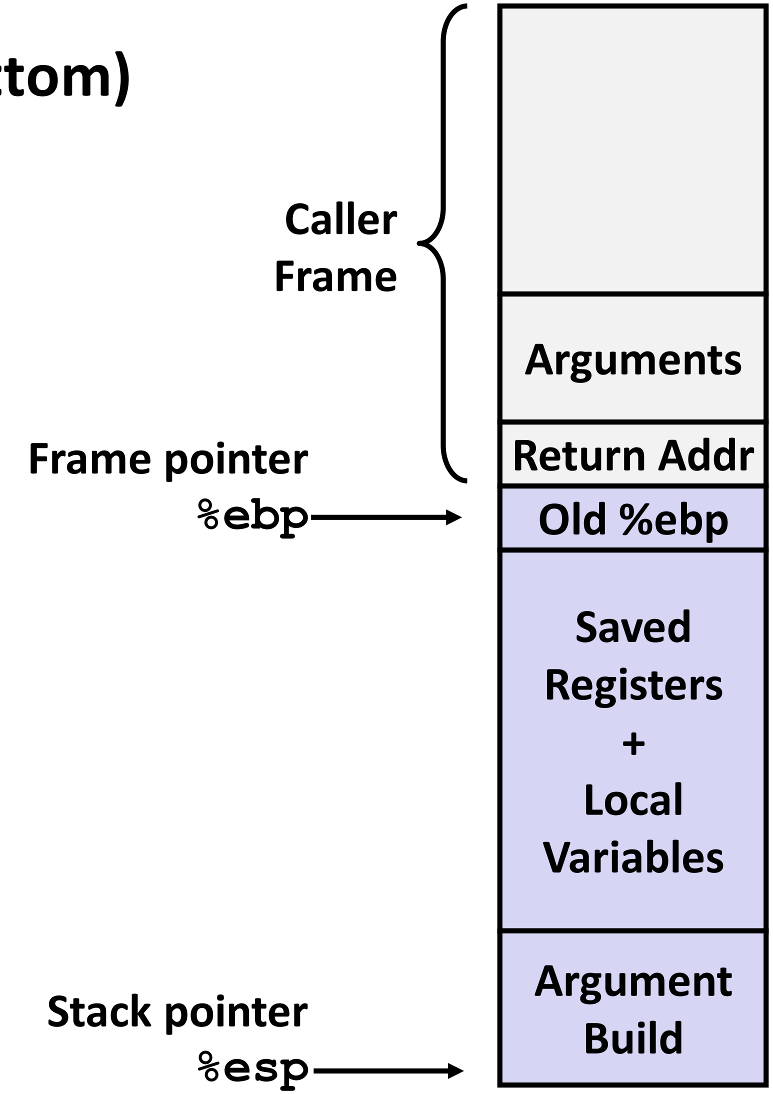
- **Management**
  - Space allocated when enter procedure
    - "Set-up" code
  - Deallocated when return
    - "Finish" code





IA32/Linux Stack Frame

- **Current Stack Frame ("Top" to Bottom)**
  - "Argument build:"
    Parameters for function about to call
  - Local variables
    If can't keep in registers
  - Saved register context
  - Old frame pointer
- **Caller Stack Frame**
  - Return address
    - Pushed by **`call`** instruction
  - Arguments for this call

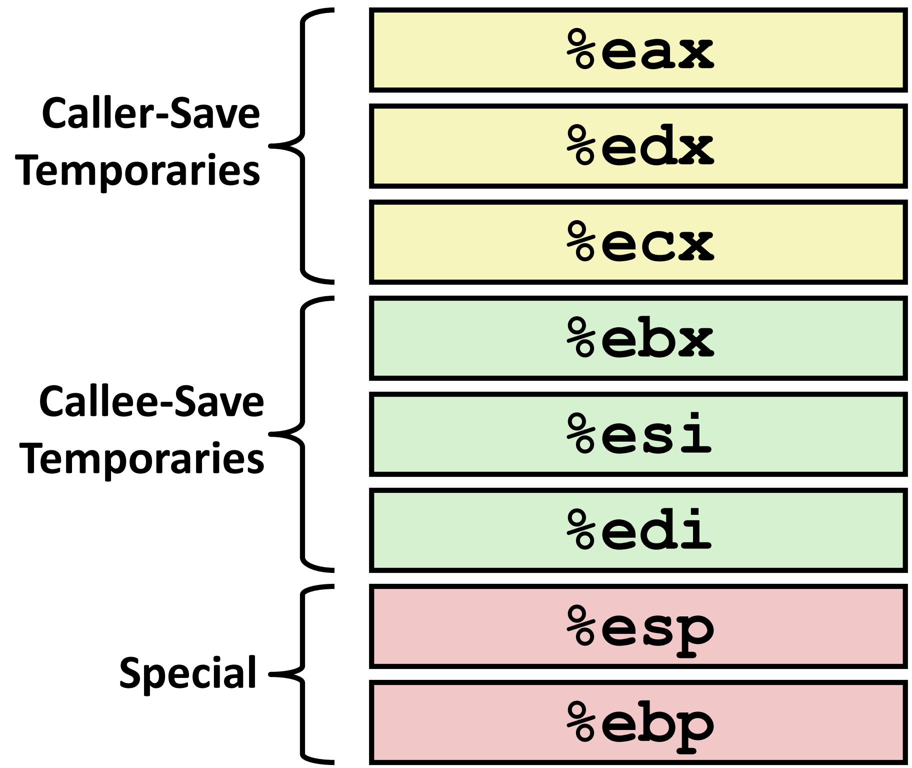


Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

IA32/Linux+Windows Register Usage

- **`%eax, %edx, %ecx`**
  - Caller saves prior to call if values are used later
- **`%eax`**
  - also used to return integer value
- **`%ebx, %esi, %edi`**
  - Callee saves if wants to use them
- **`%esp, %ebp`**
  - special form of callee save
  - Restored to original values upon exit from procedure



Today

- Switch statements
- IA 32 Procedures
  - Stack Structure
  - Calling Conventions
  - Illustrations of Recursion & Pointers

Recursive Function

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

- **Registers**
  - `%eax`, `%edx` used without first saving
  - `%ebx` used, but saved at beginning & restored at end

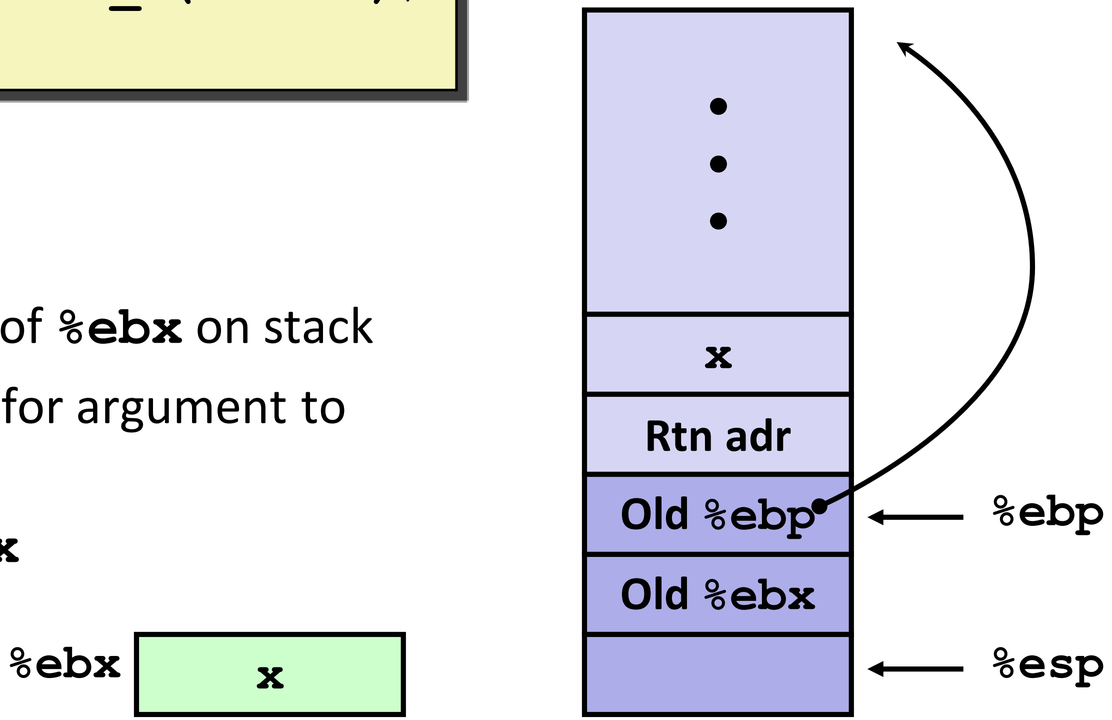
```
pcount_r:
    pushl  %ebp
    movl   %esp, %ebp
    pushl  %ebx
    subl   $4, %esp
    movl   8(%ebp), %ebx
    movl   $0, %eax
    testl  %eax, %ebx
    je   .L3
    movl %ebx, %eax
    shrl %eax
    movl %eax, (%esp)
    call pcount_r
    movl %ebx, %edx
    andl $1, %edx
    leal (%edx,%eax), %eax
.L3:
    addl $4, %esp
    popl  %ebx
    popl %ebp
    ret
```

Recursive Call #1

```
/* Recursive popcount */
int pcount_r(unsigned x) {
  if (x == 0)
    return 0;
  else return
    (x & 1) + pcount_r(x >> 1);
}
```

```
pcount_r:
    pushl %ebp
    movl  %esp, %ebp
    pushl  %ebx
    subl   $4, %esp
    movl 8(%ebp), %ebx
     • • •
```

- **Actions**
  - Save old value of `%ebx` on stack
  - Allocate space for argument to recursive call
  - Store x in `%ebx`



Observations About Recursion

- **Handled Without Special Consideration**
  - Stack frames mean that each function call has private storage
    - Saved registers & local variables
    - Saved return pointer
  - Register saving conventions prevent one function call from corrupting another's data
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out
- **Also works for mutual recursion**
  - P calls Q; Q calls P

Pointer Code

Generating Pointer

```
/* Compute x + 3 */
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

Referencing Pointer

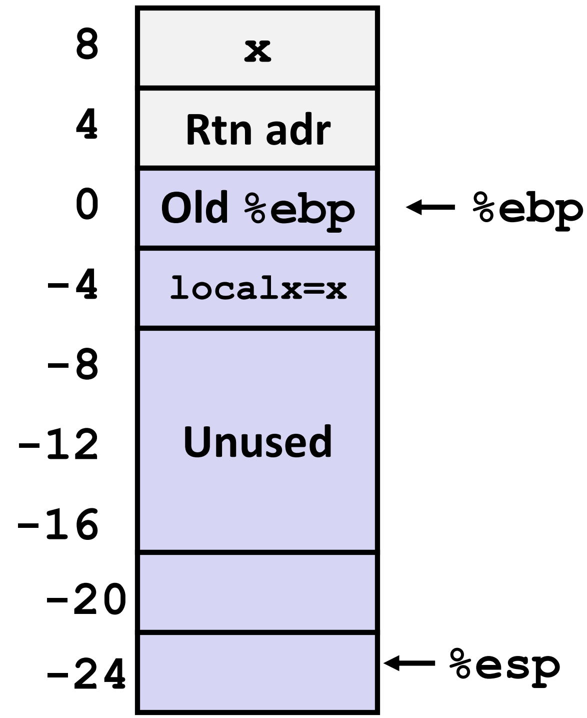
```
/* Increment value by k */
void incrk(int *ip, int k) {
  *ip += k;
}
```

- `add3` creates pointer and passes it to `incrk`

Creating and Initializing Local Variable

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- **Variable localx must be stored on stack**
  - Because: Need to create pointer to it
- **Compute pointer as -4(%ebp)**



First part of add3

```
add3:
  pushl%ebp
  movl %esp, %ebp
  subl $24, %esp     # Alloc. 24 bytes
  movl 8(%ebp), %eax
  movl %eax, -4(%ebp)# Set localx to x
```

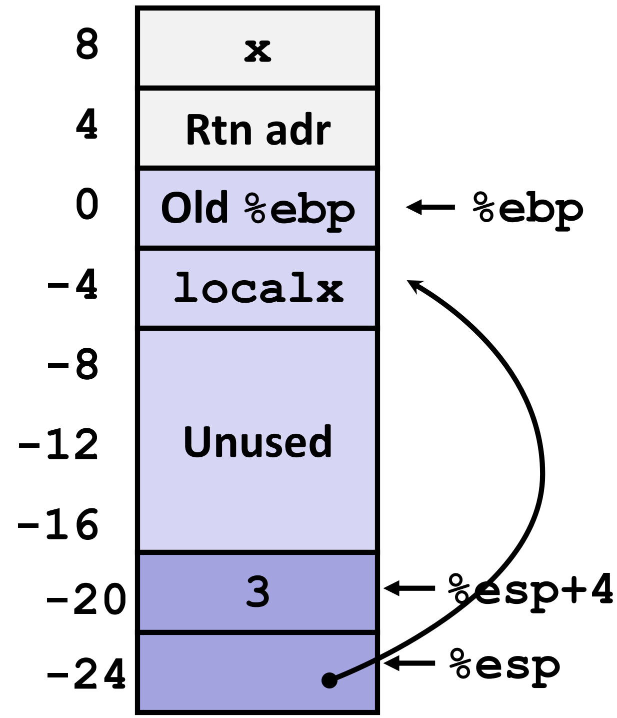
Creating Pointer as Argument

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- Use leal instruction to compute address of localx

Middle part of add3

```
  movl $3, 4(%esp)   # 2nd arg = 3
  leal -4(%ebp), %eax# &localx
  movl %eax, (%esp)  # 1st arg = &localx
  call incrk
```



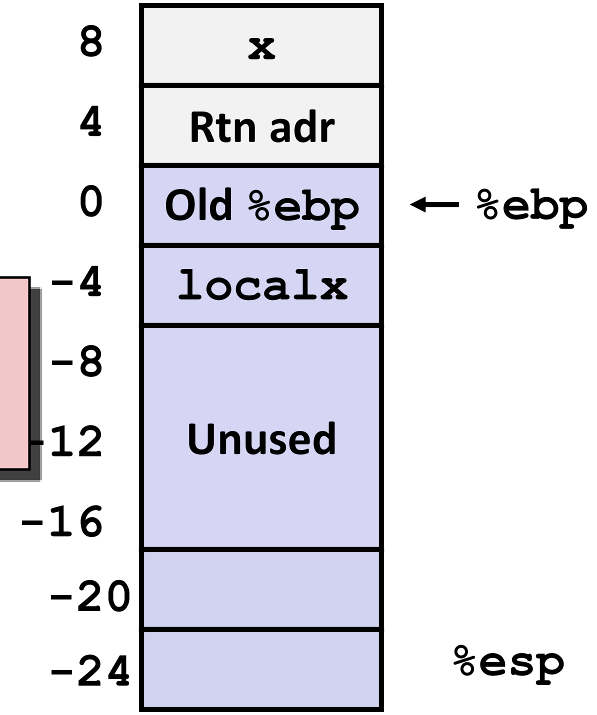
Retrieving local variable

```
int add3(int x) {
  int localx = x;
  incrk(&localx, 3);
  return localx;
}
```

- Retrieve localx from stack as return value

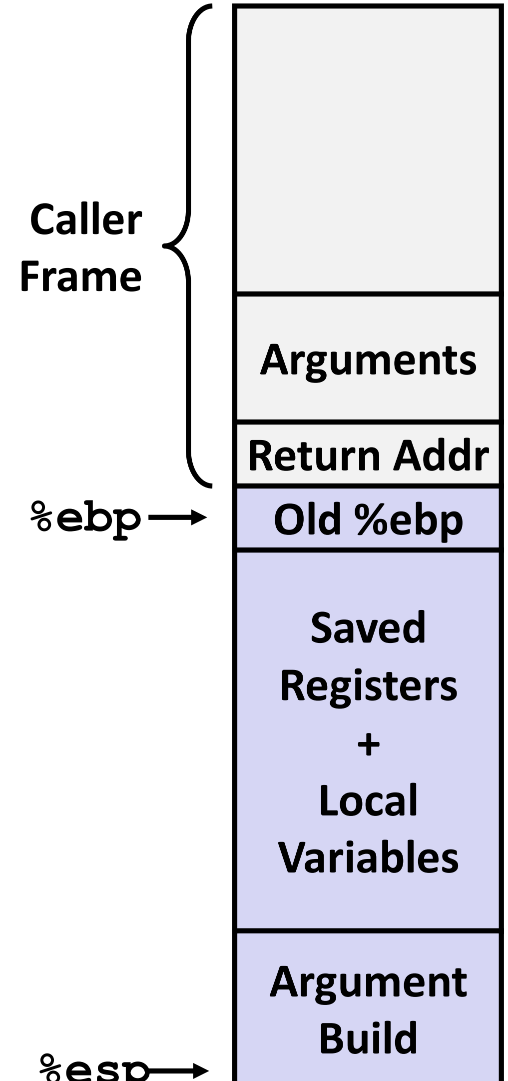
Final part of add3

```
  movl -4(%ebp), %eax # Return val= localx
  leave
  ret
```



IA 32 Procedure Summary

- **Important Points**
  - Stack is the right data structure for procedure call / return
    - If P calls Q, then Q returns before P
- **Recursion (& mutual recursion) handled by normal calling conventions**
  - Can safely store values in local stack frame and in callee-saved registers
  - Put function arguments at top of stack
  - Result return in `%eax`
- **`Pointers are addresses of values`**
  - `On stack or global`



Machine-Level Programming IV: Data

Today

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access

Today

- Procedures (x86-64)
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- Structures

Basic Data Types

Integral

- Stored & operated on in general (integer) registers
- Signed vs. unsigned depends on instructions used

Intel	ASM	Bytes	C
byte	`b`	1	`[unsigned] char`
word	`w`	2	`[unsigned] short`
double word	`l`	4	`[unsigned] int`
quad word	`q`	8	`[unsigned] long int` (x86-64)

Floating Point

- Stored & operated on in floating point registers

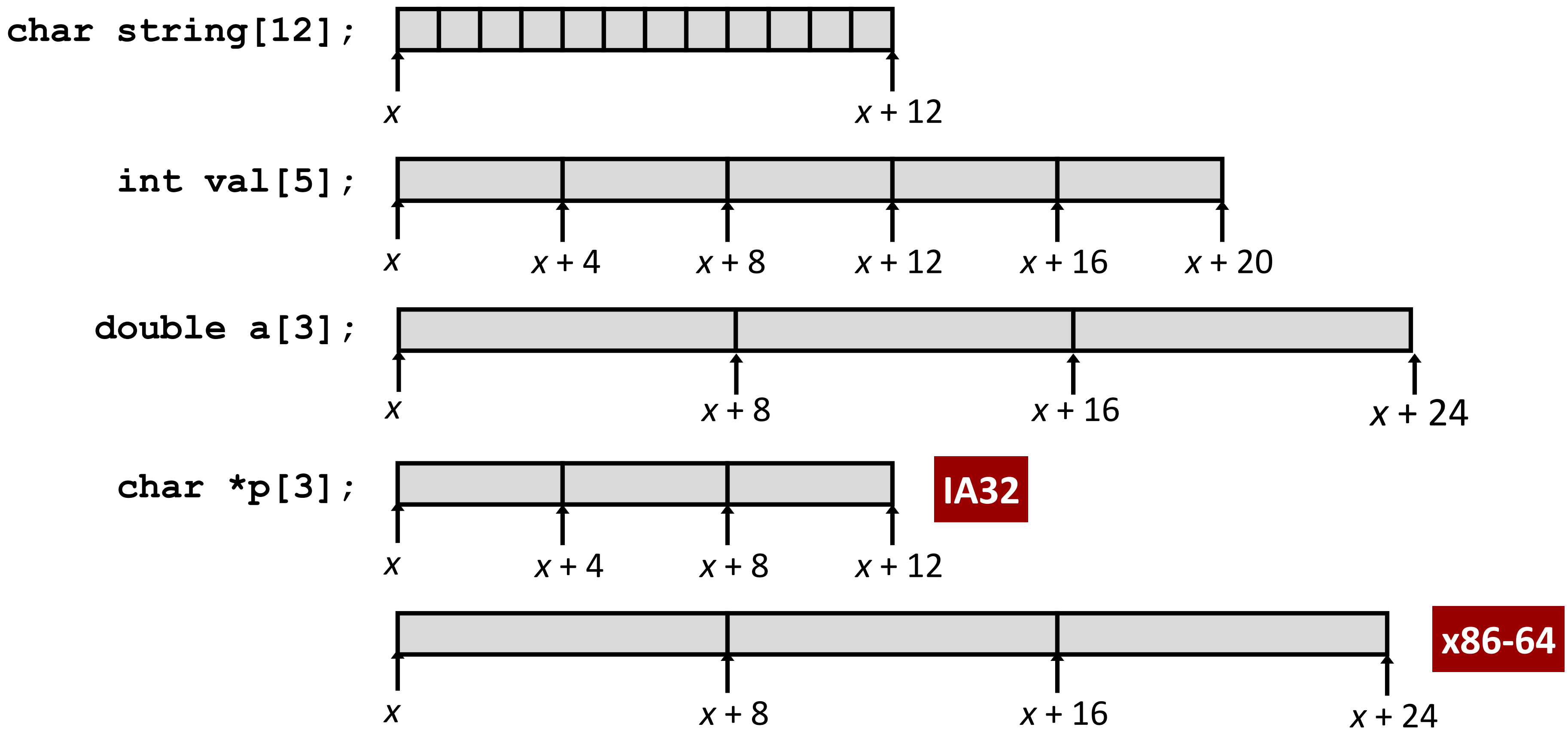
Intel	ASM	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12/16	`long double`

Array Allocation

- **Basic Principle**

  T **A[*L*];**

  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **sizeof**(*T*) bytes



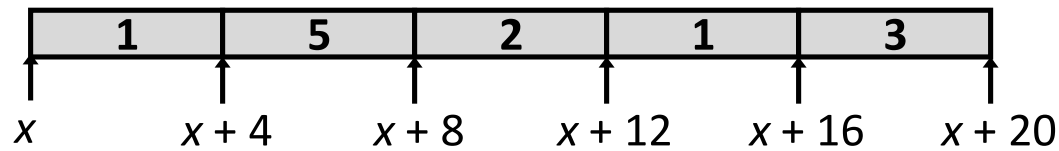
Array Access

Basic Principle

T **A**[*L*];

- Array of data type *T* and length *L*
- Identifier **A** can be used as a pointer to array element 0: Type *T**

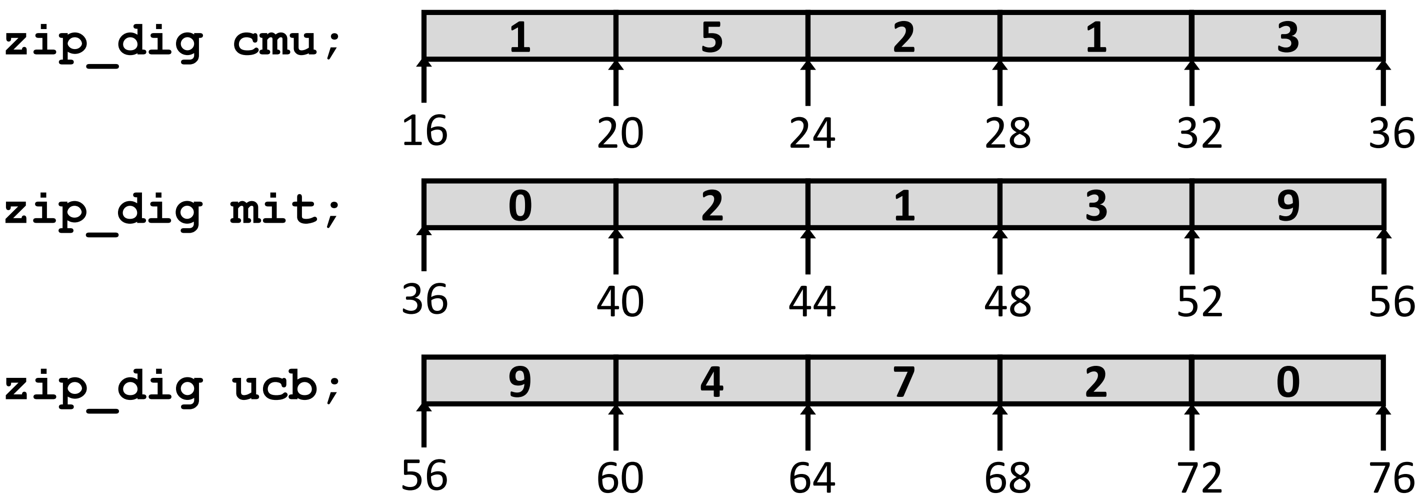
`int val[5];`



Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	x
`val+1`	`int *`	$x + 4$
`&val[2]`	`int *`	$x + 8$
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val + `*i*	`int *`	$x + 4\,i$

Array Example

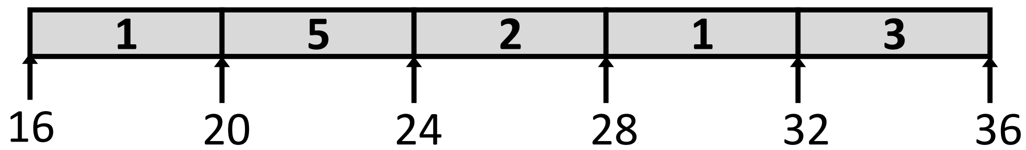
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



- **Declaration "`zip_dig cmu`" equivalent to "`int cmu[5]`"**
- **Example arrays were allocated in successive 20 byte blocks**
  - Not guaranteed to happen in general

Array Accessing Example

`zip_dig cmu;`




```
int get_digit
  (zip_dig z, int dig)
{
  return z[dig];
}
```

IA32

```
  # %edx = z
  # %eax = dig
   movl (%edx,%eax,4),%eax  # z[dig]
```

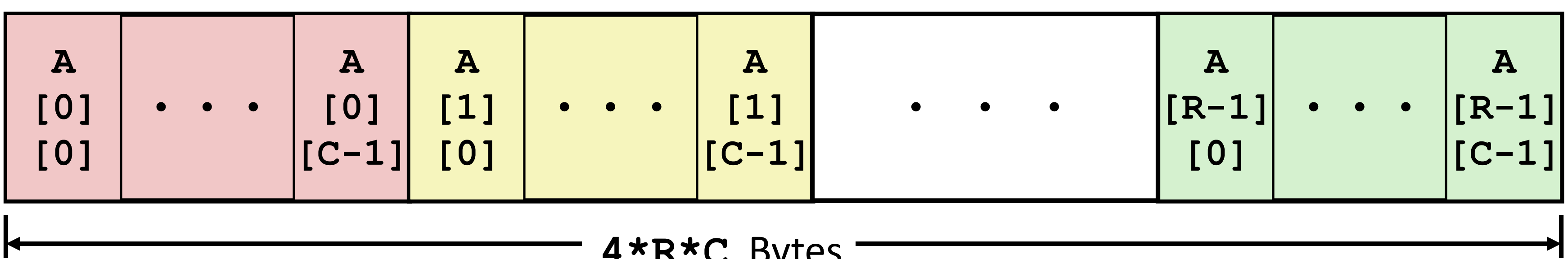
- Register `%edx` contains starting address of array
- Register `%eax` contains array index
- Desired digit at `4*%eax + %edx`
- Use memory reference `(%edx,%eax,4)`

Multidimensional (Nested) Arrays

- **Declaration**
  - *T* **A**[*R*][*C*];
  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes
- **Array Size**
  - *R* * *C* * *K* bytes
- **Arrangement**
  - Row-Major Ordering

$$\begin{bmatrix} \texttt{A[0][0]} & \cdots & \texttt{A[0][C-1]} \\ \vdots & & \vdots \\ \texttt{A[R-1][0]} & \cdots & \texttt{A[R-1][C-1]} \end{bmatrix}$$

```
int A[R][C];
```

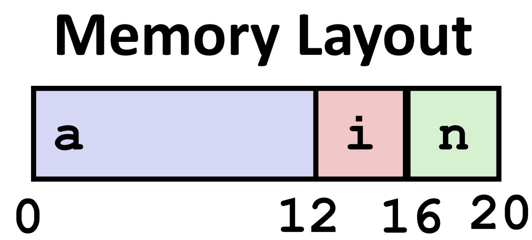


Today

- **Structures**
  - Allocation
  - Access

Structure Allocation

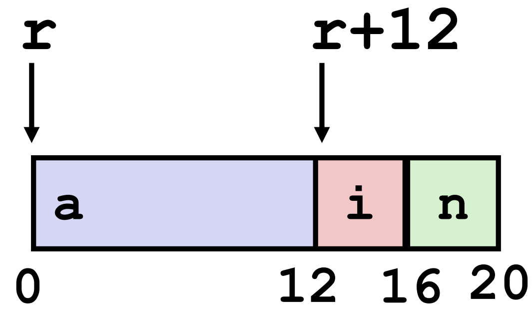
```
struct rec {
  int a[3];
  int i;
  struct rec *n;
};
```



- **Concept**
  - Contiguously-allocated region of memory
  - Refer to members within structure by names
  - Members may be of different types

Structure Access

```
struct rec {
  int a[3];
  int i;
  struct rec *n;
};
```



- **Accessing Structure Member**
  - Pointer indicates first byte of structure
  - Access elements with offsets

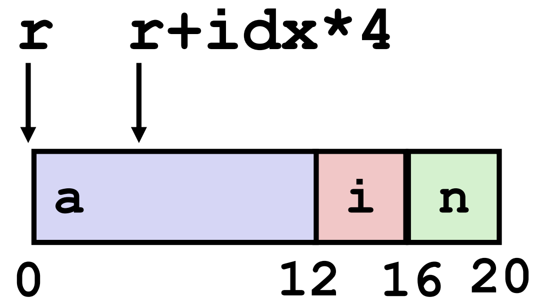
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

IA32 Assembly

```
  # %edx = val
  # %eax = r
  movl %edx, 12(%eax)  # Mem[r+12] = val
```

Generating Pointer to Structure Member

```
struct rec {
  int a[3];
  int i;
  struct rec *n;
};
```



- **Generating Pointer to Array Element**
  - Offset of each structure member determined at compile time
  - Arguments
    - Mem[%ebp+8]: **r**
    - Mem[%ebp+12]: **idx**

```
int *get_ap
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

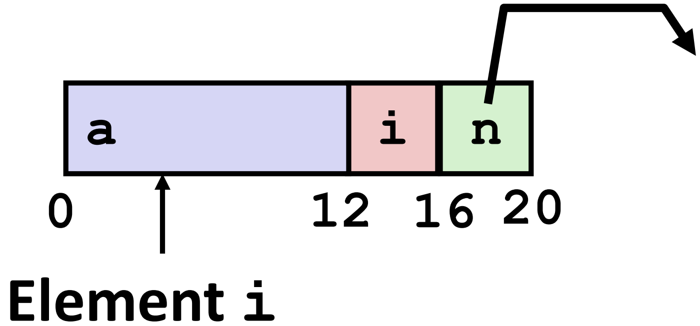
```
movl   12(%ebp), %eax   # Get idx
sall   $2, %eax         # idx*4
addl   8(%ebp), %eax    # r+idx*4
```

Following Linked List

- C Code

```
struct rec {
  int a[3];
  int i;
  struct rec *n;
};
```

```
void set_val
  (struct rec *r, int val)
{
  while (r) {
    int i = r->i;
    r->a[i] = val;
    r = r->n;
  }
}
```



Register	Value
%edx	r
%ecx	val

```
.L17:                           # loop:
  movl   12(%edx), %eax         # r->i
  movl   %ecx, (%edx,%eax,4)    # r->a[i] = val
  movl   16(%edx), %edx         # r = r->n
  testl  %edx, %edx             # Test r
  jne    .L17                   # If != 0 goto loop
```

Summary

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
- **Structures**
  - Allocation
  - Access

The Memory Hierarchy

Today

- **Storage technologies and trends**
- Locality of reference
- Caching in the memory hierarchy

Random-Access Memory (RAM)

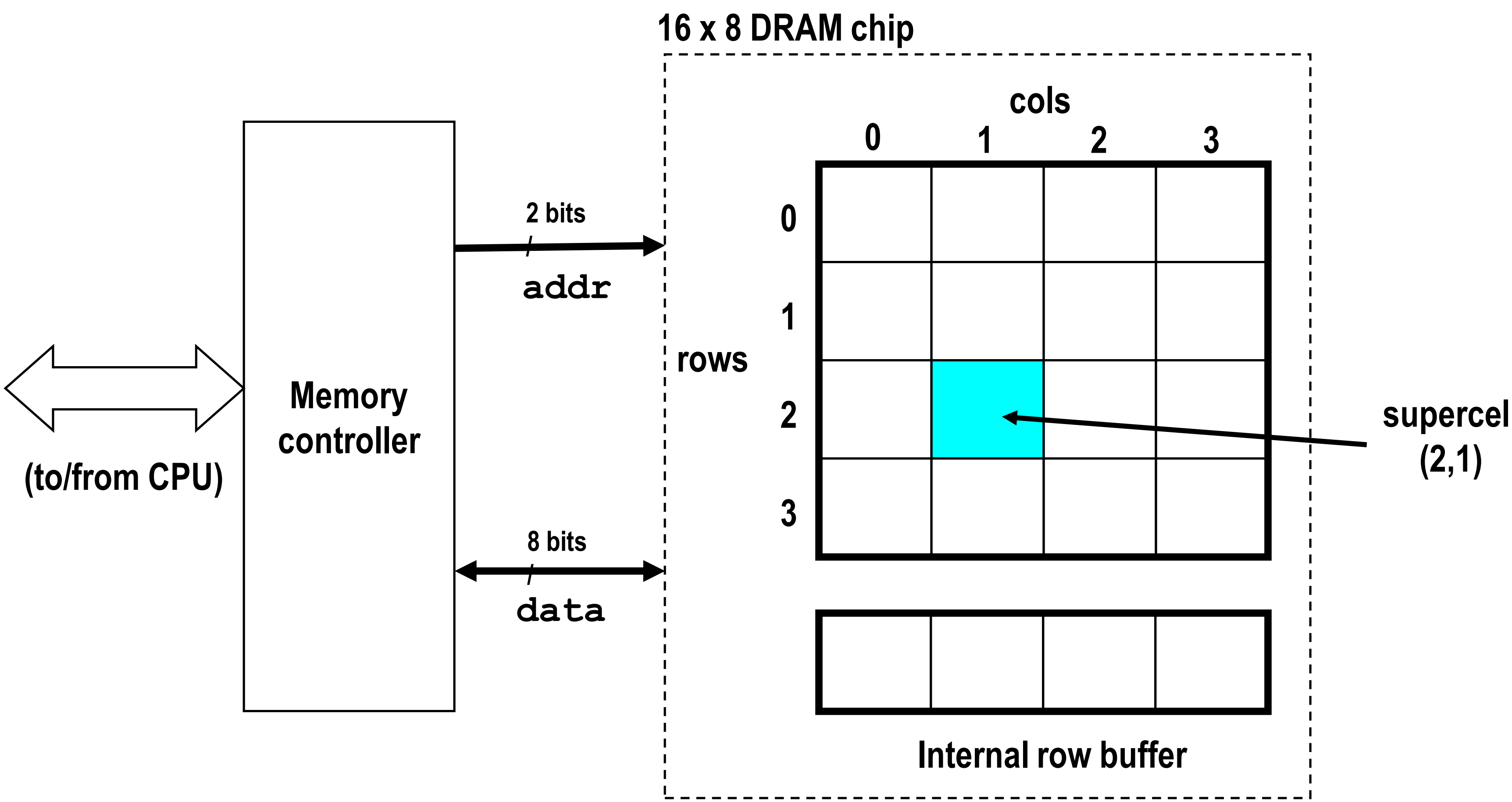
- **Key features**
  - RAM is traditionally packaged as a chip.
  - Basic storage unit is normally a cell (one bit per cell).
  - Multiple RAM chips form a memory.
- **Static RAM (SRAM)**
  - Each cell stores a bit with a four or six-transistor circuit.
  - Retains value indefinitely, as long as it is kept powered.
  - Relatively insensitive to electrical noise (EMI), radiation, etc.
  - Faster and more expensive than DRAM.
- **Dynamic RAM (DRAM)**
  - Each cell stores bit with a capacitor. One transistor is used for access
  - Value must be refreshed every 10-100 ms.
  - More sensitive to disturbances (EMI, radiation,…) than SRAM.
  - Slower and cheaper than SRAM.

SRAM vs DRAM Summary

	Trans. per bit	Access time	Needs refresh?	Needs EDC?	Cost	Applications
SRAM	4 or 6	1X	No	Maybe	100x	Cache memories
DRAM	1	10X	Yes	Yes	1X	Main memories, frame buffers

Conventional DRAM Organization

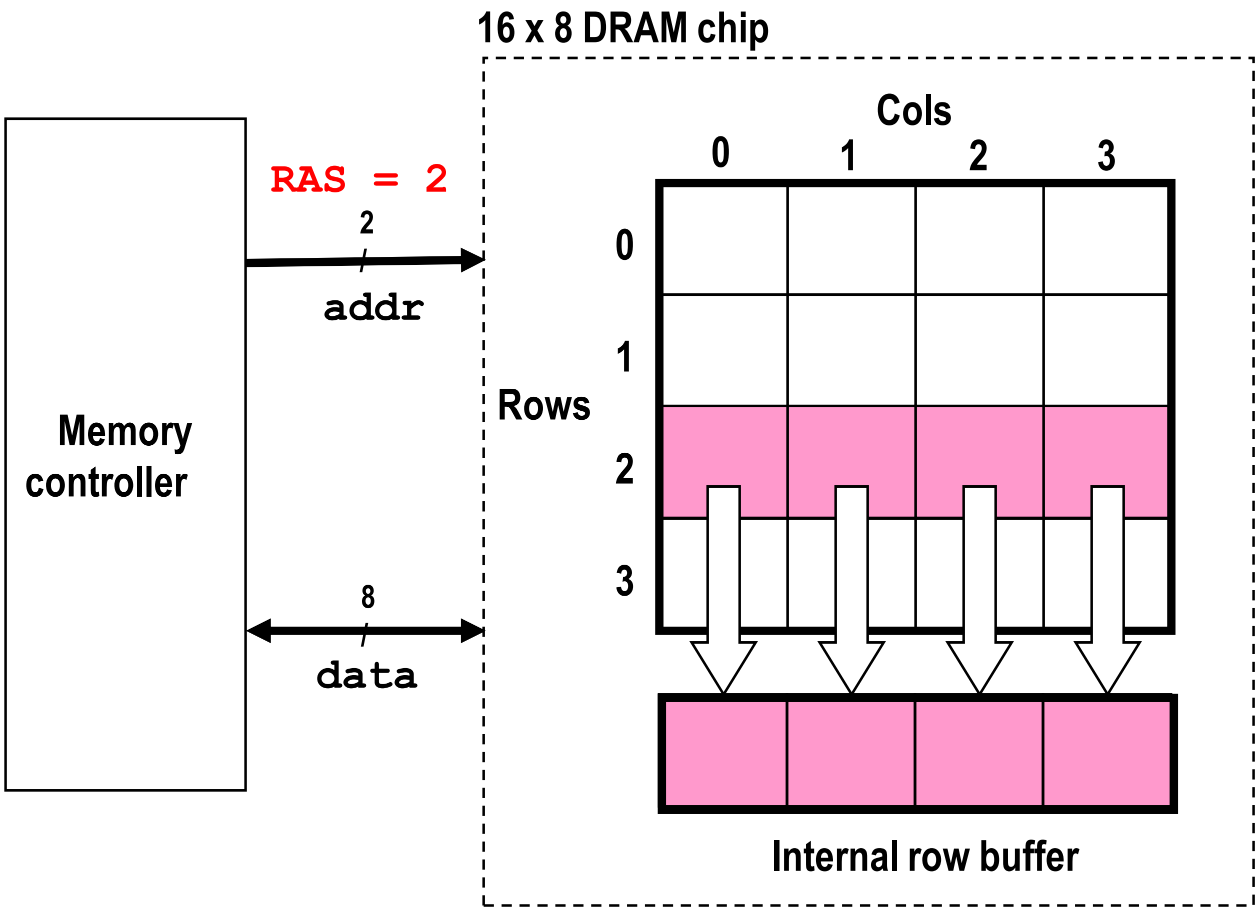
- **d x w DRAM:**
  - dw total bits organized as d supercells of size w bits



Reading DRAM Supercell (2,1)

Step 1(a): Row access strobe (RAS) selects row 2.

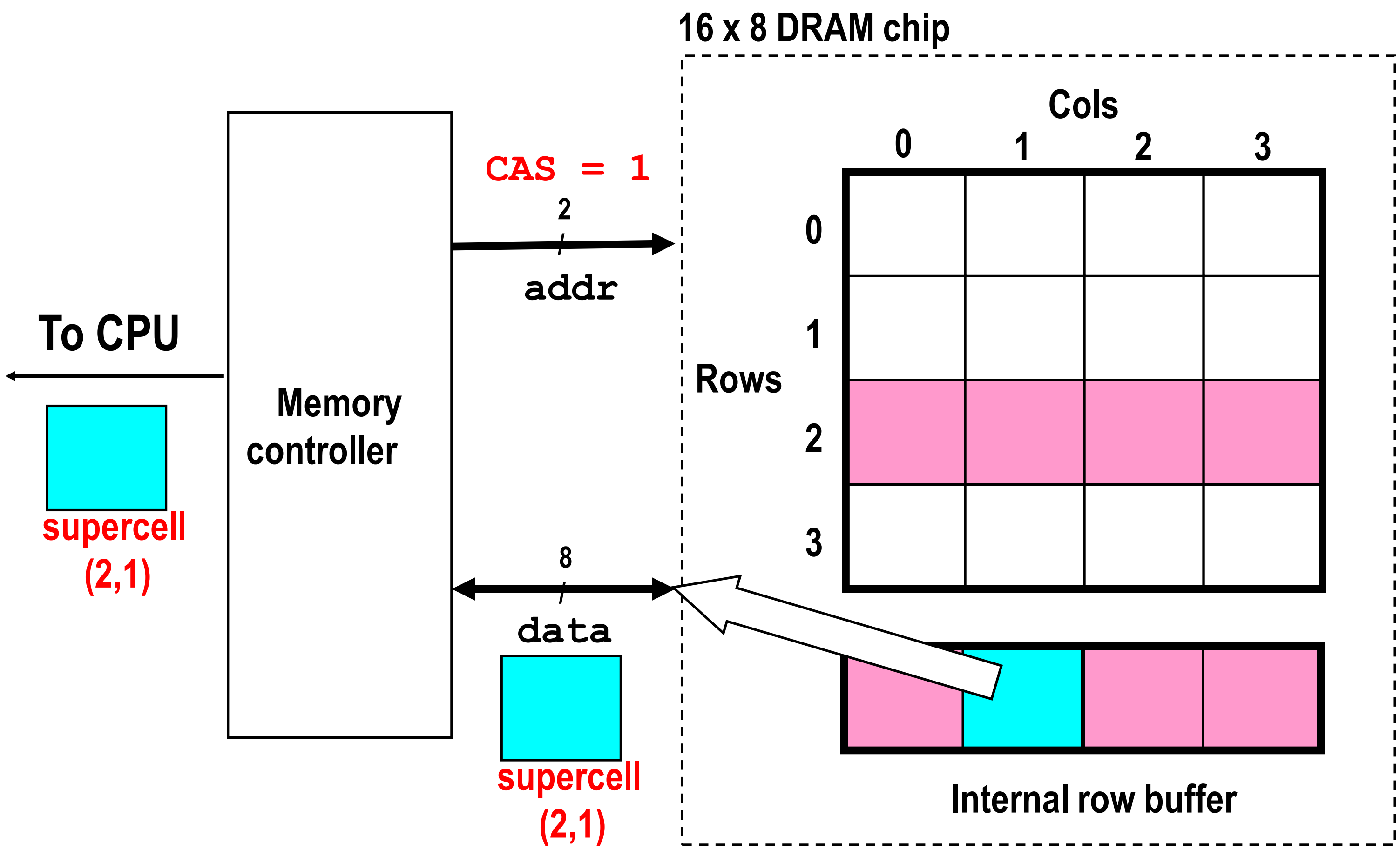
Step 1(b): Row 2 copied from DRAM array to row buffer.



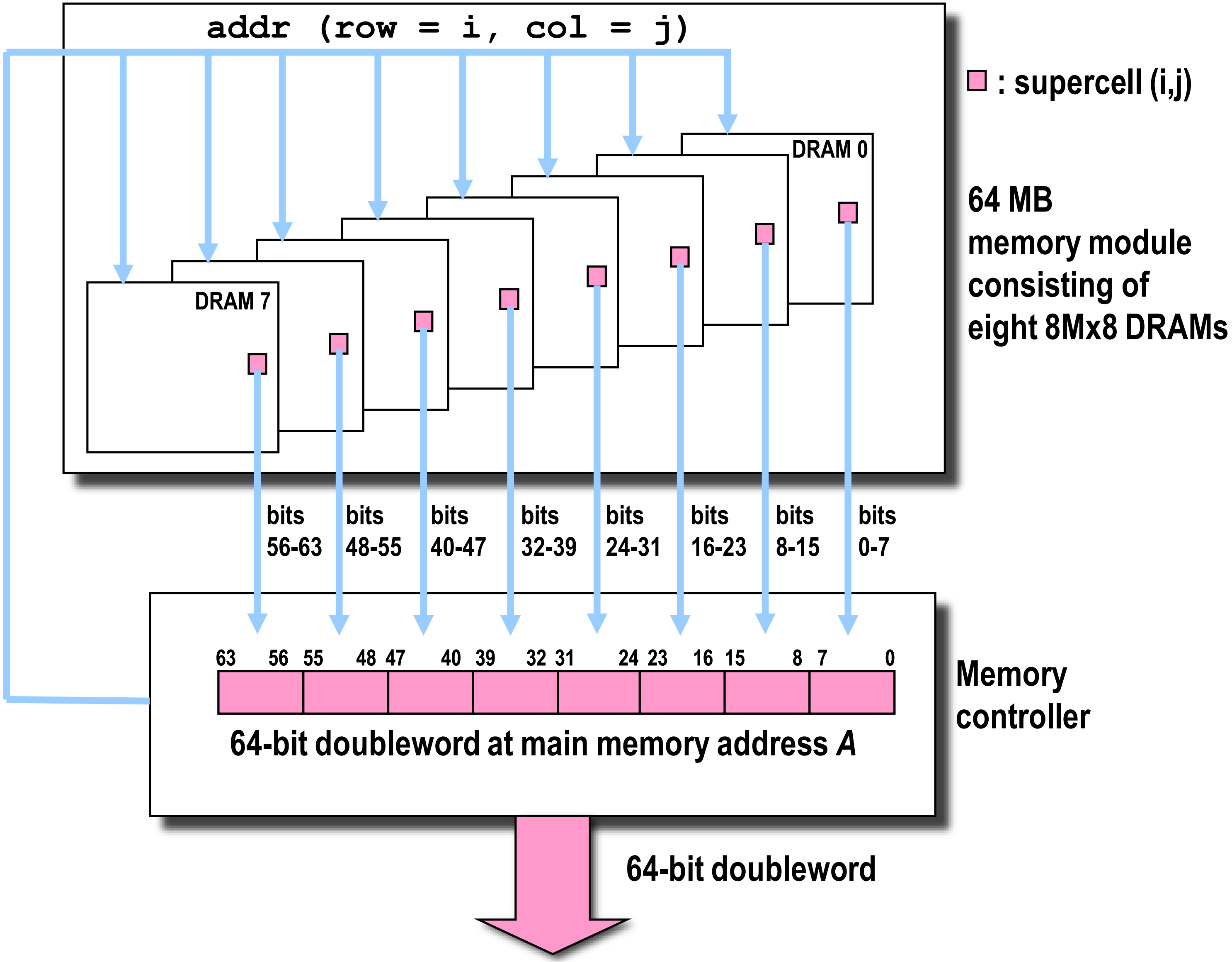
Reading DRAM Supercell (2,1)

Step 2(a): Column access strobe (CAS) selects column 1.

Step 2(b): Supercell (2,1) copied from buffer to data lines, and eventually back to the CPU.



Memory Modules



Enhanced DRAMs

- **Basic DRAM cell has not changed since its invention in 1966.**
  - Commercialized by Intel in 1970.
- **DRAM cores with better interface logic and faster I/O :**
  - Synchronous DRAM (SDRAM)
    - Uses a conventional clock signal instead of asynchronous control
    - Allows reuse of the row addresses (e.g., RAS, CAS, CAS, CAS)

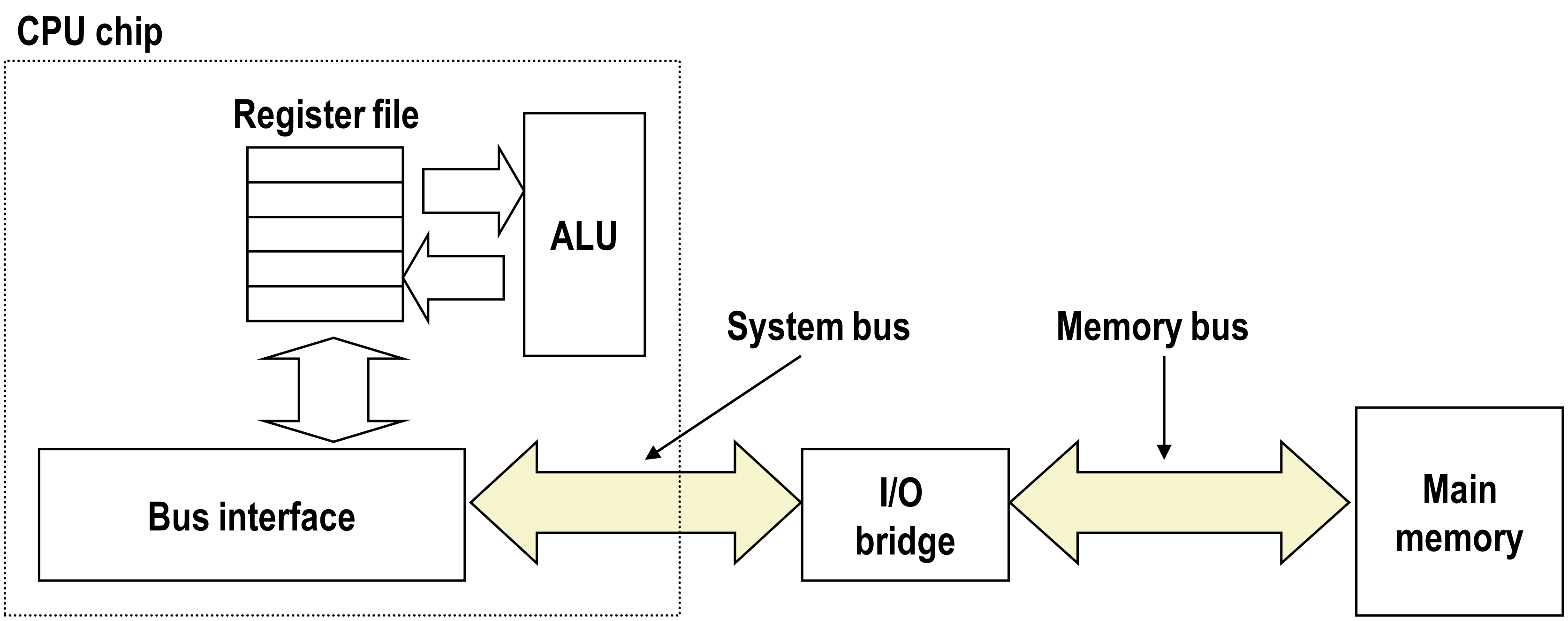
  - Double data-rate synchronous DRAM (DDR SDRAM)
    - Double edge clocking sends two bits per cycle per pin
    - Different types distinguished by size of small prefetch buffer:
      - DDR (2 bits), DDR2 (4 bits), DDR4 (8 bits)
    - By 2010, standard for most server and desktop systems
    - Intel Core i7 supports only DDR3 SDRAM

Nonvolatile Memories

- **DRAM and SRAM are volatile memories**
  - Lose information if powered off.
- **Nonvolatile memories retain value even if powered off**
  - Read-only memory (ROM): programmed during production
  - Programmable ROM (PROM): can be programmed once
  - Eraseable PROM (EPROM): can be bulk erased (UV, X-Ray)
  - Electrically eraseable PROM (EEPROM): electronic erase capability
  - Flash memory: EEPROMs with partial (sector) erase capability
    - Wears out after about 100,000 erasings.
- **Uses for Nonvolatile Memories**
  - Firmware programs stored in a ROM (BIOS, controllers for disks, network cards, graphics accelerators, security subsystems,…)
  - Solid state disks (replace rotating disks in thumb drives, smart phones, mp3 players, tablets, laptops,…)
  - Disk caches

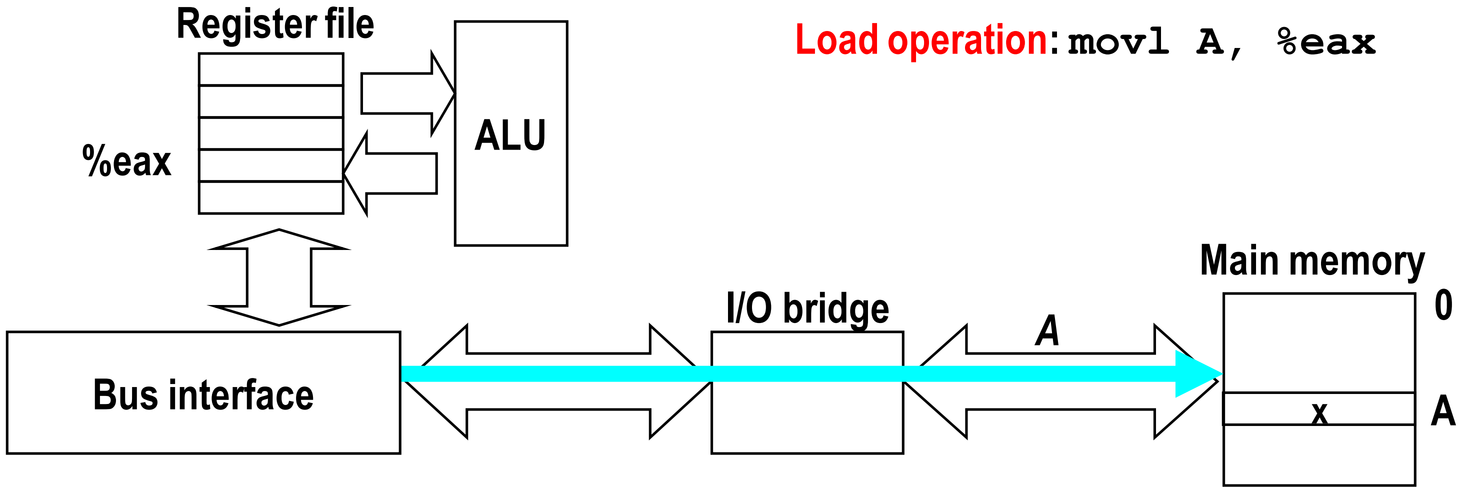
Traditional Bus Structure Connecting CPU and Memory

- A **bus** is a collection of parallel wires that carry address, data, and control signals.
- Buses are typically shared by multiple devices.



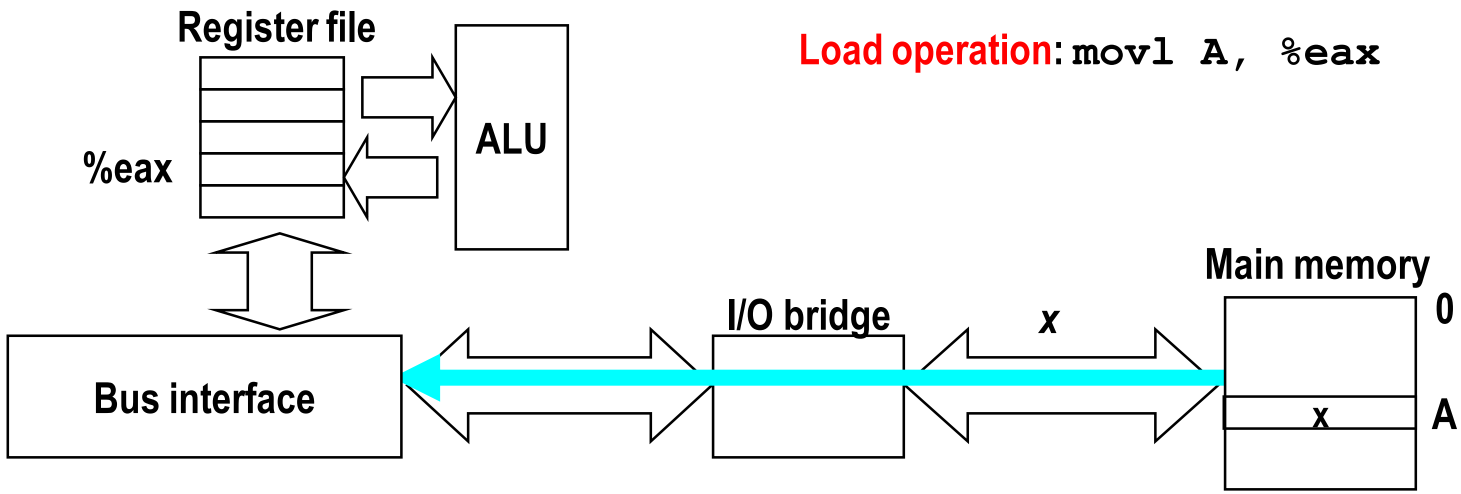
Memory Read Transaction (1)

- CPU places address A on the memory bus.



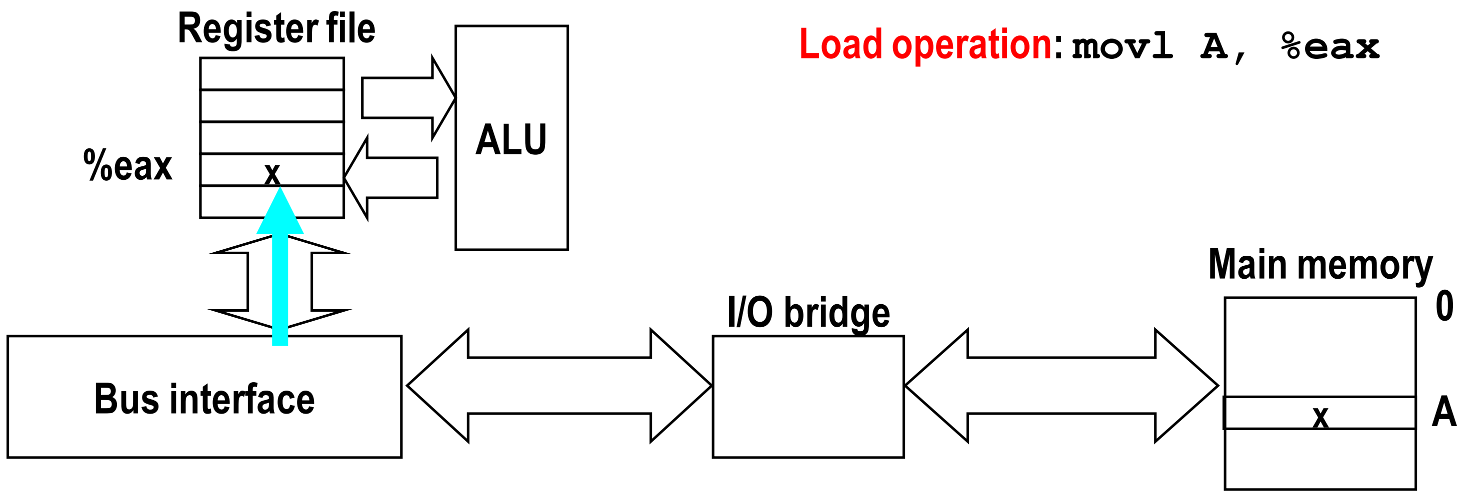
Memory Read Transaction (2)

- Main memory reads A from the memory bus, retrieves word x, and places it on the bus.



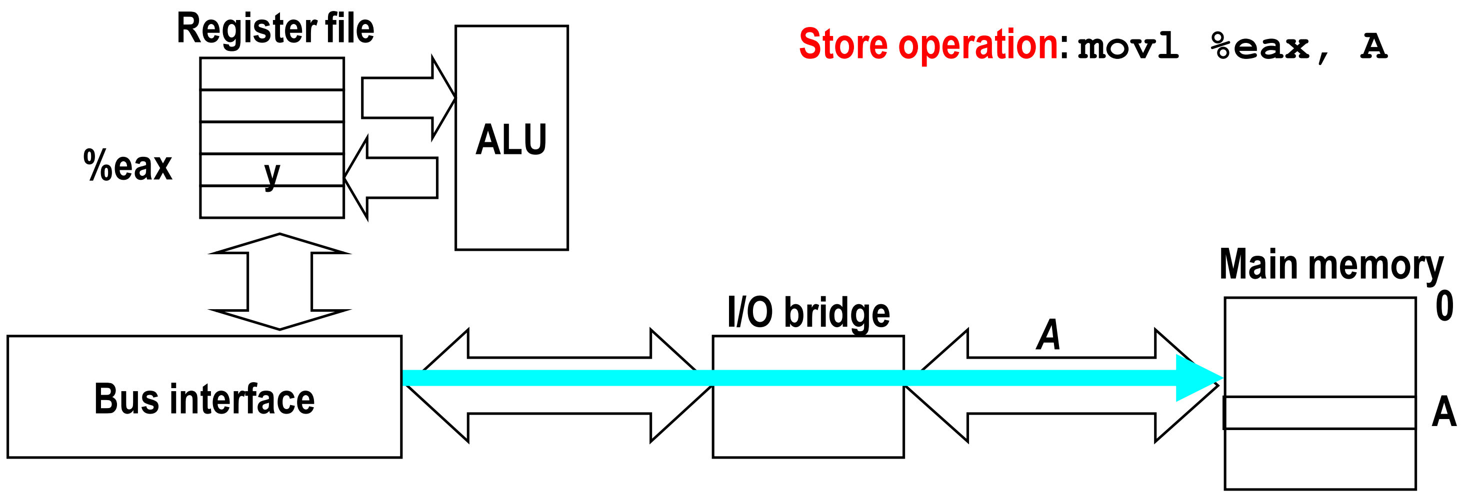
Memory Read Transaction (3)

- **CPU read word x from the bus and copies it into register %eax.**



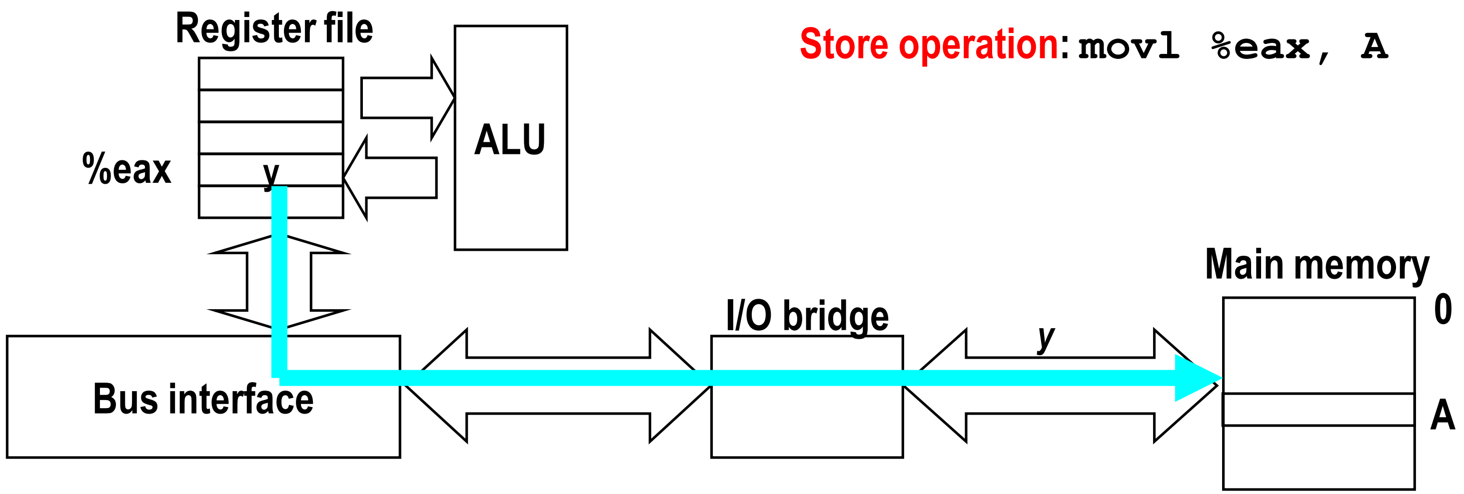
Memory Write Transaction (1)

- CPU places address A on bus. Main memory reads it and waits for the corresponding data word to arrive.



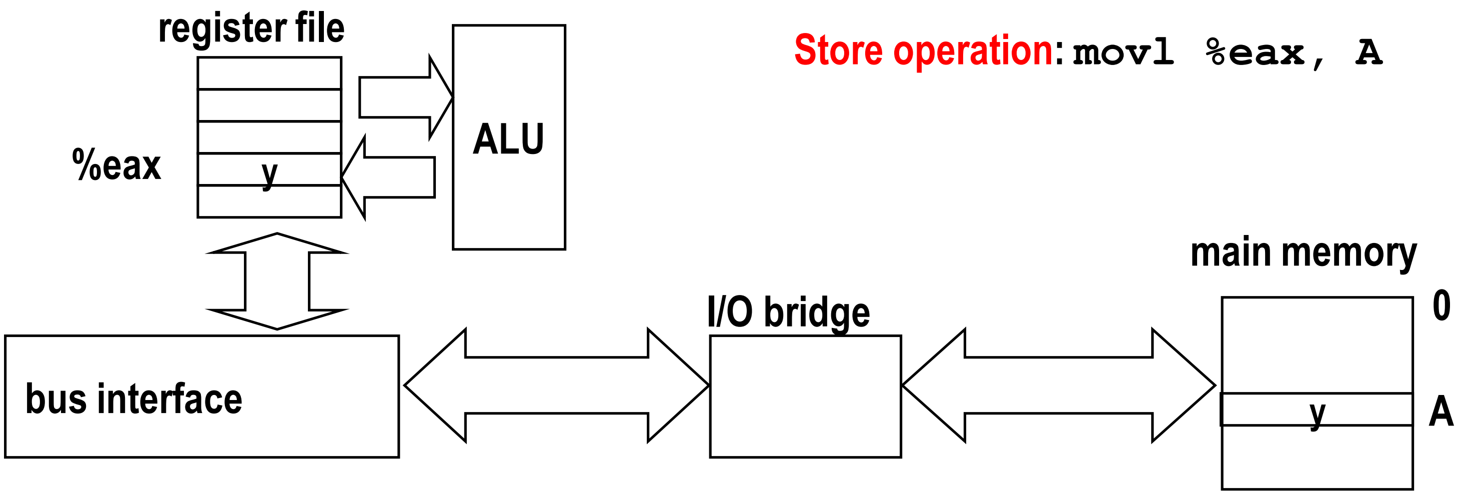
Memory Write Transaction (2)

- CPU places data word y on the bus.

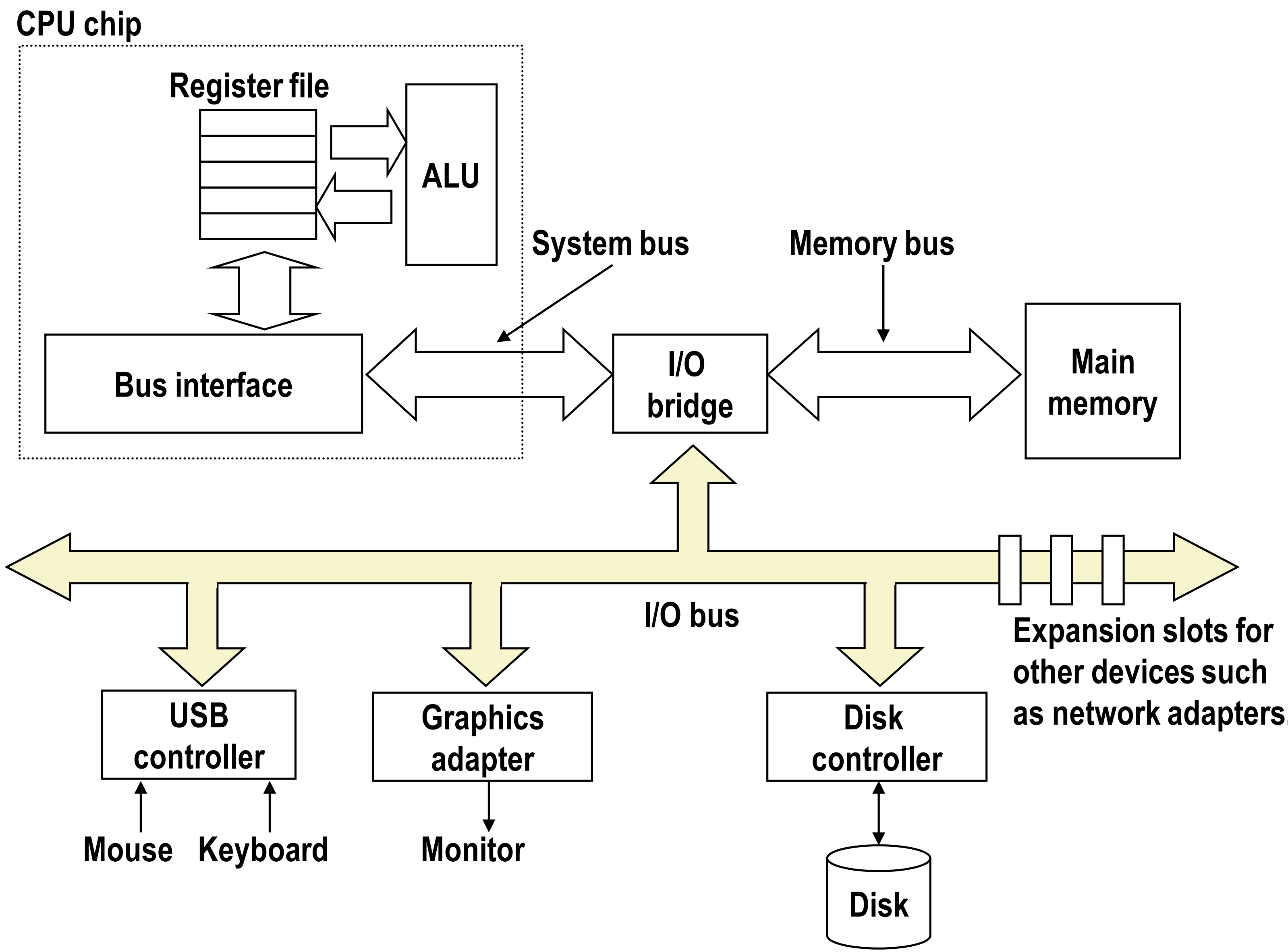


Memory Write Transaction (3)

- Main memory reads data word y from the bus and stores it at address A.

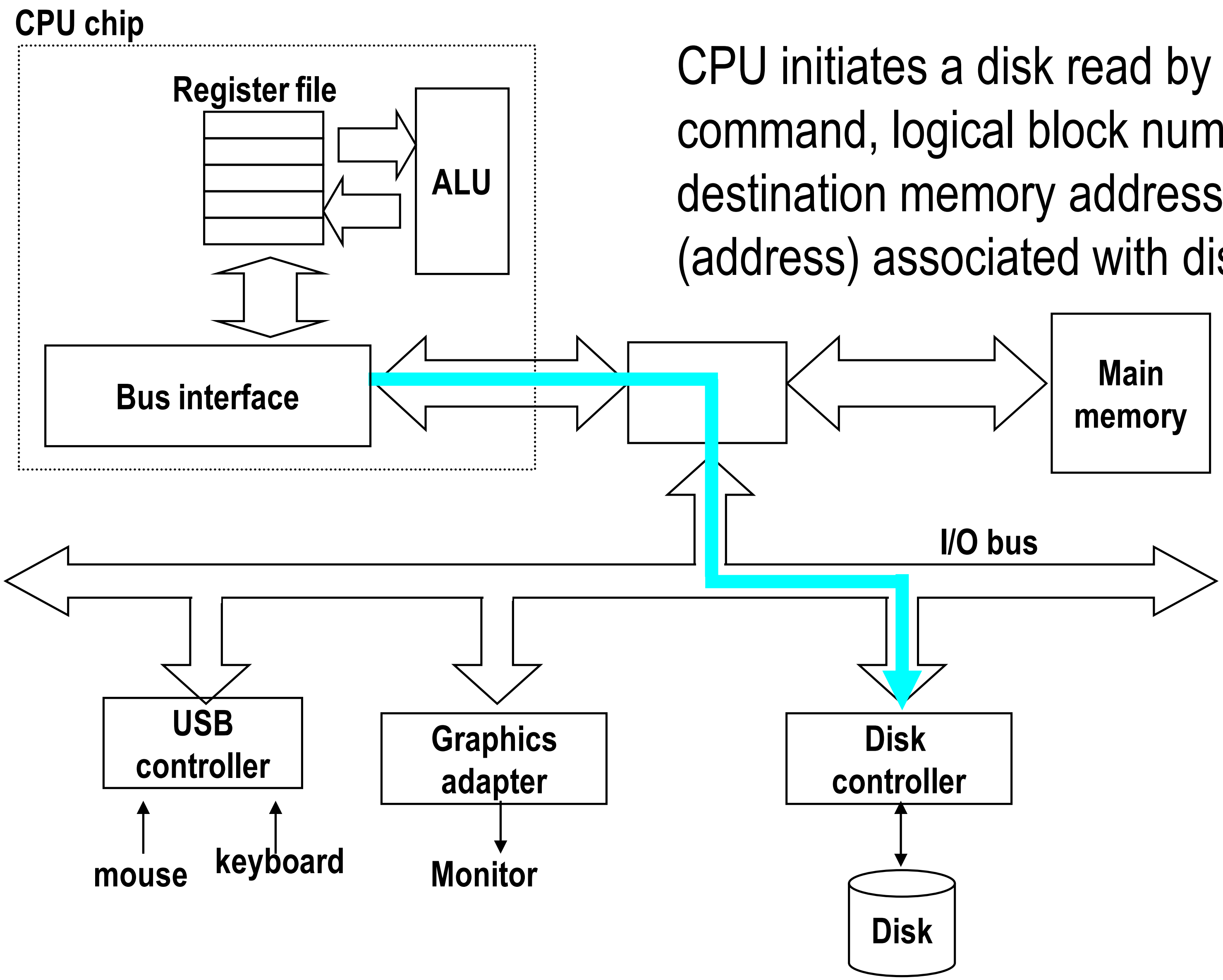


I/O Bus

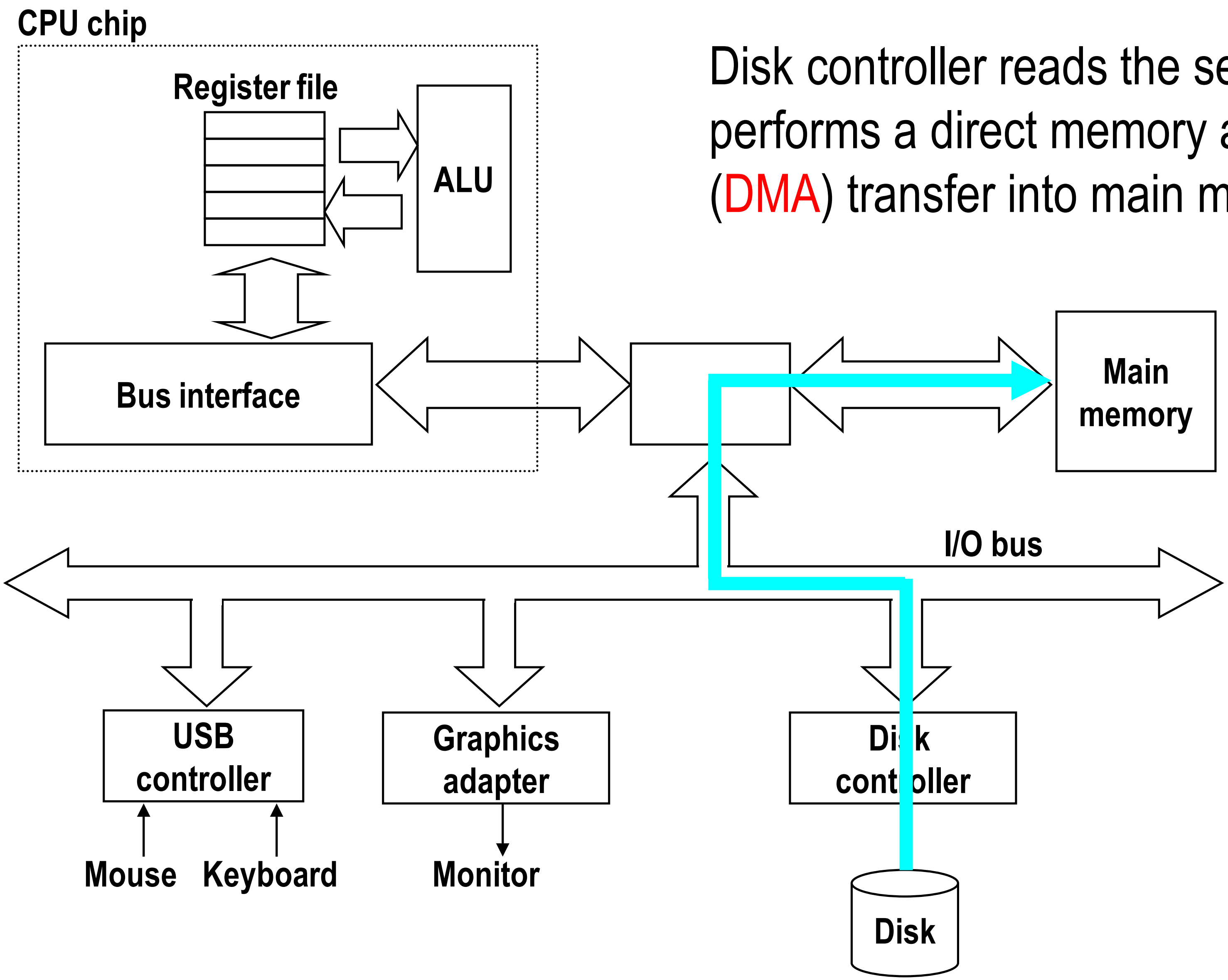

CPU chip
Register file
ALU
System bus
Memory bus
Bus interface
I/O
bridge
Main
memory
I/O bus
Expansion slots for
other devices such
as network adapters.
USB
controller
Graphics
adapter
Disk
controller
Mouse
Keyboard
Monitor
Disk

Reading a Disk Sector (1)

CPU initiates a disk read by writing a command, logical block number, and destination memory address to a port (address) associated with disk controller.



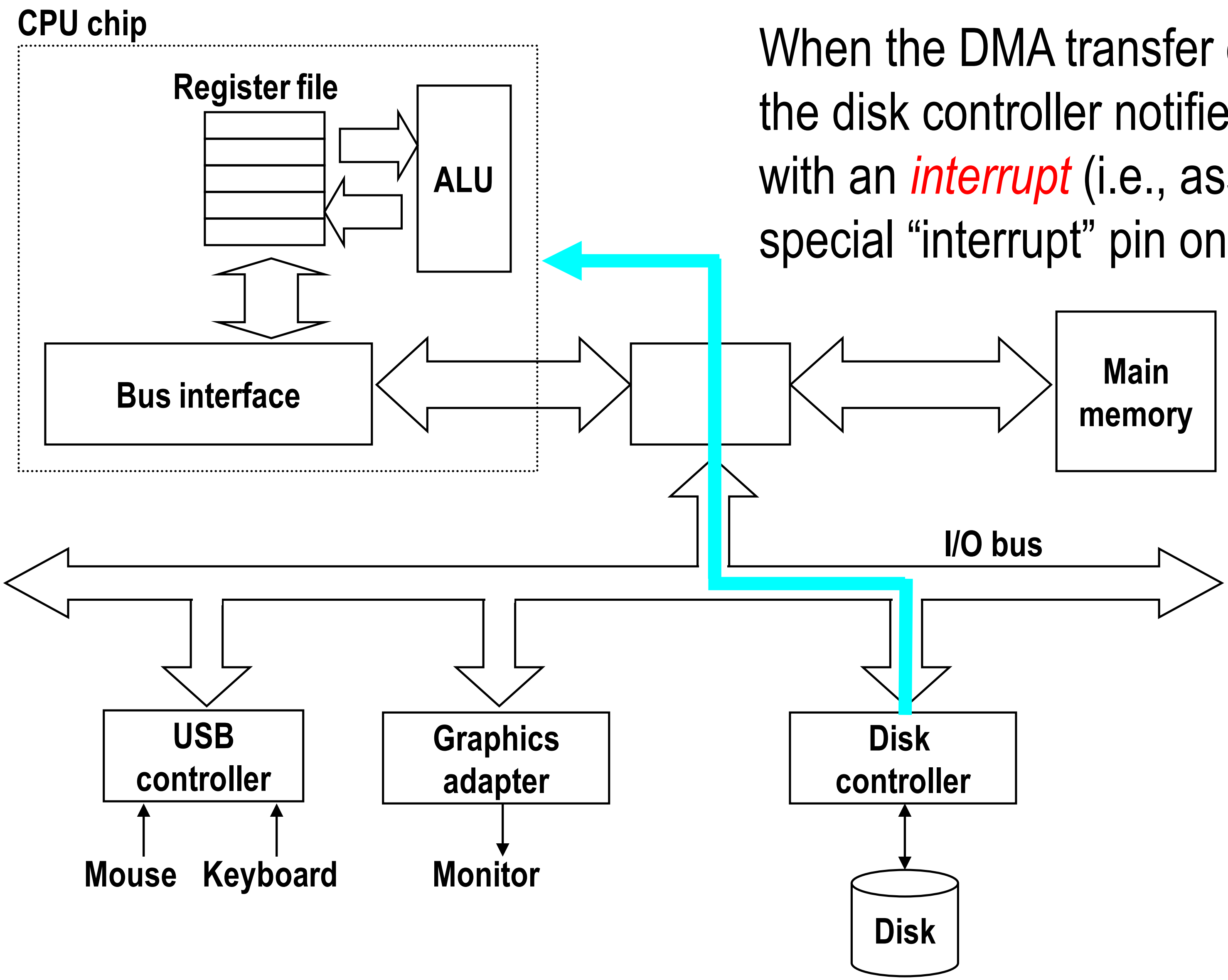
Reading a Disk Sector (2)



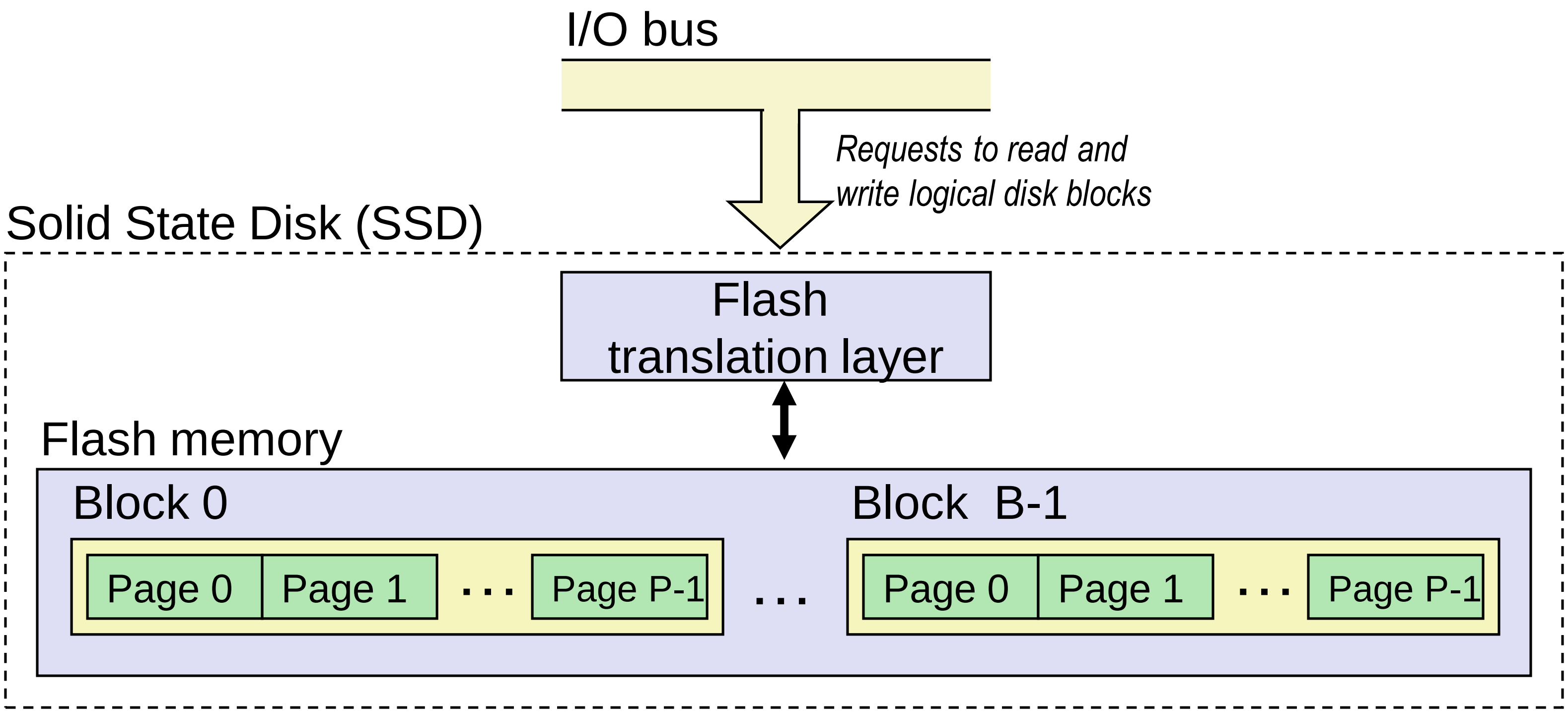
Disk controller reads the sector and performs a direct memory access (DMA) transfer into main memory.

Reading a Disk Sector (3)

When the DMA transfer completes, the disk controller notifies the CPU with an *interrupt* (i.e., asserts a special "interrupt" pin on the CPU)



Solid State Disks (SSDs)



- Pages: 512KB to 4KB, Blocks: 32 to 128 pages
- Data read/written in units of pages.
- Page can be written only after its block has been erased
- A block wears out after 100,000 repeated writes.

SSD Performance Characteristics

Sequential read tput	250 MB/s	Sequential write tput	170 MB/s
Random read tput	140 MB/s	Random write tput	14 MB/s
Rand read access	30 us	Random write access	300 us

- **Why are random writes so slow?**
  - Erasing a block is slow (around 1 ms)
  - Write to a page triggers a copy of all useful pages in the block
    - Find an used block (new block) and erase it
    - Write the page into the new block
    - Copy other pages from old block to the new block

SSD Tradeoffs vs Rotating Disks

- **Advantages**
  - No moving parts → faster, less power, more rugged
- **Disadvantages**
  - Have the potential to wear out
    - Mitigated by "wear leveling logic" in flash translation layer
    - E.g. Intel X25 guarantees 1 petabyte (10^{15} bytes) of random writes before they wear out
  - In 2010, about 100 times more expensive per byte
- **Applications**
  - MP3 players, smart phones, laptops
  - Beginning to appear in desktops and servers

Storage Trends

SRAM

Metric	1980	1985	1990	1995	2000	2005	2010	*2010:1980*
$/MB	19,200	2,900	320	256	100	75	60	*320*
access (ns)	300	150	35	15	3	2	1.5	*200*

DRAM

Metric	1980	1985	1990	1995	2000	2005	2010	*2010:1980*
$/MB	8,000	880	100	30	1	0.1	0.06	*130,000*
access (ns)	375	200	100	70	60	50	40	*9*
typical size (MB)	0.064	0.256	4	16	64	2,000	8,000	*125,000*

Disk

Metric	1980	1985	1990	1995	2000	2005	2010	*2010:1980*
$/MB	500	100	8	0.30	0.01	0.005	0.0003	*1,600,000*
access (ms)	87	75	28	10	8	*4*	*3*	*29*
typical size (MB)	1	10	160	1,000	20,000	160,000	1,500,000	*1,500,000*

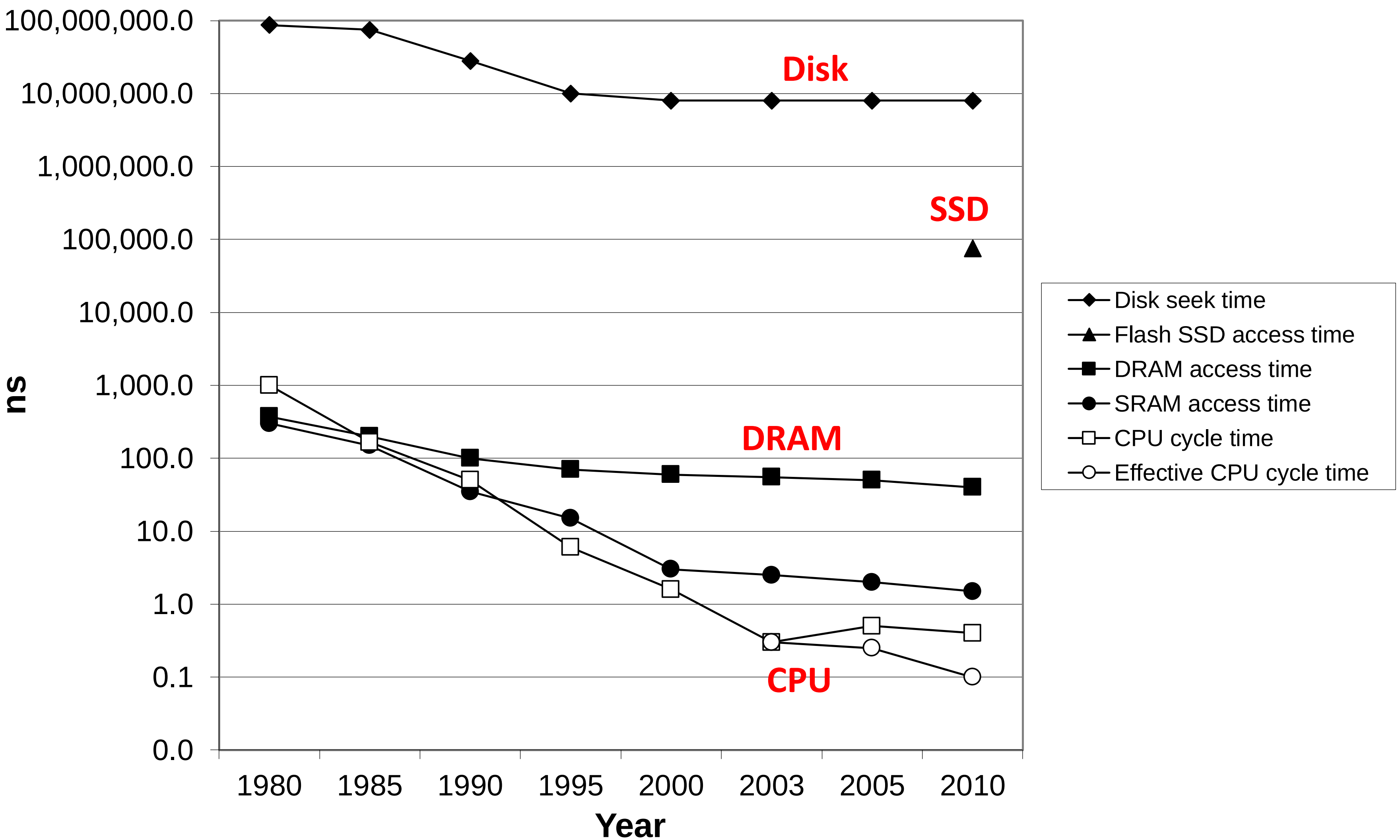
CPU Clock Rates

Inflection point in computer history
when designers hit the "Power Wall"

	1980	1990	1995	2000	2003	2005	2010	*2010:1980*
CPU	8080	386	Pentium	P-III	P-4	Core 2	Core i7	---
Clock rate (MHz)	1	20	150	600	3300	2000	2500	2500
Cycle time (ns)	1000	50	6	1.6	0.3	0.50	0.4	2500
Cores	1	1	1	1	1	2	4	4
Effective cycle time (ns)	1000	50	6	1.6	0.3	0.25	0.1	10,000

The CPU-Memory Gap

The gap widens between DRAM, disk, and CPU speeds.



Locality to the Rescue!

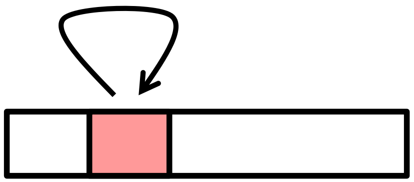
The key to bridging this CPU-Memory gap is a fundamental property of computer programs known as **locality**

Today

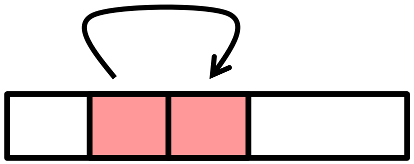
- Storage technologies and trends
- Locality of reference
- Caching in the memory hierarchy

Locality

- **Principle of Locality: Programs tend to use data and instructions with addresses near or equal to those they have used recently**



- **Temporal locality:**
  - Recently referenced items are likely to be referenced again in the near future



- **Spatial locality:**
  - Items with nearby addresses tend to be referenced close together in time

Locality Example

```
sum = 0;
for (i = 0; i < n; i++)
    sum += a[i];
return sum;
```

- **Data references**
  - Reference array elements in succession (stride-1 reference pattern). **Spatial locality**
  - Reference variable `sum` each iteration. **Temporal locality**
- **Instruction references**
  - Reference instructions in sequence. **Spatial locality**
  - Cycle through loop repeatedly. **Temporal locality**

Qualitative Estimates of Locality

- **Claim:** Being able to look at code and get a qualitative sense of its locality is a key skill for a professional programmer.

- **Question:** Does this function have good locality with respect to array `a`?

```
int sum_array_rows(int a[M][N])
{
    int i, j, sum = 0;

    for (i = 0; i < M; i++)
        for (j = 0; j < N; j++)
            sum += a[i][j];
    return sum;
}
```

Locality Example

- **Question:** **Does this function have good locality with respect to array `a`?**

```
int sum_array_cols(int a[M][N])
{
    int i, j, sum = 0;

    for (j = 0; j < N; j++)
        for (i = 0; i < M; i++)
            sum += a[i][j];
    return sum;
}
```

Memory Hierarchies

- **Some fundamental and enduring properties of hardware and software:**
  - Fast storage technologies cost more per byte, have less capacity, and require more power (heat!).
  - The gap between CPU and main memory speed is widening.
  - Well-written programs tend to exhibit good locality.

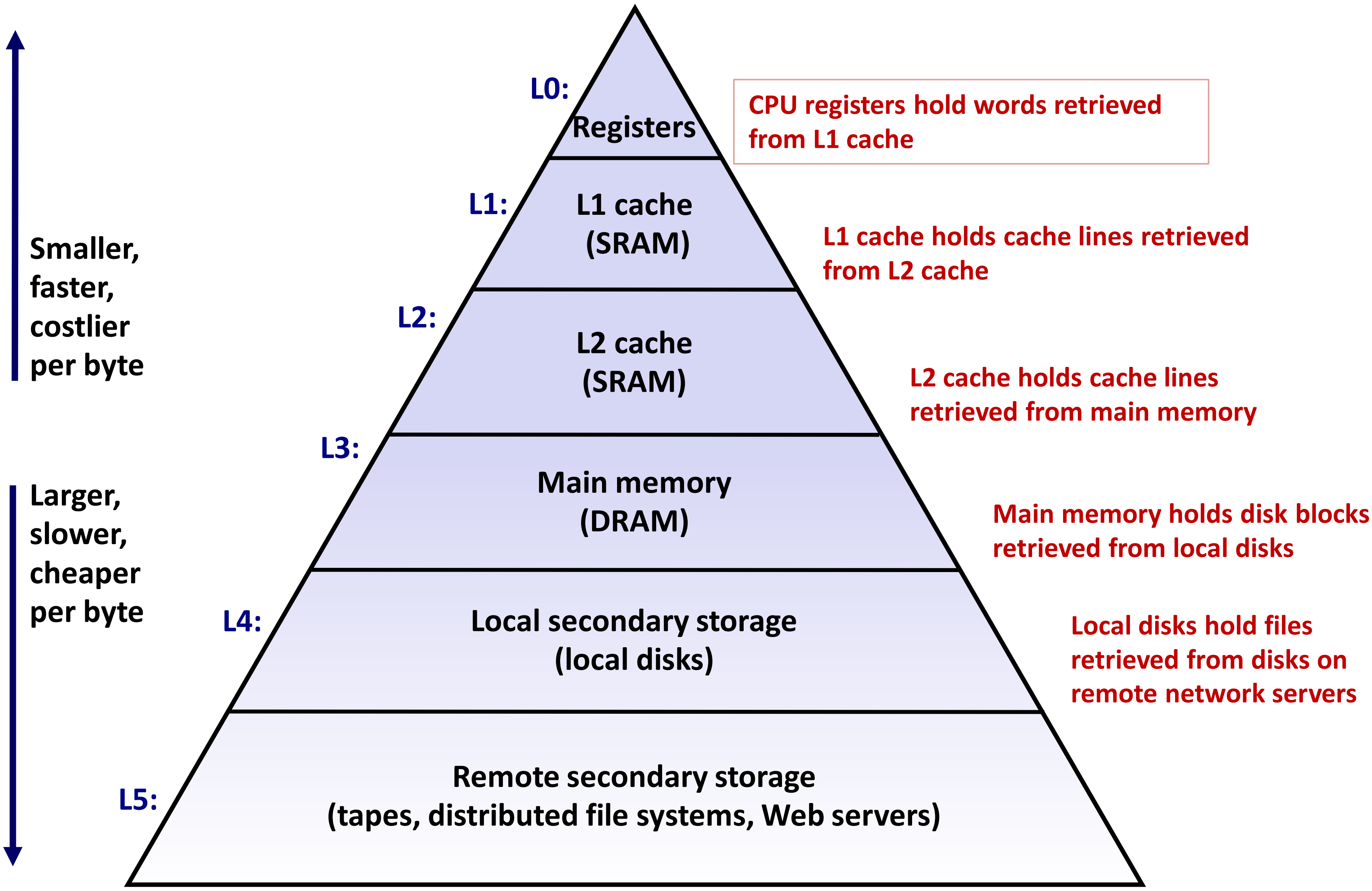
- **These fundamental properties complement each other beautifully.**

- **They suggest an approach for organizing memory and storage systems known as a memory hierarchy.**

Today

- Storage technologies and trends
- Locality of reference
- **Caching in the memory hierarchy**

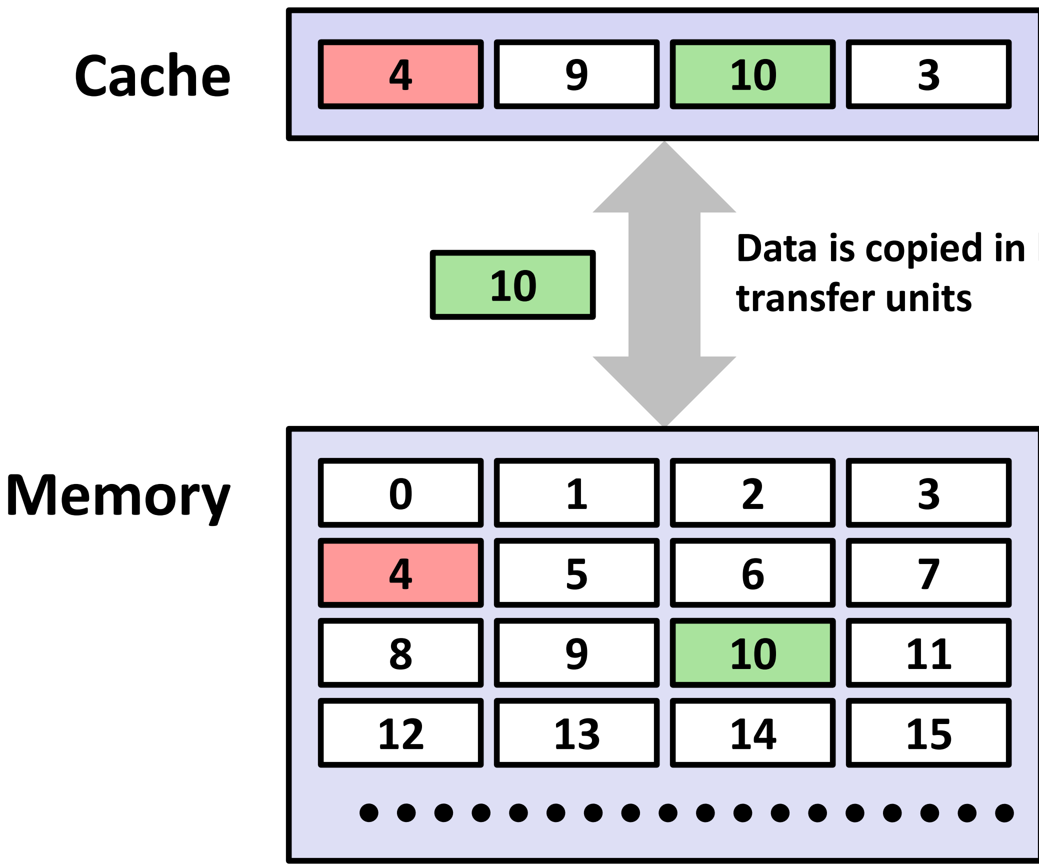
An Example Memory Hierarchy



Caches

- ***Cache:*** **A smaller, faster storage device that acts as a staging area for a subset of the data in a larger, slower device.**
- **Fundamental idea of a memory hierarchy:**
  - For each k, the faster, smaller device at level k serves as a cache for the larger, slower device at level k+1.
- **Why do memory hierarchies work?**
  - Because of locality, programs tend to access the data at level k more often than they access the data at level k+1.
  - Thus, the storage at level k+1 can be slower, and thus larger and cheaper per bit.
- ***Big Idea:*** **The memory hierarchy creates a large pool of storage that costs as much as the cheap storage near the bottom, but that serves data to programs at the rate of the fast storage near the top.**

General Cache Concepts

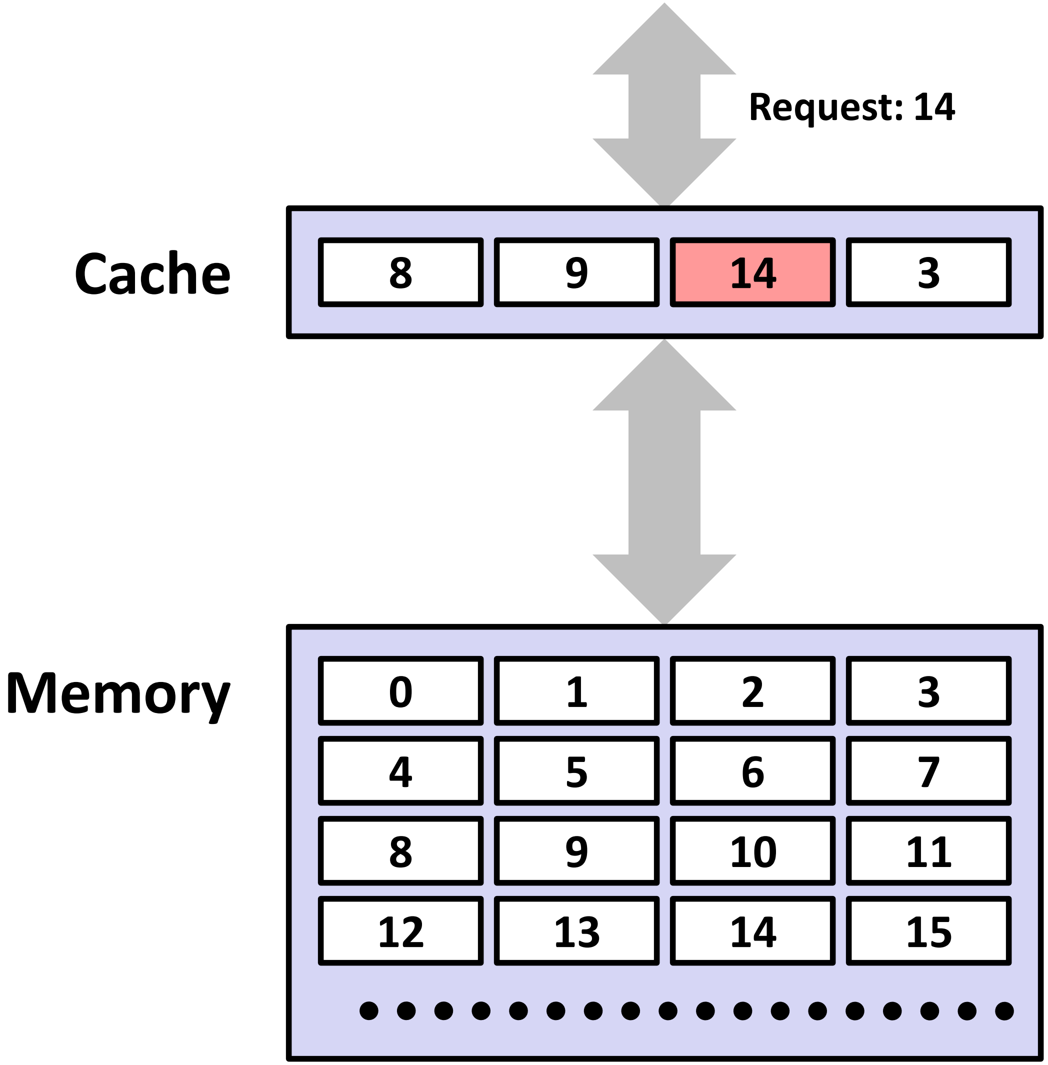


Smaller, faster, more expensive memory caches a subset of the blocks

Data is copied in block-sized transfer units

Larger, slower, cheaper memory viewed as partitioned into “blocks”

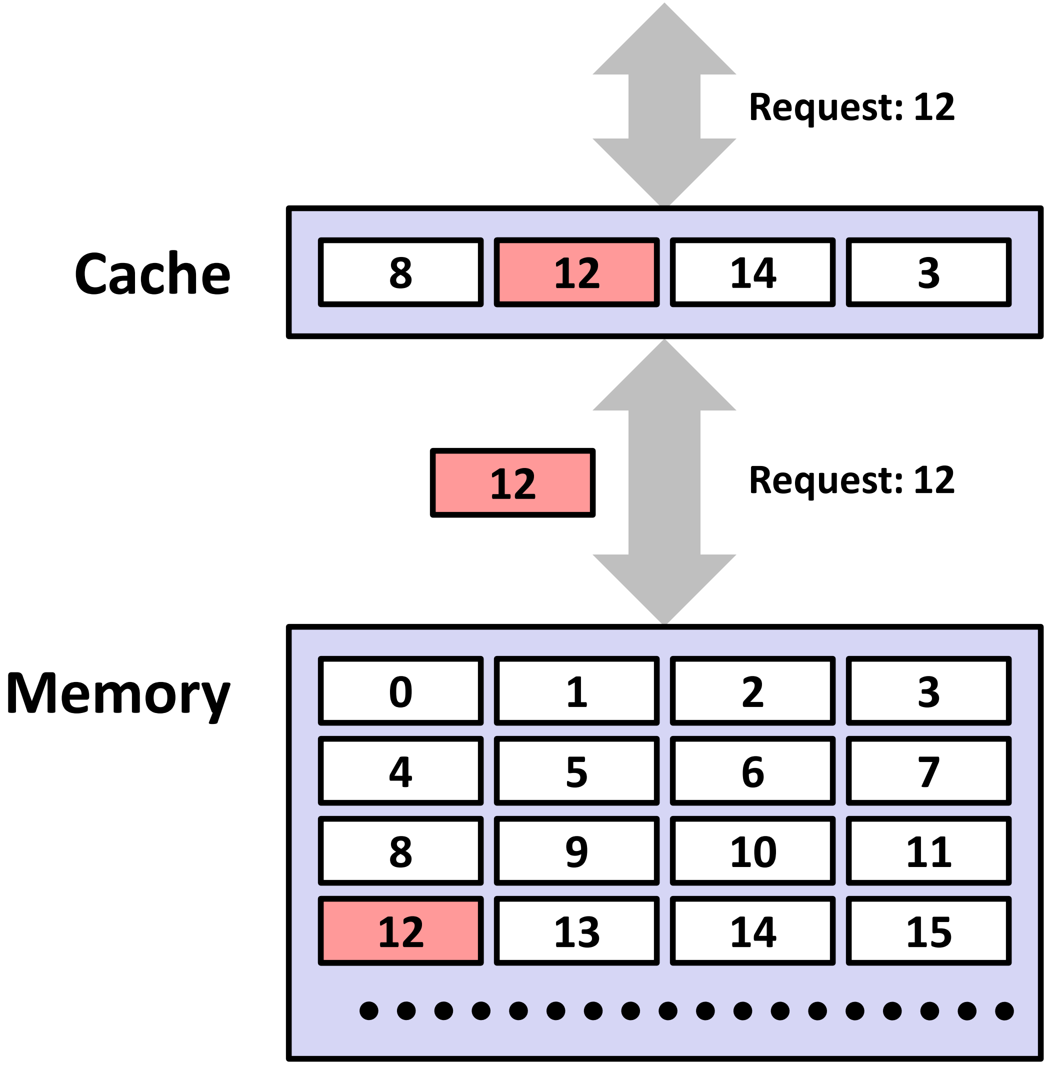
General Cache Concepts: Hit



Data in block b is needed

Block b is in cache:
Hit!

General Cache Concepts: Miss



Data in block b is needed

Block b is not in cache:
Miss!

Block b is fetched from memory

Block b is stored in cache

- Placement policy: determines where b goes
- Replacement policy: determines which block gets evicted (victim)

General Caching Concepts: Types of Cache Misses

- **Cold (compulsory) miss**
  - Cold misses occur because the cache is empty.
- **Conflict miss**
  - Most caches limit blocks at level k+1 to a small subset (sometimes a singleton) of the block positions at level k.
    - E.g. Block i at level k+1 must be placed in block (i mod 4) at level k.
  - Conflict misses occur when the level k cache is large enough, but multiple data objects all map to the same level k block.
    - E.g. Referencing blocks 0, 8, 0, 8, 0, 8, ... would miss every time.
- **Capacity miss**
  - Occurs when the set of active cache blocks (working set) is larger than the cache.

Examples of Caching in the Hierarchy

Cache Type	What is Cached?	Where is it Cached?	Latency (cycles)	Managed By
Registers	4-8 bytes words	CPU core	0	Compiler
TLB	Address translations	On-Chip TLB	0	Hardware
L1 cache	64-bytes block	On-Chip L1	1	Hardware
L2 cache	64-bytes block	On/Off-Chip L2	10	Hardware
Virtual Memory	4-KB page	Main memory	100	Hardware + OS
Buffer cache	Parts of files	Main memory	100	OS
Disk cache	Disk sectors	Disk controller	100,000	Disk firmware
Network buffer cache	Parts of files	Local disk	10,000,000	AFS/NFS client
Browser cache	Web pages	Local disk	10,000,000	Web browser
Web cache	Web pages	Remote server disks	1,000,000,000	Web proxy server

Summary

- The speed gap between CPU, memory and mass storage continues to widen.

- Well-written programs exhibit a property called locality.

- Memory hierarchies based on caching close the gap by exploiting locality.

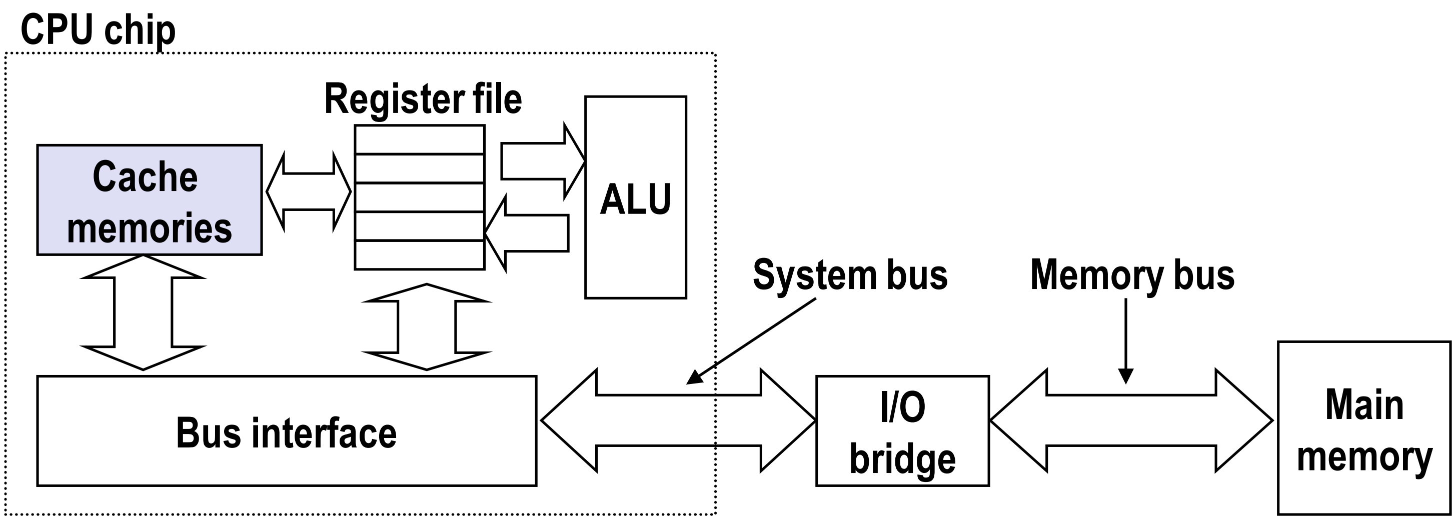
Cache Memories

Today

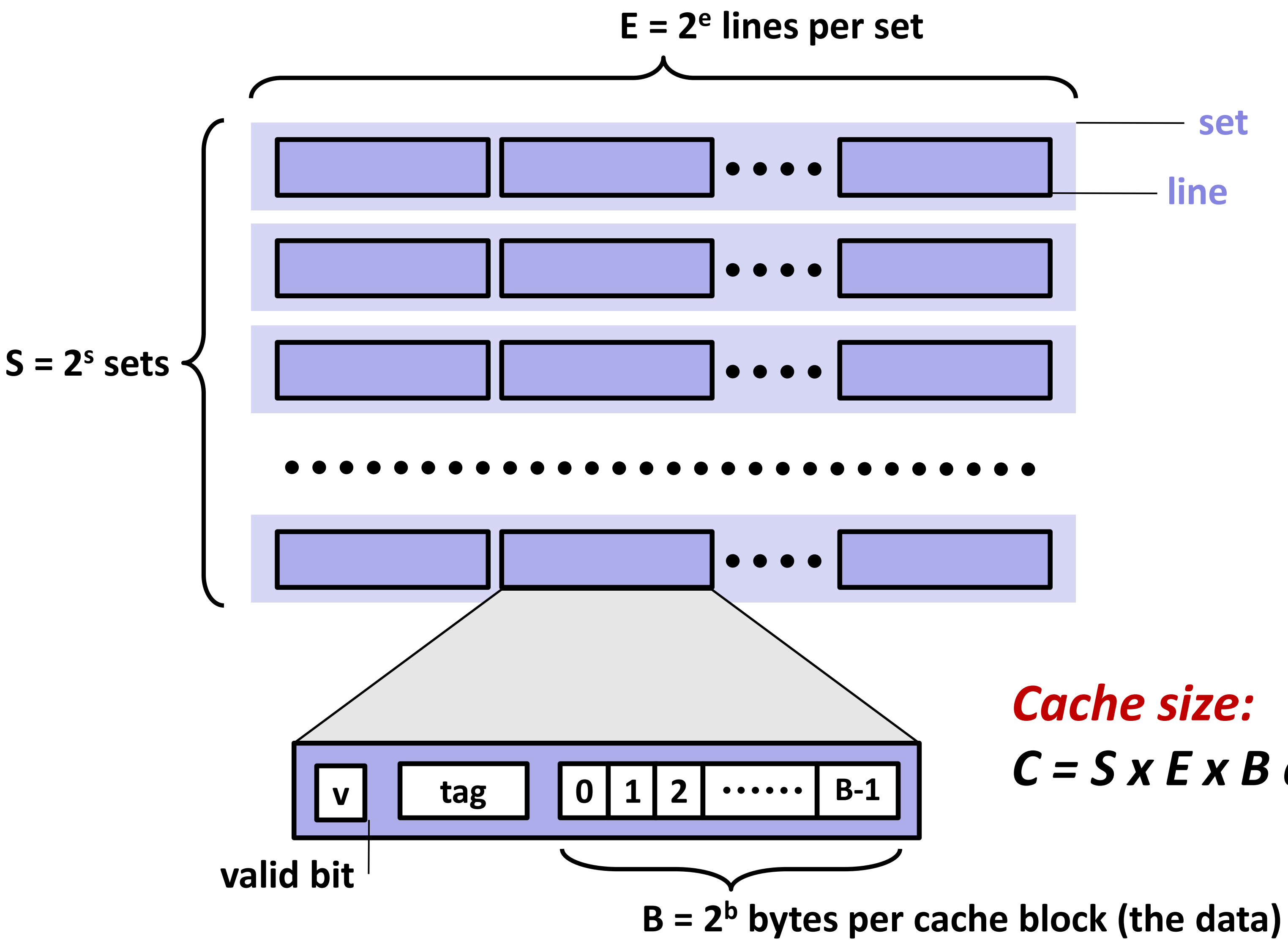
- **Cache memory organization and operation**
- Performance impact of caches
  - The memory mountain
  - Rearranging loops to improve spatial locality
  - Using blocking to improve temporal locality

Cache Memories

- **Cache memories are small, fast SRAM-based memories managed automatically in hardware.**
  - Hold frequently accessed blocks of main memory
- **CPU looks first for data in caches (e.g., L1, L2, and L3), then in main memory.**
- **Typical system structure:**



General Cache Organization (S, E, B)

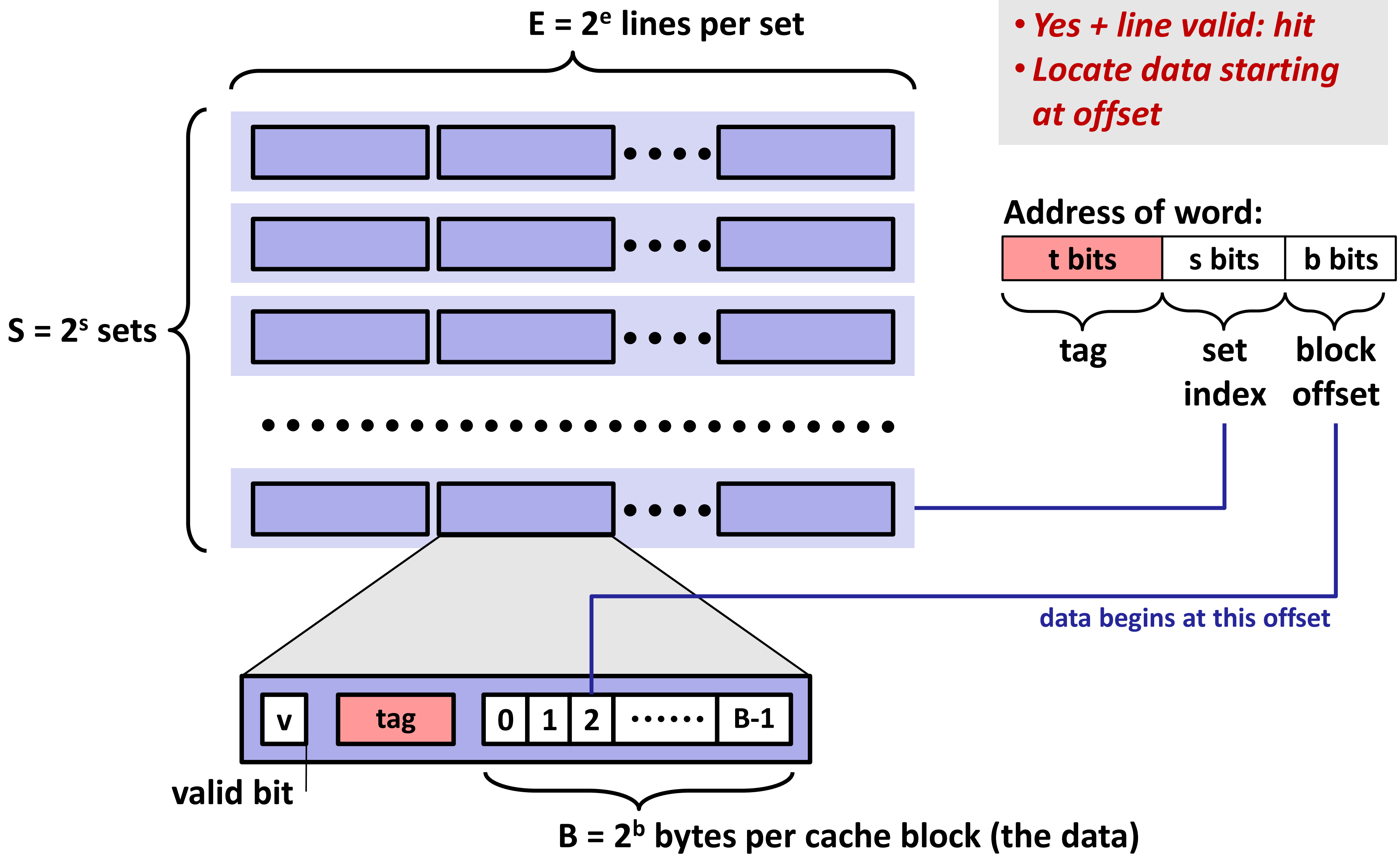


Cache size:

C = S x E x B data bytes

Cache Read

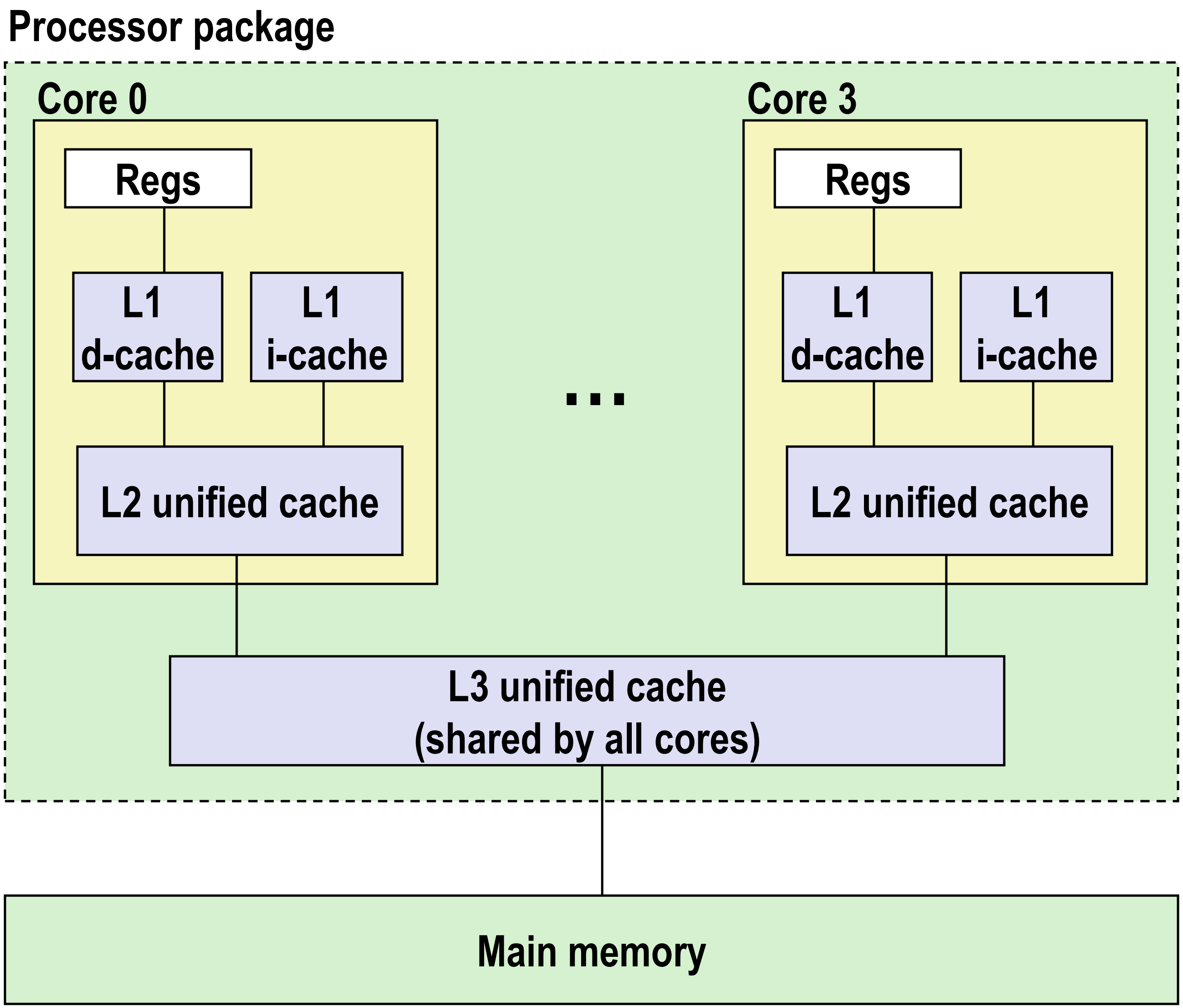
- *Locate set*
- *Check if any line in set has matching tag*
- *Yes + line valid: hit*
- *Locate data starting at offset*



What about writes?

- **Multiple copies of data exist:**
  - L1, L2, Main Memory, Disk
- **What to do on a write-hit?**
  - Write-through (write immediately to memory)
  - Write-back (defer write to memory until replacement of line)
    - Need a dirty bit (line different from memory or not)
- **What to do on a write-miss?**
  - Write-allocate (load into cache, update line in cache)
    - Good if more writes to the location follow
  - No-write-allocate (writes immediately to memory)
- **Typical**
  - Write-through + No-write-allocate
  - **Write-back + Write-allocate**

Intel Core i7 Cache Hierarchy



L1 i-cache and d-cache:
32 KB, 8-way,
Access: 4 cycles

L2 unified cache:
256 KB, 8-way,
Access: 11 cycles

L3 unified cache:
8 MB, 16-way,
Access: 30-40 cycles

Block size: 64 bytes for all caches.

Knights Landing (KNL): 2nd Generation Intel® Xeon Phi™ Processor (2016)

Knights Landing Overview

Omni-path not shown

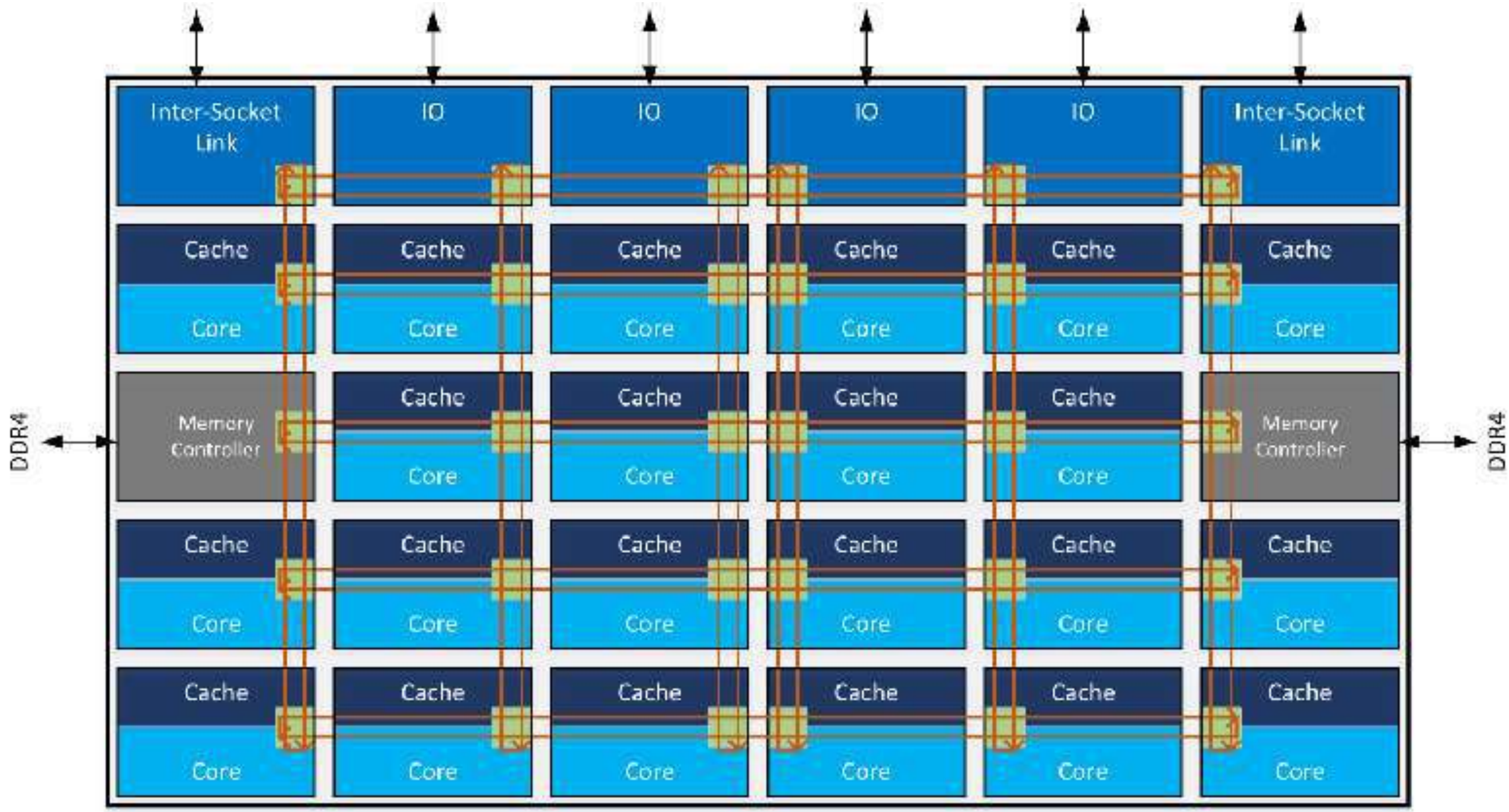
Chip: 36 Tiles interconnected by **2D Mesh**
Tile: 2 Cores + 2 VPU/core + 1 MB L2

Memory: MCDRAM: 16 GB on-package; High BW
DDR4: 6 channels @ 2400 up to 384GB
IO: 36 lanes PCIe Gen3. 4 lanes of DMI for chipset
Node: 1-Socket only
Fabric: Omni-Path on-package (not shown)

Vector Peak Perf: 3+TF DP and 6+TF SP Flops
Scalar Perf: ~3x over Knights Corner
Streams Triad (GB/s): MCDRAM : 400+; DDR: 90+

Source Intel: All products, computer systems, dates and figures specified are preliminary based on current expectations, and are subject to change without notice. KNL data are preliminary based on current expectations and are subject to change without notice. 1Binary Compatible with Intel Xeon processors using Haswell Instruction Set (except TSX). 2Bandwidth numbers are based on STREAM-like memory access pattern when MCDRAM used as flat memory. Results have been estimated based on internal Intel analysis and are provided for informational purposes only. Any difference in system hardware or software design or configuration may affect actual performance.

Intel Xeon Scalable processors



Cache Performance Metrics

- **Miss Rate**
  - Fraction of memory references not found in cache (misses / accesses) = 1 – hit rate
  - Typical numbers (in percentages):
    - 3-10% for L1
    - can be quite small (e.g., < 1%) for L2, depending on size, etc.
- **Hit Time**
  - Time to deliver a line in the cache to the processor
    - includes time to determine whether the line is in the cache
  - Typical numbers:
    - 1-2 clock cycle for L1
    - 5-20 clock cycles for L2
- **Miss Penalty**
  - Additional time required because of a miss
    - typically 50-200 cycles for main memory (Trend: increasing!)

Lets think about those numbers

- **Huge difference between a hit and a miss**
  - Could be 100x, if just L1 and main memory

- **Would you believe 99% hits is twice as good as 97%?**
  - Consider:
    cache hit time of 1 cycle
    miss penalty of 100 cycles

  - Average access time:

    97% hits: 1 cycle + 0.03 * 100 cycles = **4 cycles**

    99% hits: 1 cycle + 0.01 * 100 cycles = **2 cycles**

- **This is why "miss rate" is used instead of "hit rate"**

Writing Cache Friendly Code

- **Make the common case go fast**
  - Focus on the inner loops of the core functions

- **Minimize the misses in the inner loops**
  - Repeated references to variables are good (temporal locality)
  - Stride-1 reference patterns are good (spatial locality)

Key idea: Our qualitative notion of locality is quantified through our understanding of cache memories.

Concluding Observations

- **Programmer can optimize for cache performance**
  - How data structures are organized
  - How data are accessed
    - Nested loop structure
    - Blocking is a general technique
- **All systems favor "cache friendly code"**
  - Getting absolute optimum performance is very platform specific
    - Cache sizes, line sizes, associativities, etc.
  - Can get most of the advantage with generic code
    - Keep working set reasonably small (temporal locality)
    - Use small strides (spatial locality)

Linking

Example C Program

main.c

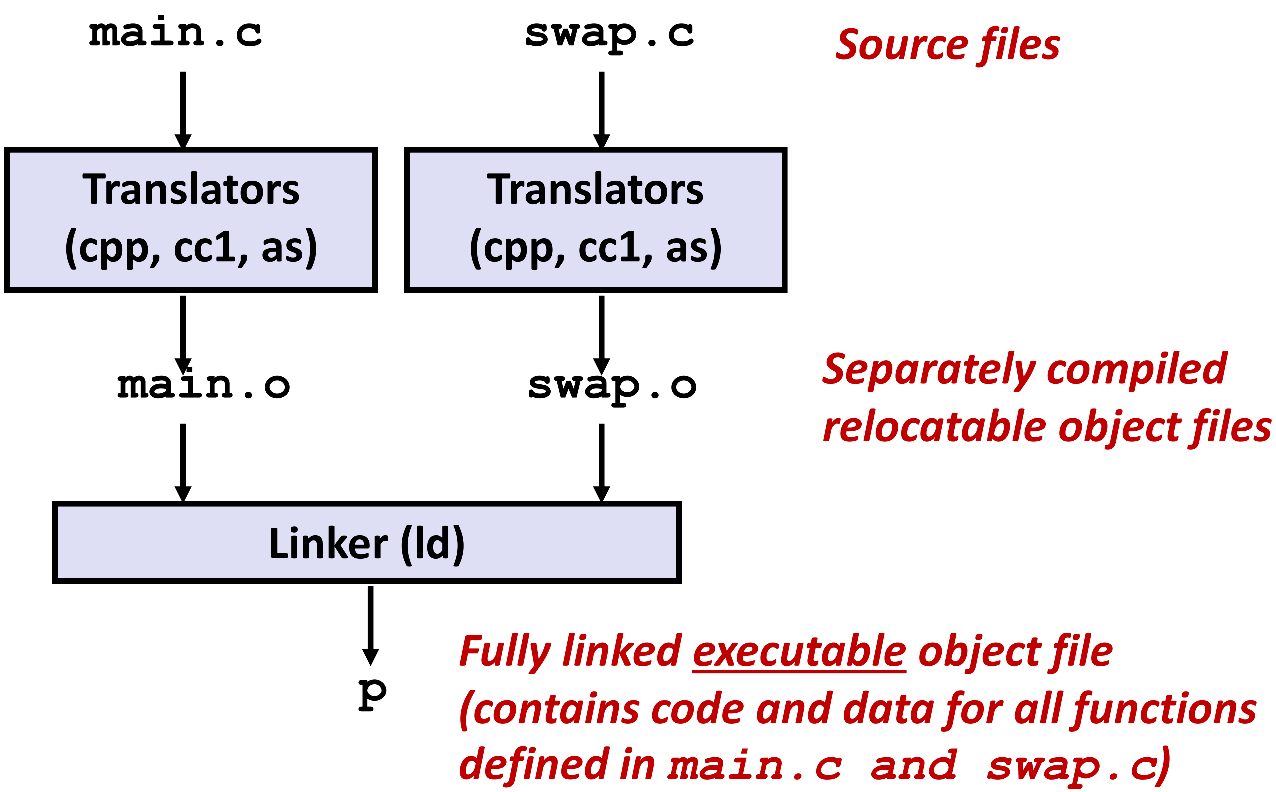
```
int buf[2] = {1, 2};

int main()
{
  swap();
  return 0;
}
```

swap.c

```
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

Static Linking

- Programs are translated and linked using a *compiler driver*:
  - `unix> gcc -O2 -g -o p main.c swap.c`
  - `unix> ./p`



Why Linkers?

- **Reason 1: Modularity**

  - Program can be written as a collection of smaller source files, rather than one monolithic mass.

  - Can build libraries of common functions (more on this later)
    - e.g., Math library, standard C library

Why Linkers? (cont)

- **Reason 2: Efficiency**
  - Time: Separate compilation
    - Change one source file, compile, and then relink.
    - No need to recompile other source files.
  - Space: Libraries
    - Common functions can be aggregated into a single file...
    - Yet executable files and running memory images contain only code for the functions they actually use.

What Do Linkers Do?

- **Step 1. Symbol resolution**
  - Programs define and reference *symbols* (variables and functions):
    - `void swap() {…}    /* define symbol swap */`
    - `swap();            /* reference symbol a */`
    - `int *xp = &x;      /* define symbol xp, reference x */`
  - Symbol definitions are stored (by compiler) in *symbol table*.
    - Symbol table is an array of structs
    - Each entry includes name, size, and location of symbol.
  - Linker associates each symbol reference with exactly one symbol definition.

What Do Linkers Do? (cont)

- **Step 2. Relocation**
  - Merges separate code and data sections into single sections
  - Relocates symbols from their relative locations in the `.o` files to their final absolute memory locations in the executable.
  - Updates all references to these symbols to reflect their new positions.

Three Kinds of Object Files (Modules)

- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one source (`.c`) file
- **Executable object file (`a.out` file)**
  - Contains code and data in a form that can be copied directly into memory and then executed.
- **Shared object file (`.so` file)**
  - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
  - Called *Dynamic Link Libraries* (DLLs) by Windows

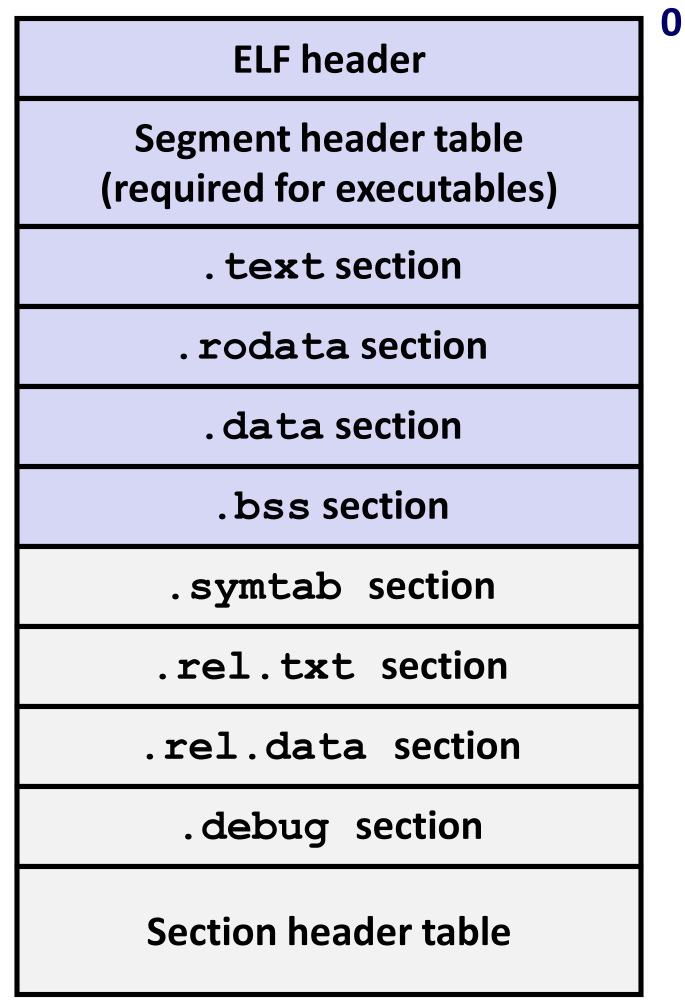
Executable and Linkable Format (ELF)

- **Standard binary format for object files**
- **Originally proposed by AT&T System V Unix**
  - Later adopted by BSD Unix variants and Linux
- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files (`a.out`)
  - Shared object files (`.so`)

- **Generic name: ELF binaries**

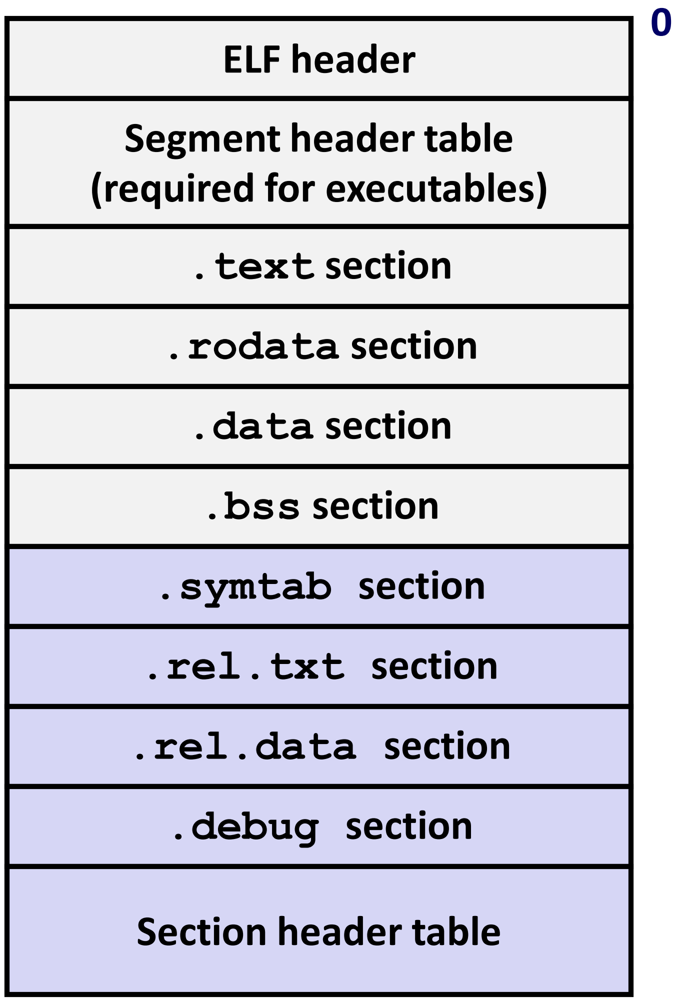
ELF Object File Format

- **Elf header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **Segment header table**
  - Page size, virtual addresses memory segments (sections), segment sizes.
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, ...
- **`.data` section**
  - Initialized global variables
- **`.bss` section**
  - Uninitialized global variables
  - "Block Started by Symbol"
  - "Better Save Space"
  - Has section header but occupies no space



ELF Object File Format (cont.)

- **`.symtab` section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- **`.rel.text` section**
  - Relocation info for **`.text`** section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.
- **`.rel.data` section**
  - Relocation info for **`.data`** section
  - Addresses of pointer data that will need to be modified in the merged executable
- **`.debug` section**
  - Info for symbolic debugging (**`gcc -g`**)
- **Section header table**
  - Offsets and sizes of each section



Linker Symbols

- **Global symbols**
  - Symbols defined by module *m* that can be referenced by other modules.
  - E.g.: non-`static` C functions and non-`static` global variables.

- **External symbols**
  - Global symbols that are referenced by module *m* but defined by some other module.

- **Local symbols**
  - Symbols that are defined and referenced exclusively by module *m*.
  - E.g.: C functions and variables defined with the `static` attribute.
  - **Local linker symbols are *not* local program variables**

Resolving Symbols

Global

```
int buf[2] = {1, 2};

int main()
{
  swap();
  return 0;
}
```

main.c

External

Global

External

Local

```
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

Global

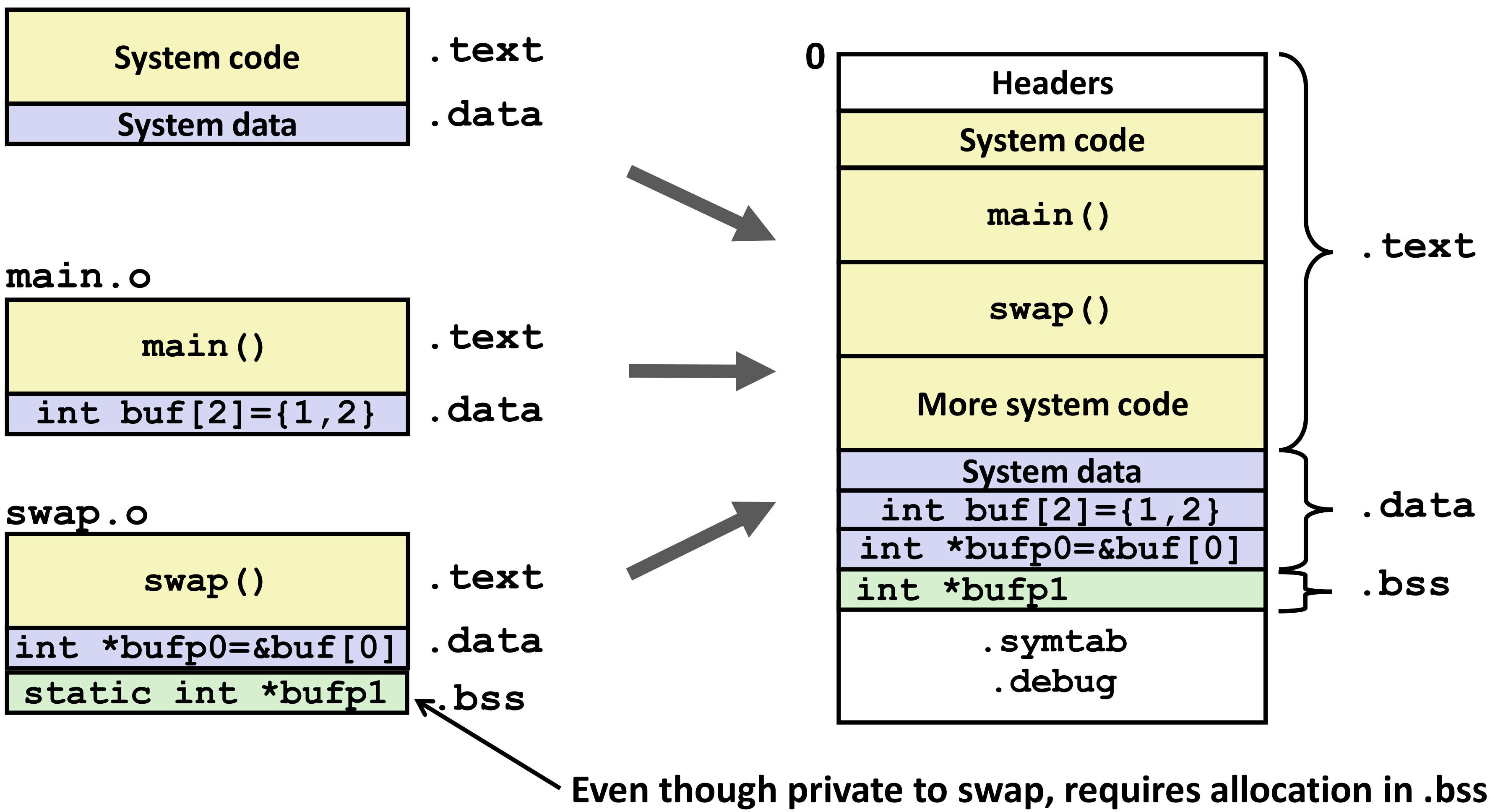
swap.c

Linker knows nothing of temp

Relocating Code and Data

Relocatable Object Files

Executable Object File



Relocation Info (main)

main.c

```
int buf[2] =
   {1,2};

int main()
{
   swap();
   return 0;
}
```

main.o

```
0000000 <main>:
   0:   8d 4c 24 04       lea    0x4(%esp),%ecx
   4:   83 e4 f0          and    $0xfffffff0,%esp
   7:   ff 71 fc          pushl  0xfffffffc(%ecx)
   a:   55                push   %ebp
   b:   89 e5             mov    %esp,%ebp
   d:   51                push   %ecx
   e:   83 ec 04          sub    $0x4,%esp
  11:   e8 fc ff ff ff    call   12 <main+0x12>
                 12: R_386_PC32 swap
  16:   83 c4 04          add    $0x4,%esp
  19:   31 c0             xor    %eax,%eax
  1b:   59                pop    %ecx
  1c:   5d                pop    %ebp
  1d:   8d 61 fc          lea    0xfffffffc(%ecx),%esp
  20:   c3                ret
```

```
Disassembly of section .data:

 00000000 <buf>:
   0:   01 00 00 00 02 00 00 00
```

Source: `objdump -r -d`

Relocation Info (swap, .text)

swap.c

```
extern int buf[];

int
  *bufp0 = &buf[0];

static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

swap.o

```
Disassembly of section .text:

00000000 <swap>:
   0:   8b 15 00 00 00 00       mov    0x0,%edx
                2: R_386_32     buf
   6:   a1 04 00 00 00          mov    0x4,%eax
                7: R_386_32     buf
   b:   55                      push   %ebp
   c:   89 e5                   mov    %esp,%ebp
   e:   c7 05 00 00 00 00 04    movl   $0x4,0x0
  15:   00 00 00
                10: R_386_32    .bss
                14: R_386_32    buf
  18:   8b 08                   mov    (%eax),%ecx
  1a:   89 10                   mov    %edx,(%eax)
  1c:   5d                      pop    %ebp
  1d:   89 0d 04 00 00 00       mov    %ecx,0x4
                1f: R_386_32    buf
  23:   c3                      ret
```

Relocation Info (swap, .data)

swap.c

```
extern int buf[];

int *bufp0 =
            &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

```
Disassembly of section .data:

00000000 <bufp0>:
   0:    00 00 00 00

         0: R_386_32 buf
```

Executable Before/After Relocation (.text)

```
0000000 <main>:
   . . .
   e:   83 ec 04          sub    $0x4,%esp
  11:   e8 fc ff ff ff    call   12 <main+0x12>
              12: R_386_PC32 swap
  16:   83 c4 04          add    $0x4,%esp
  . . .
```

```
0x8048396 + 0x1a
= 0x80483b0
```

```
08048380 <main>:
 8048380:      8d 4c 24 04         lea    0x4(%esp),%ecx
 8048384:      83 e4 f0            and    $0xfffffff0,%esp
 8048387:      ff 71 fc            pushl  0xfffffffc(%ecx)
 804838a:      55                  push   %ebp
 804838b:      89 e5               mov    %esp,%ebp
 804838d:      51                  push   %ecx
 804838e:      83 ec 04            sub    $0x4,%esp
 8048391:      e8 1a 00 00 00      call   80483b0 <swap>
 8048396:      83 c4 04            add    $0x4,%esp
 8048399:      31 c0               xor    %eax,%eax
 804839b:      59                  pop    %ecx
 804839c:      5d                  pop    %ebp
 804839d:      8d 61 fc            lea    0xfffffffc(%ecx),%esp
 80483a0:      c3                  ret
```

```
  0:   8b 15 00 00 00 00       mov    0x0,%edx
                2: R_386_32    buf
  6:   a1 04 00 00 00          mov    0x4,%eax
                7: R_386_32    buf
 ...
  e:   c7 05 00 00 00 00 04    movl   $0x4,0x0
 15:   00 00 00
                10: R_386_32   .bss
                14: R_386_32   buf
 . . .
 1d:   89 0d 04 00 00 00       mov    %ecx,0x4
                1f: R_386_32   buf
 23:   c3                      ret
```

```
080483b0 <swap>:
 80483b0:      8b 15 20 96 04 08       mov    0x8049620,%edx
 80483b6:      a1 24 96 04 08          mov    0x8049624,%eax
 80483bb:      55                      push   %ebp
 80483bc:      89 e5                   mov    %esp,%ebp
 80483be:      c7 05 30 96 04 08 24    movl   $0x8049624,0x8049630
 80483c5:      96 04 08
 80483c8:      8b 08                   mov    (%eax),%ecx
 80483ca:      89 10                   mov    %edx,(%eax)
 80483cc:      5d                      pop    %ebp
 80483cd:      89 0d 24 96 04 08       mov    %ecx,0x8049624
 80483d3:      c3                      ret
```

Executable After Relocation (.data)

```
Disassembly of section .data:

08049620 <buf>:
 8049620:       01 00 00 00 02 00 00 00

08049628 <bufp0>:
 8049628:       20 96 04 08
```

Strong and Weak Symbols

- **Program symbols are either strong or weak**
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals

`p1.c`

```
int foo=5;

p1() {
}
```

strong → `int foo=5;`

strong → `p1() {`

`p2.c`

```
int foo;

p2() {
}
```

`int foo;` ← weak

`p2() {` ← strong

Linker's Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error
- **Rule 2: Given a strong symbol and multiple weak symbol, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol
- **Rule 3: If there are multiple weak symbols, pick an arbitrary one**
  - Can override this with **`gcc -fno-common`**

Linker Puzzles

`int x;` `p1() {}`	`p1() {}`	Link time error: two strong symbols (**`p1`**)
`int x;` `p1() {}`	`int x;` `p2() {}`	References to **`x`** will refer to the same uninitialized int. Is this what you really want?

`int x;`
`int y;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to **`x`** in **`p2`** might overwrite **`y`**! Evil!

`int x=7;`
`int y=5;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to **`x`** in **`p2`** will overwrite **`y`**! Nasty!

`int x=7;` `p1() {}`	`int x;` `p2() {}`	References to **`x`** will refer to the same initialized variable.

Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

Role of .h Files

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

c2.c

```
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

Running Preprocessor

c1.c

```c
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```c
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

-DINITIALIZE

```c
int g = 23;
static int init = 1;
int f() {
  return g+1;
}
```

no initialization

```c
int g;
static int init = 0;
int f() {
  return g+1;
}
```

#include causes C preprocessor to insert file verbatim

Role of .h Files (cont.)

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

c2.c

```
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

What happens:

```
gcc -o p c1.c c2.c
```

??

```
gcc -o p c1.c c2.c \
  -DINITIALIZE
```

??

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use `static` if you can
  - Initialize if you define a global variable
  - Use `extern` if you use external global variable

Packaging Commonly Used Functions

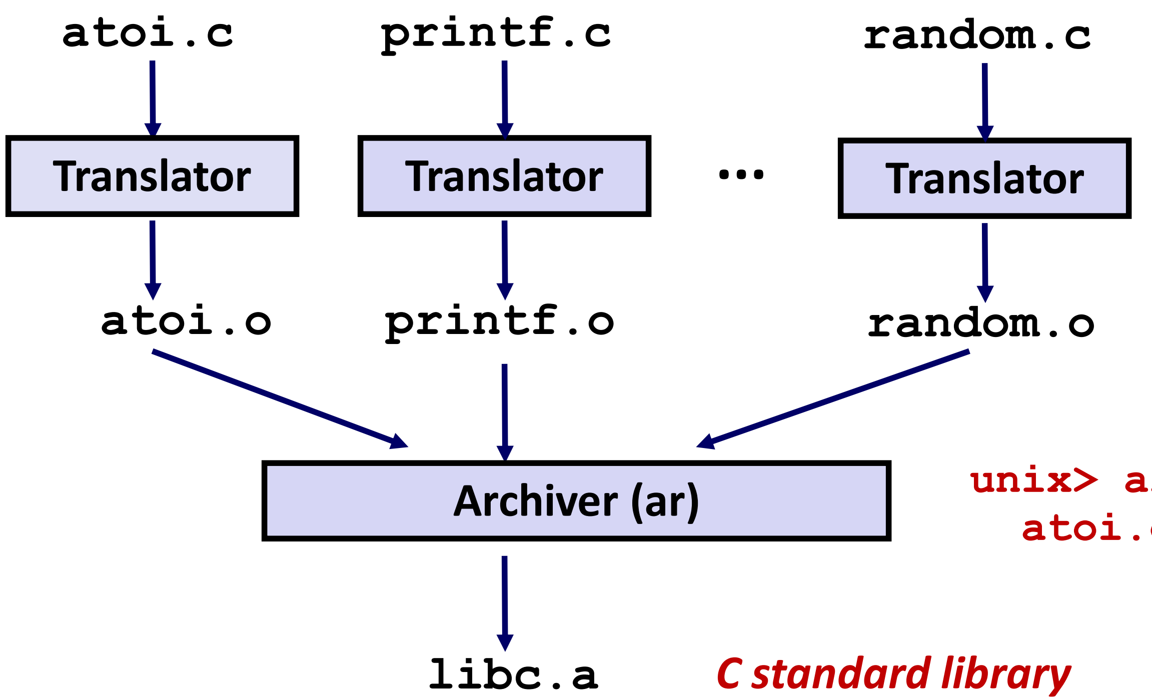
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into a single source file
    - Programmers link big object file into their programs
    - Space and time inefficient
  - **Option 2:** Put each function in a separate source file
    - Programmers explicitly link appropriate binaries into their programs
    - More efficient, but burdensome on the programmer

Solution: Static Libraries

- **Static libraries (`.a` archive files)**
  - Concatenate related relocatable object files into a single file with an index (called an *archive*).
  - Enhance linker so that it tries to resolve unresolved external references by looking for the symbols in one or more archives.
  - If an archive member file resolves reference, link it into the executable.

Creating Static Libraries




```
unix> ar rs libc.a \
  atoi.o printf.o … random.o
```

- Archiver allows incremental updates
- Recompile function that changes and replace .o file in archive.

Commonly Used Libraries

`libc.a` (the C standard library)

- 8 MB archive of 1392 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

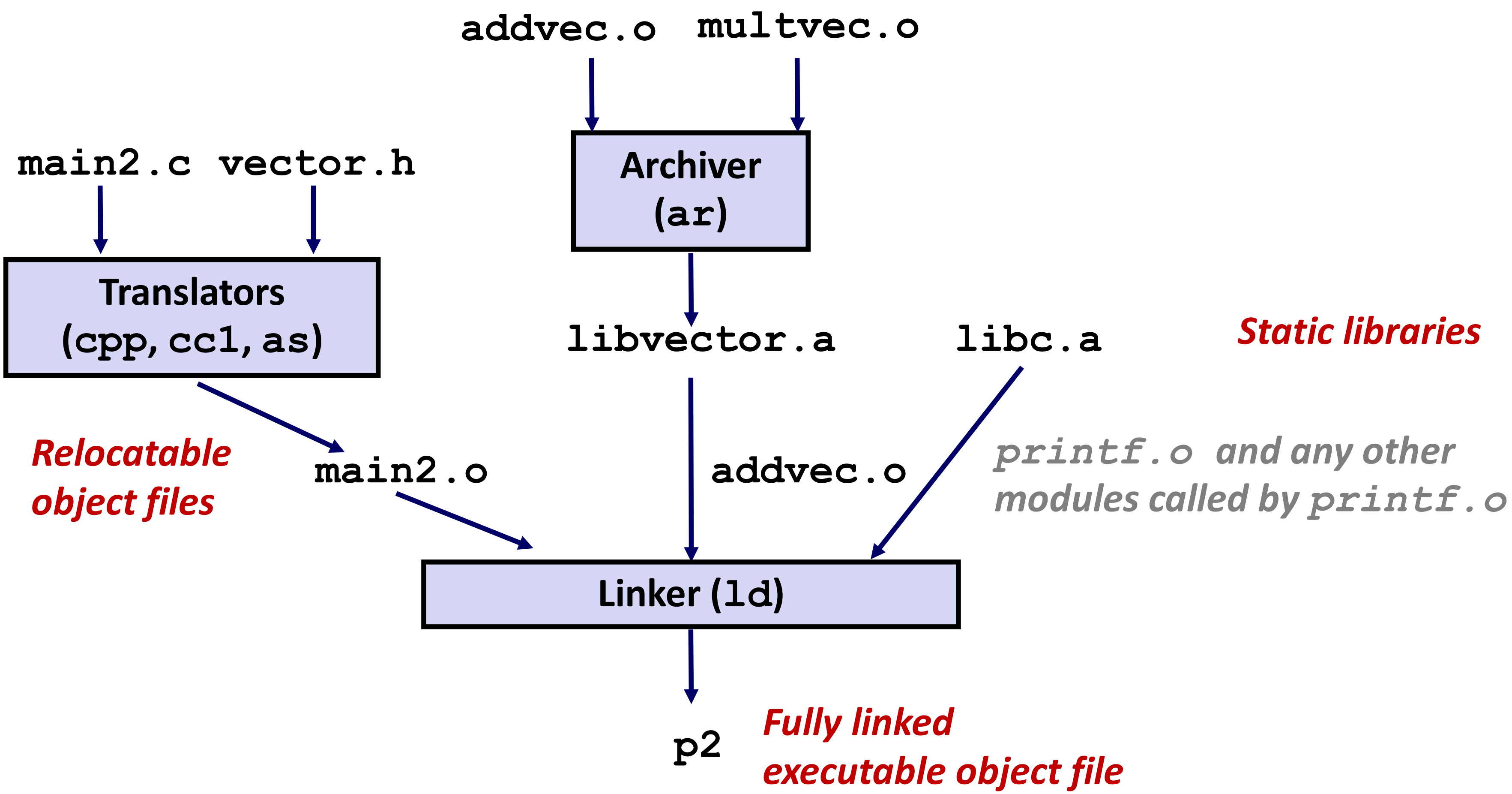
`libm.a` (the C math library)

- 1 MB archive of 401 object files.
- floating point math (sin, cos, tan, log, exp, sqrt, …)

```
% ar -t /usr/lib/libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t /usr/lib/libm.a | sort
…
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.o
…
```

Linking with Static Libraries



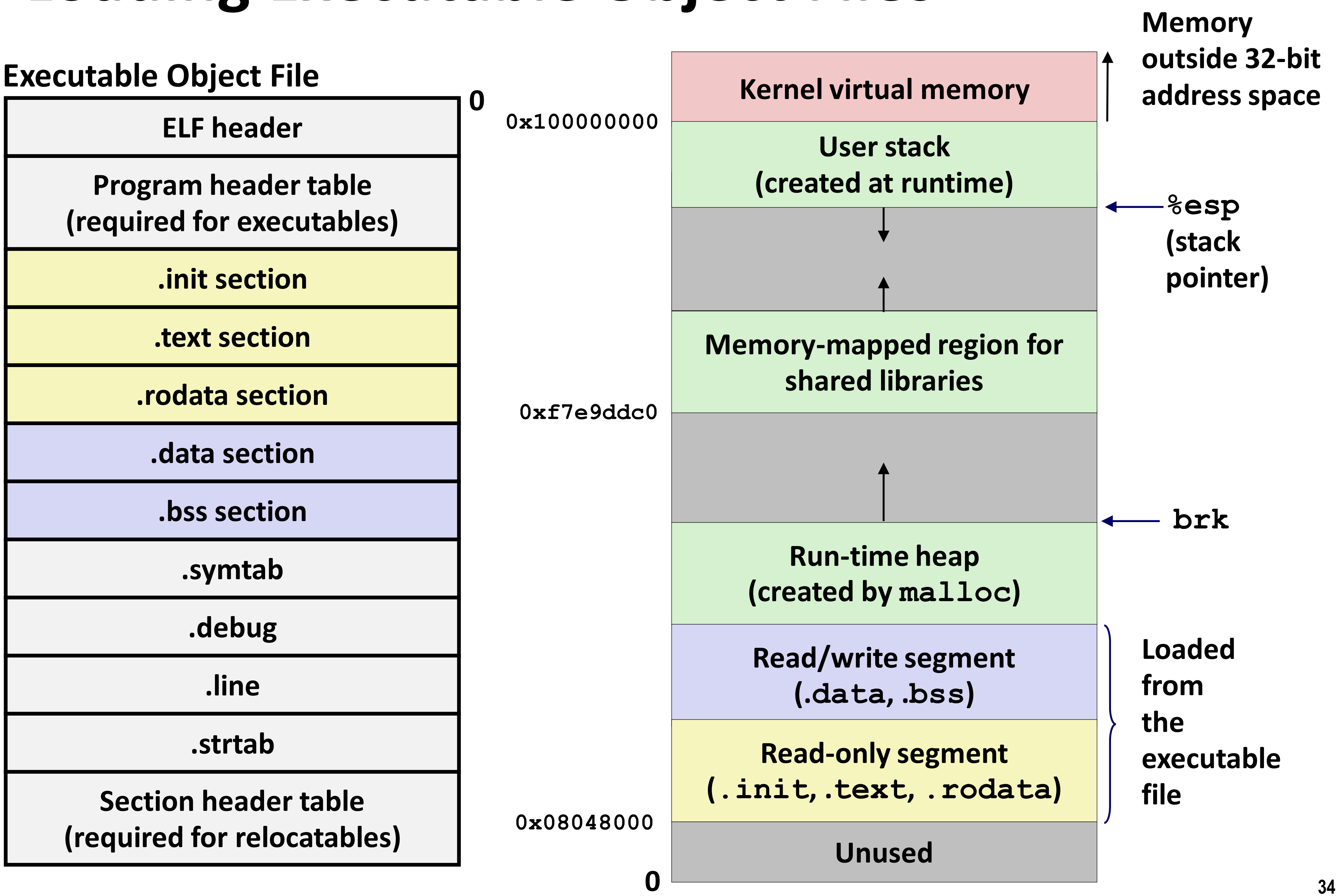
Using Static Libraries

- **Linker's algorithm for resolving external references:**
  - Scan `.o` files and `.a` files in the command line order.
  - During the scan, keep a list of the current unresolved references.
  - As each new `.o` or `.a` file, *obj*, is encountered, try to resolve each unresolved reference in the list against the symbols defined in *obj*.
  - If any entries in the unresolved list at end of scan, then error.

- **Problem:**
  - Command line order matters!
  - Moral: put libraries at the end of the command line.

```
unix> gcc -L. libtest.o -lmine
unix> gcc -L. -lmine libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```

Loading Executable Object Files



Shared Libraries

- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function need std libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **Modern solution: Shared Libraries**
  - Object files that contain code and data that are loaded and linked into an application *dynamically,* at either *load-time* or *run-time*
  - Also called: dynamic link libraries, DLLs, `.so` files

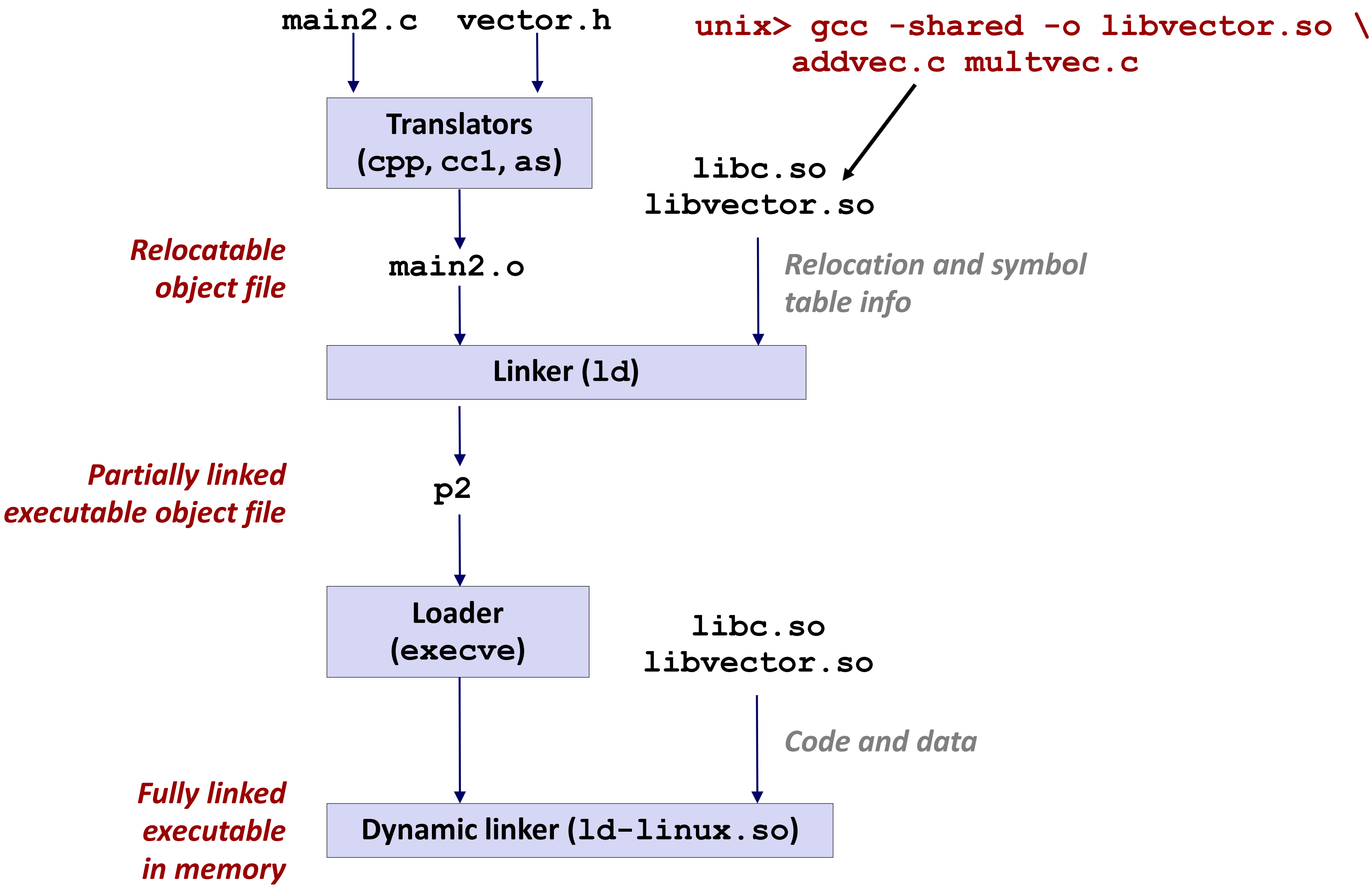
Shared Libraries (cont.)

- **Dynamic linking can occur when executable is first loaded and run (load-time linking).**
  - Common case for Linux, handled automatically by the dynamic linker (**`ld-linux.so`**).
  - Standard C library (**`libc.so`**) usually dynamically linked.

- **Dynamic linking can also occur after program has begun (run-time linking).**
  - In Linux, this is done by calls to the **`dlopen()`** interface.
    - Distributing software.
    - High-performance web servers.
    - Runtime library interpositioning.

- **Shared library routines can be shared by multiple processes.**
  - More on this when we learn about virtual memory

Dynamic Linking at Load-time



Dynamic Linking at Run-time

```
#include <stdio.h>
#include <dlfcn.h>

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main()
{
    void *handle;
    void (*addvec)(int *, int *, int *, int);
    char *error;

    /* dynamically load the shared lib that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
```

Dynamic Linking at Run-time

```
    ...

    /* get a pointer to the addvec() function we just loaded */
    addvec = dlsym(handle, "addvec");
    if ((error = dlerror()) != NULL) {
        fprintf(stderr, "%s\n", error);
        exit(1);
    }

    /* Now we can call addvec() just like any other function */
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n", z[0], z[1]);

    /* unload the shared library */
    if (dlclose(handle) < 0) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
    return 0;
}
```

Exceptional Control Flow: Exceptions and Processes

Today

- **Exceptional Control Flow**
- Processes

Control Flow

- **Processors do only one thing:**
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)

Physical control flow

Time

<startup>
inst_1
inst_2
inst_3
…
inst_n
<shutdown>

Altering the Control Flow

- **Up to now: two mechanisms for changing control flow:**
  - Jumps and branches
  - Call and return

  Both react to changes in ***program state***

- **Insufficient for a useful system:**
  Difficult to react to changes in *system state*
  - data arrives from a disk or a network adapter
  - instruction divides by zero
  - user hits Ctrl-C at the keyboard
  - System timer expires

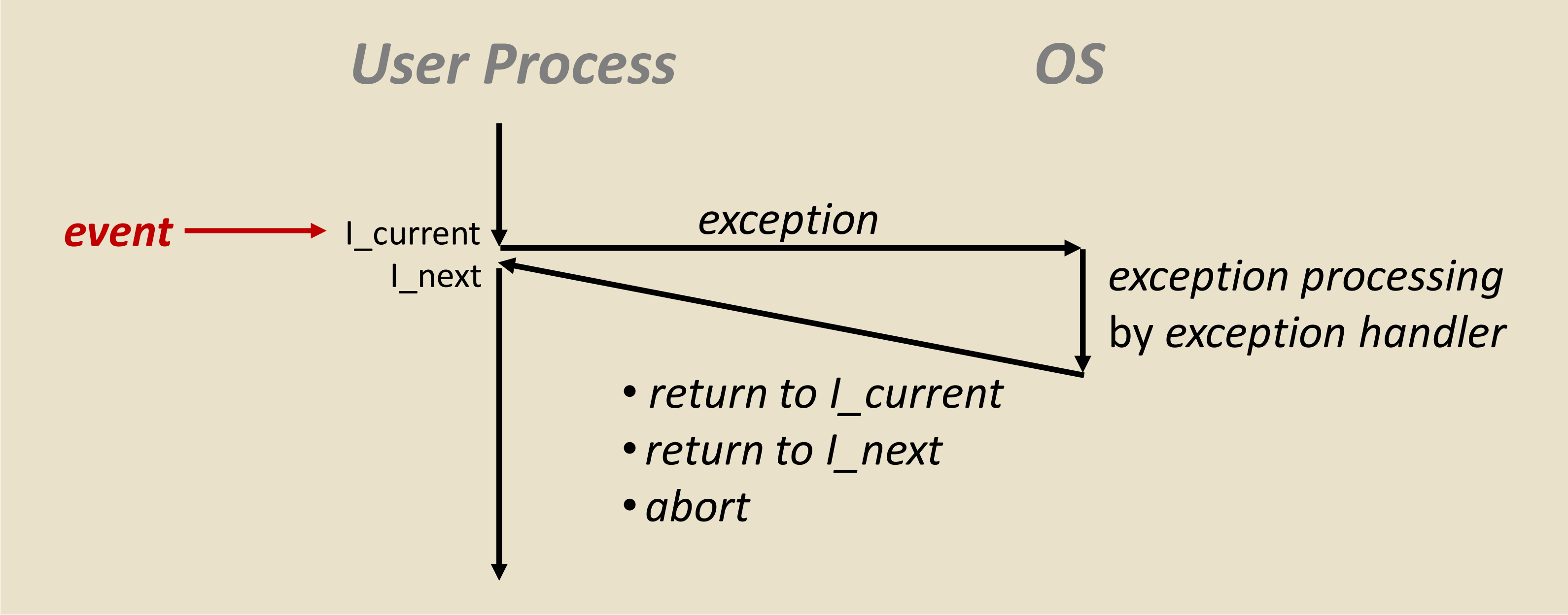
- **System needs mechanisms for "exceptional control flow"**

Exceptional Control Flow

- **Exists at all levels of a computer system**
- **Low level mechanisms**
  - Exceptions
    - change in control flow in response to a system event (i.e., change in system state)
  - Combination of hardware and OS software
- **Higher level mechanisms**
  - Process context switch
  - Signals
  - Nonlocal jumps: setjmp()/longjmp()
  - Implemented by either:
    - OS software (context switch and signals)
    - C language runtime library (nonlocal jumps)

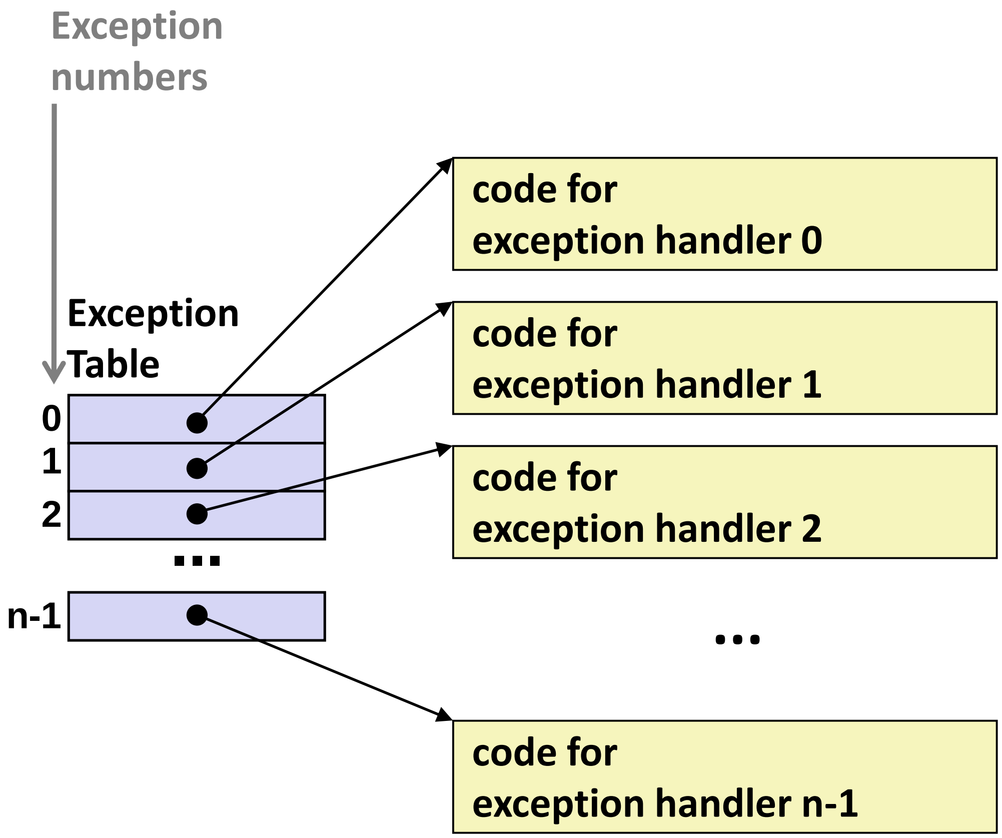
Exceptions

- **An *exception* is a transfer of control to the OS in response to some *event* (i.e., change in processor state)**



- **Examples:**
  div by 0, arithmetic overflow, page fault, I/O request completes, Ctrl-C

Interrupt Vectors



- Each type of event has a unique exception number k
- k = index into exception table (a.k.a. interrupt vector)
- Handler k is called each time exception k occurs

Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**
  - Indicated by setting the processor's interrupt pin
  - Handler returns to "next" instruction

- **Examples:**
  - I/O interrupts
    - hitting Ctrl-C at the keyboard
    - arrival of a packet from a network
    - arrival of data from a disk
  - Hard reset interrupt
    - hitting the reset button
  - Soft reset interrupt
    - hitting Ctrl-Alt-Delete on a PC

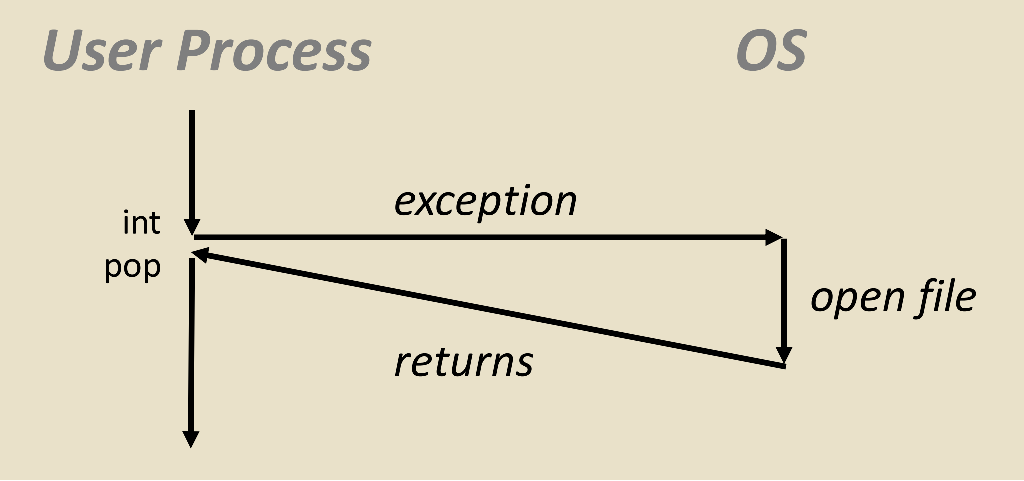
Synchronous Exceptions

- **Caused by events that occur as a result of executing an instruction:**
  - ***Traps***
    - Intentional
    - Examples: ***system calls***, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - unintentional and unrecoverable
    - Examples: parity error, machine check
    - Aborts current program

Trap Example: Opening File

- User calls: **`open(filename, options)`**
- Function **`open`** executes system call instruction **`int`**

```
0804d070 <__libc_open>:
 . . .
 804d082:       cd 80                    int    $0x80
 804d084:       5b                       pop    %ebx
 . . .
```



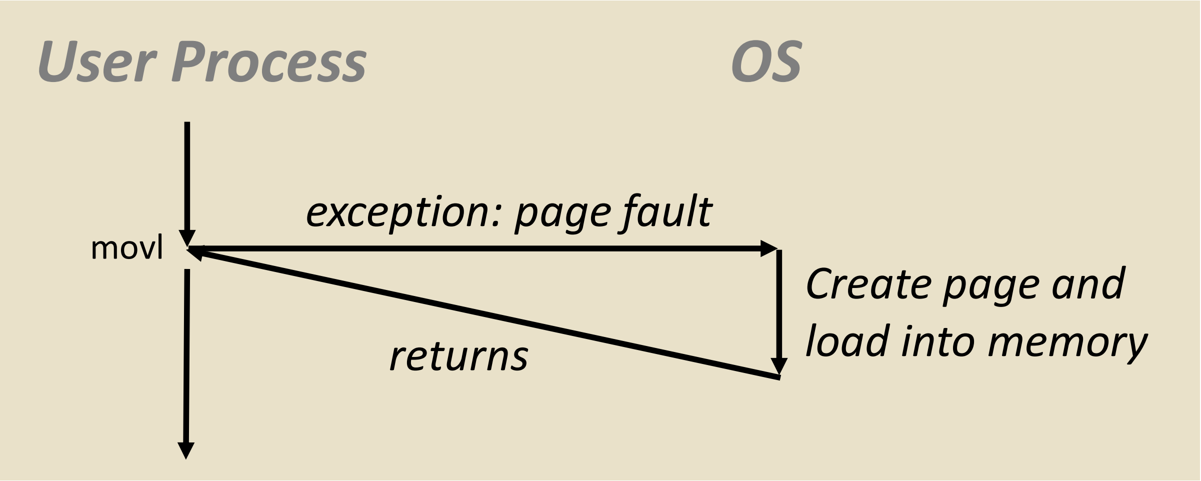
- OS must find or create file, get it ready for reading or writing
- Returns integer file descriptor

Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

```
80483b7:    c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```

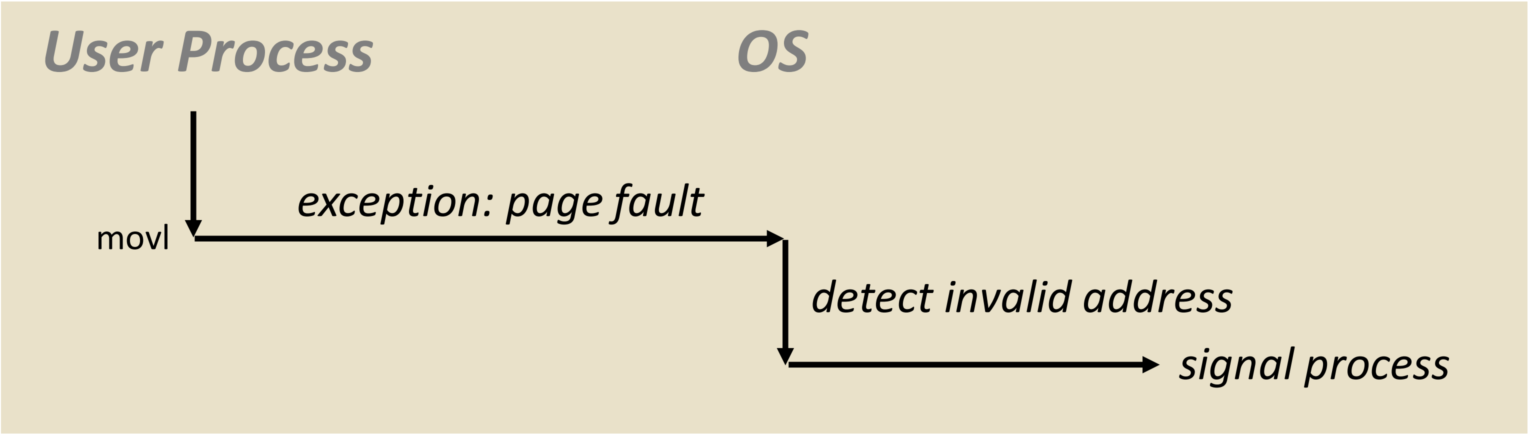


- Page handler must load page into physical memory
- Returns to faulting instruction
- Successful on second try

Fault Example: Invalid Memory Reference

```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

```
80483b7:        c7 05 60 e3 04 08 0d    movl    $0xd,0x804e360
```



- Page handler detects invalid address
- Sends **`SIGSEGV`** signal to user process
- User process exits with "segmentation fault"

Exception Table IA32 (Excerpt)

Exception Number	*Description*	*Exception Class*
0	Divide error	Fault
13	General protection fault	Fault
14	Page fault	Fault
18	Machine check	Abort
32-127	OS-defined	Interrupt or trap
128 (0x80)	System call	Trap
129-255	OS-defined	Interrupt or trap

Check Table 6-1:
http://download.intel.com/design/processor/manuals/253665.pdf

Today

- Exceptional Control Flow
- **Processes**

Processes

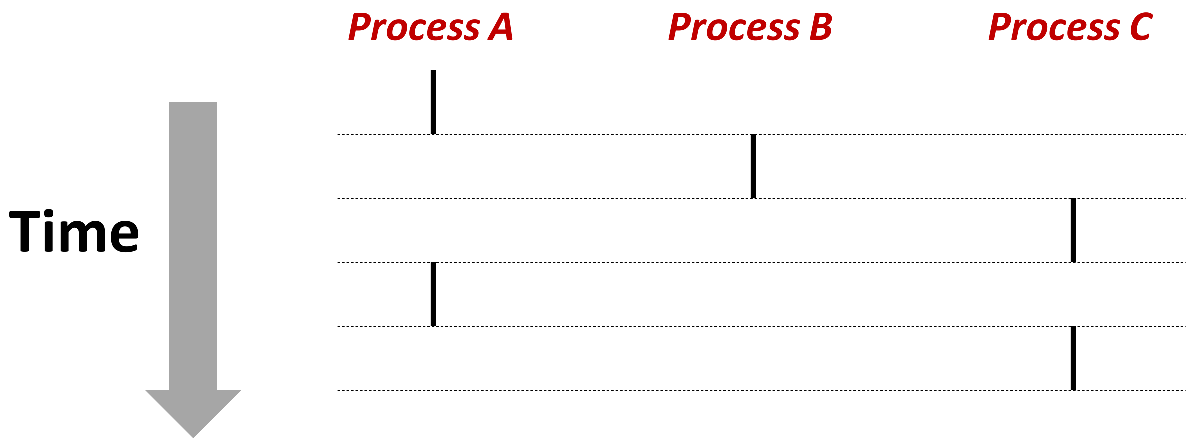
- **Definition: A *process* is an instance of a running program.**
  - One of the most profound ideas in computer science
  - Not the same as “program” or “processor”

- **Process provides each program with two key abstractions:**
  - Logical control flow
    - Each program seems to have exclusive use of the CPU
  - Private virtual address space
    - Each program seems to have exclusive use of main memory

- **How are these Illusions maintained?**
  - Process executions interleaved (multitasking) or run on separate cores
  - Address spaces managed by virtual memory system
    - we’ll talk about this in a couple of weeks

Concurrent Processes

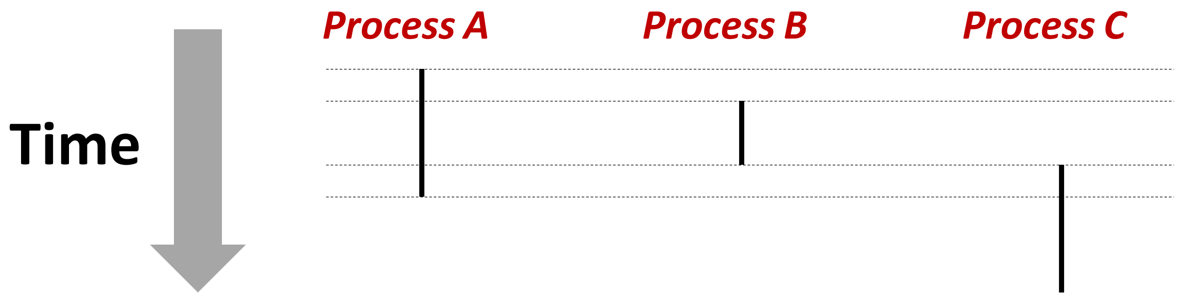
- **Two processes *run concurrently* (*are concurrent)* if their flows overlap in time**
- **Otherwise, they are *sequential***
- **Examples (running on single core):**
  - Concurrent: A & B, A & C
  - Sequential: B & C



User View of Concurrent Processes

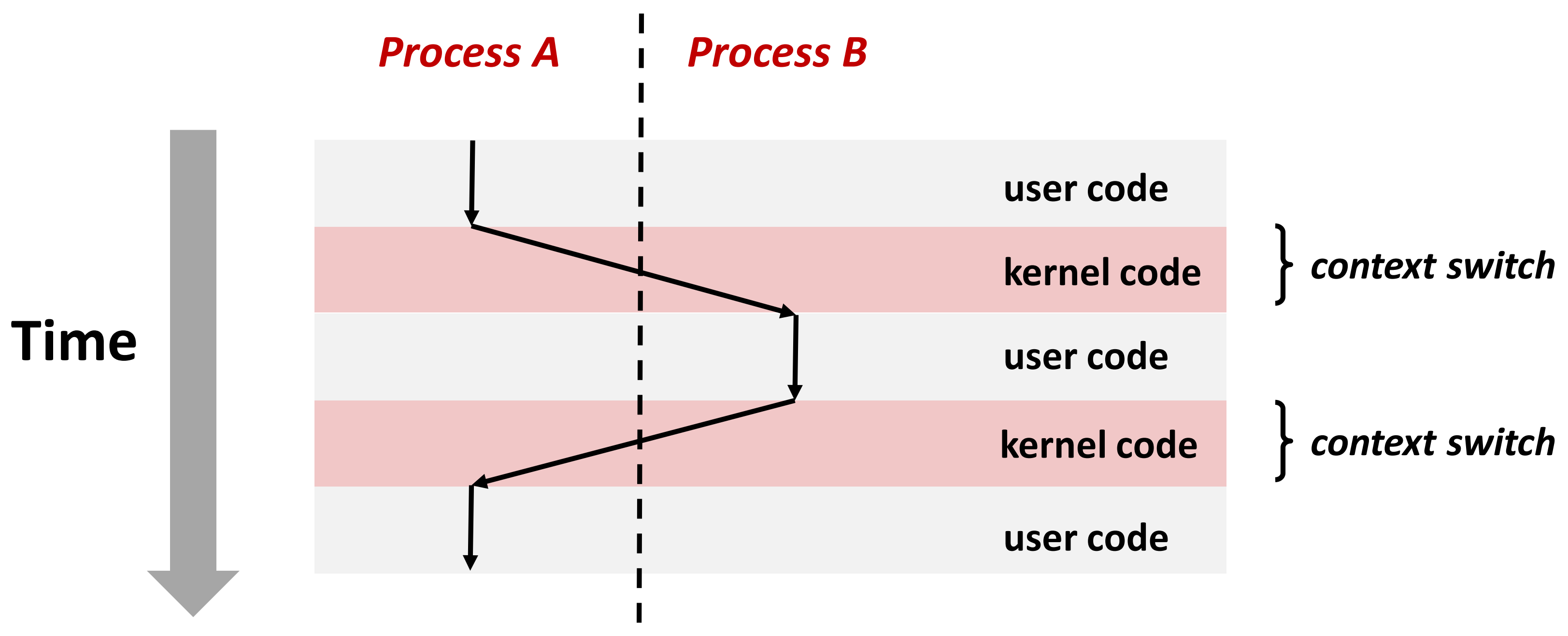
- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes are running in parallel with each other



Context Switching

- **Processes are managed by a shared chunk of OS code called the *kernel***
  - Important: the kernel is not a separate process, but rather runs as part of some user process
- **Control flow passes from one process to another via a *context switch***



`fork`: Creating New Processes

- `int fork(void)`
  - creates a new process (child process) that is identical to the calling process (parent process)
  - returns 0 to the child process
  - returns child's `pid` to the parent process

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

- **Fork is interesting (and often confusing) because it is called *once* but returns *twice***

Understanding fork

Process n

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = m

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Child Process m

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = 0

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

`hello from parent` *Which one is first?* `hello from child`

Fork Example #1

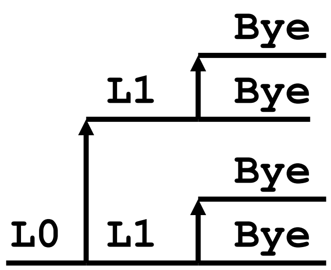
- **Parent and child both run same code**
  - Distinguish parent from child by return value from **`fork`**
- **Start with same state, but each has private copy**
  - Including shared output file descriptor
  - Relative ordering of their print statements undefined

```
void fork1()
{
    int x = 1;
    pid_t pid = fork();
    if (pid == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

Fork Example #2

- Both parent and child can continue forking

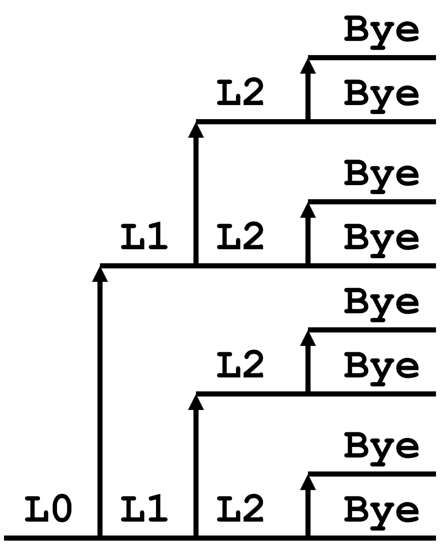
```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #3

- Both parent and child can continue forking

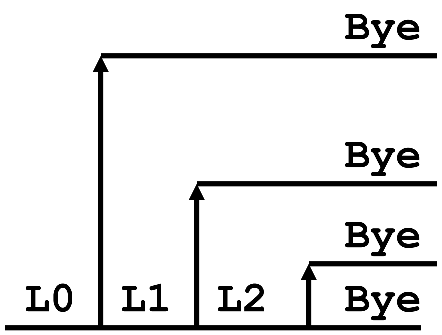
```
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #4

- The parent can continue forking

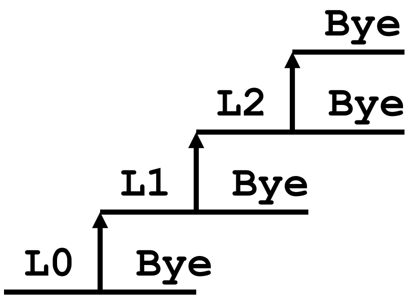
```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
       printf("L1\n");
       if (fork() != 0) {
           printf("L2\n");
           fork();
       }
    }
    printf("Bye\n");
}
```



Fork Example #5

- Both parent and child can continue forking

```
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
            fork();
        }
    }
    printf("Bye\n");
}
```



`exit`: Ending a process

- **`void exit(int status)`**
  - exits a process
    - Normally return with status 0
  - **`atexit()`** registers functions to be executed upon exit

```
void cleanup(void) {
   printf("cleaning up\n");
}

void fork6() {
   atexit(cleanup);
   fork();
   exit(0);
}
```

Zombies

- **Idea**
  - When process terminates, still consumes system resources
    - Various tables maintained by OS
  - Called a "zombie"
    - Living corpse, half alive and half dead
- **Reaping**
  - Performed by parent on terminated child
  - Parent is given exit status information
  - Kernel discards process
- **What if parent doesn't reap?**
  - If any parent terminates without reaping a child, then child will be reaped by `init` process
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers

Zombie Example

```
void fork7()
{
    if (fork() == 0) {
        /* Child */
        printf("Terminating Child, PID = %d\n",
               getpid());
        exit(0);
    } else {
        printf("Running Parent, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    }
}
```

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

- **ps** shows child process as "defunct"
- Killing parent allows child to be reaped by **init**

Nonterminating Child Example

```
void fork8()
{
    if (fork() == 0) {
        /* Child */
        printf("Running Child, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n",
               getpid());
        exit(0);
    }
}
```

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

- Child process still active even though parent has terminated
- Must kill explicitly, or else will keep running indefinitely

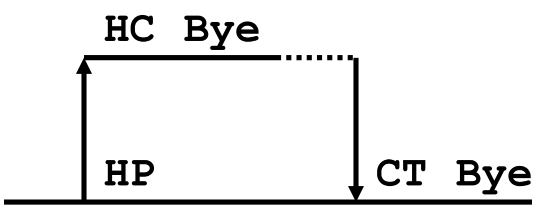
`wait`: Synchronizing with Children

- `int wait(int *child_status)`
  - suspends current process until one of its children terminates
  - return value is the `pid` of the child process that terminated
  - if `child_status != NULL`, then the object it points to will be set to a status indicating why the child process terminated

`wait`: Synchronizing with Children

```
void fork9() {
   int child_status;

   if (fork() == 0) {
      printf("HC: hello from child\n");
   }
   else {
      printf("HP: hello from parent\n");
      wait(&child_status);
      printf("CT: child has terminated\n");
   }
   printf("Bye\n");
   exit();
}
```



wait() Example

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```
void fork10()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminate abnormally\n", wpid);
    }
}
```

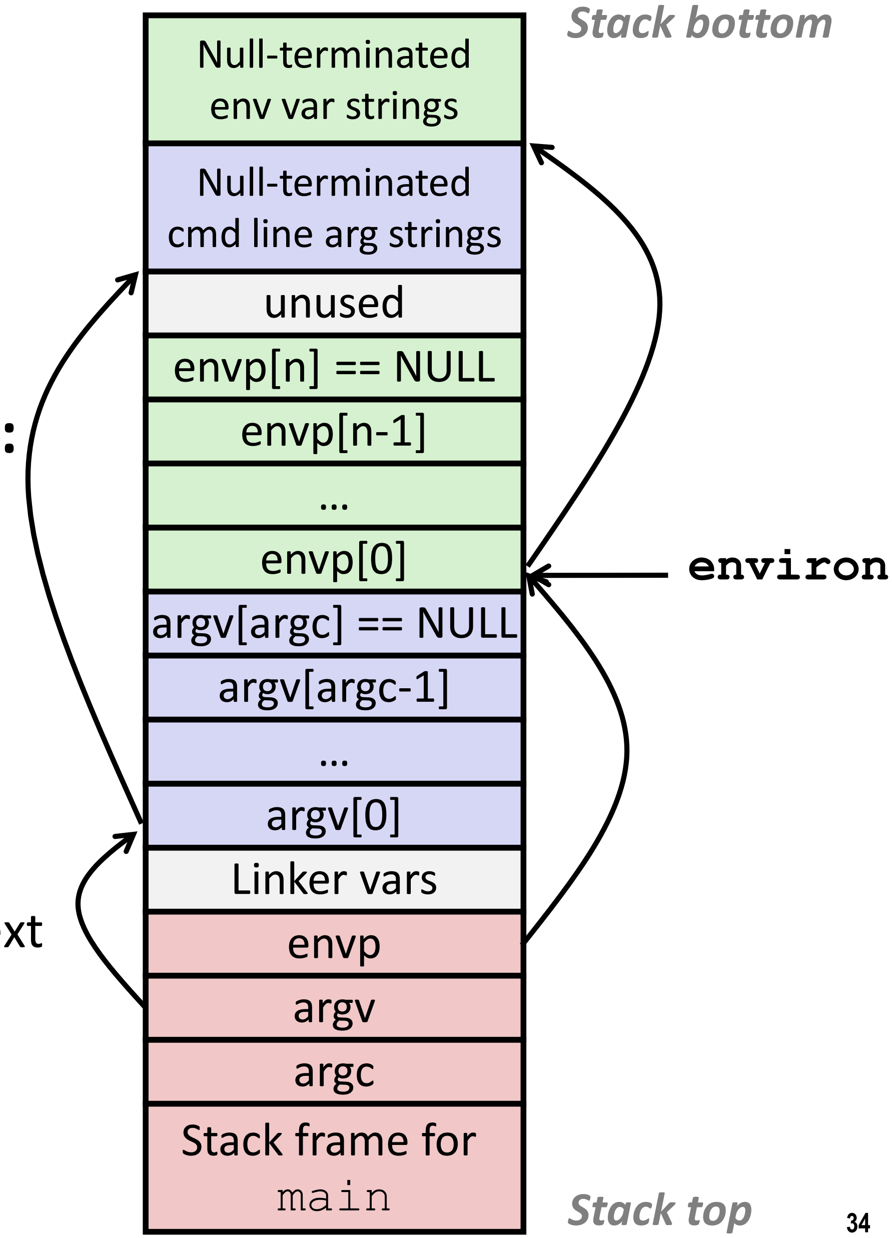
`waitpid()`: Waiting for a Specific Process

- `waitpid(pid, &status, options)`
  - suspends current process until specific process terminates
  - various options (see textbook)

```
void fork11()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = N-1; i >= 0; i--) {
        pid_t wpid = waitpid(pid[i], &child_status, 0);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

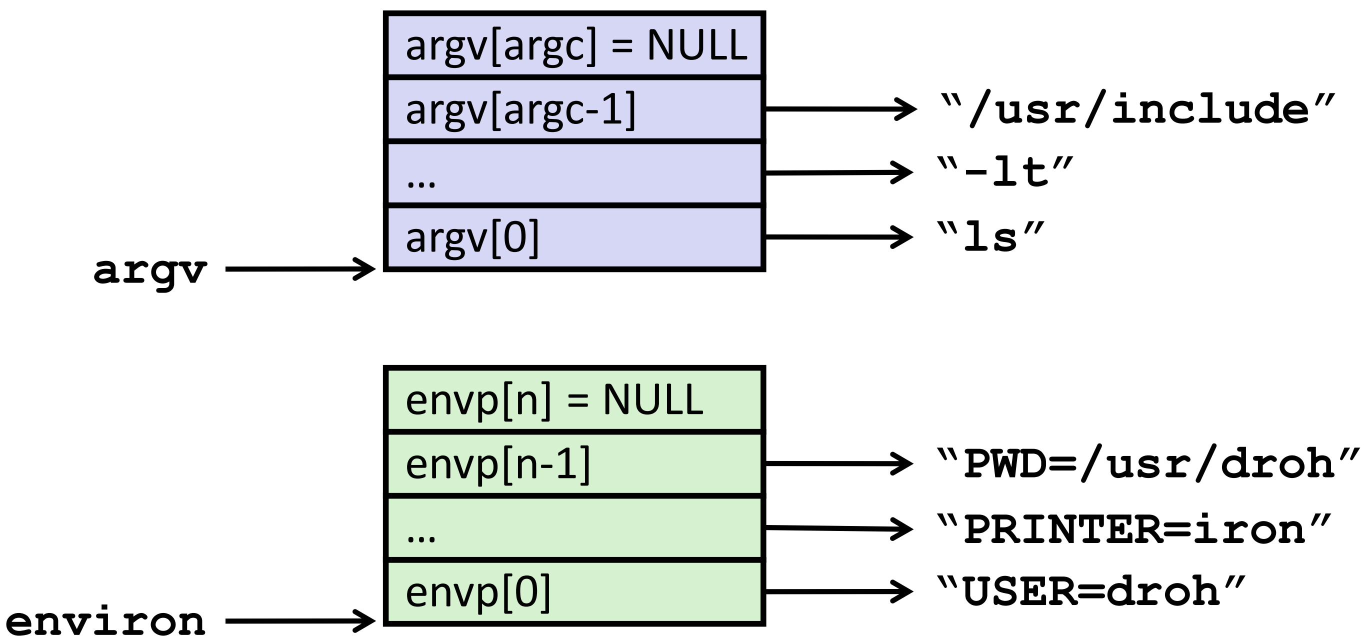
`execve`: Loading and Running Programs

- ```
  int execve(
     char *filename,
     char *argv[],
     char *envp[]
  )
  ```
- **Loads and runs in current process:**
  - Executable **`filename`**
  - With argument list **`argv`**
  - And environment variable list **`envp`**
- **Does not return (unless error)**
- **Overwrites code, data, and stack**
  - keeps pid, open files and signal context
- **Environment variables:**
  - "name=value" strings
  - `getenv` and `putenv`


  ```

execve Example

```
if ((pid = Fork()) == 0) { /* Child runs user job */
    if (execve(argv[0], argv, environ) < 0) {
        printf("%s: Command not found.\n", argv[0]);
        exit(0);
    }
}
```



Summary

- **Exceptions**
  - Events that require nonstandard control flow
  - Generated externally (interrupts) or internally (traps and faults)

- **Processes**
  - At any given time, system has multiple active processes
  - Only one can execute at a time on a single core, though
  - Each process appears to have total control of processor + private memory space

Summary (cont.)

- **Spawning processes**
  - Call `fork`
  - One call, two returns
- **Process completion**
  - Call `exit`
  - One call, no return
- **Reaping and waiting for Processes**
  - Call `wait` or `waitpid`
- **Loading and running Programs**
  - Call `execve` (or variant)
  - One call, (normally) no return

Exceptional Control Flow: Signals and Nonlocal Jumps

ECF Exists at All Levels of a System

- **Exceptions**
  - Hardware and operating system kernel software
- **Process Context Switch**
  - Hardware timer and kernel software
- **Signals**
  - Kernel software
- **Nonlocal jumps**
  - Application code

Previous Lecture

This Lecture

Today

- **Multitasking, shells**
- Signals
- Nonlocal jumps

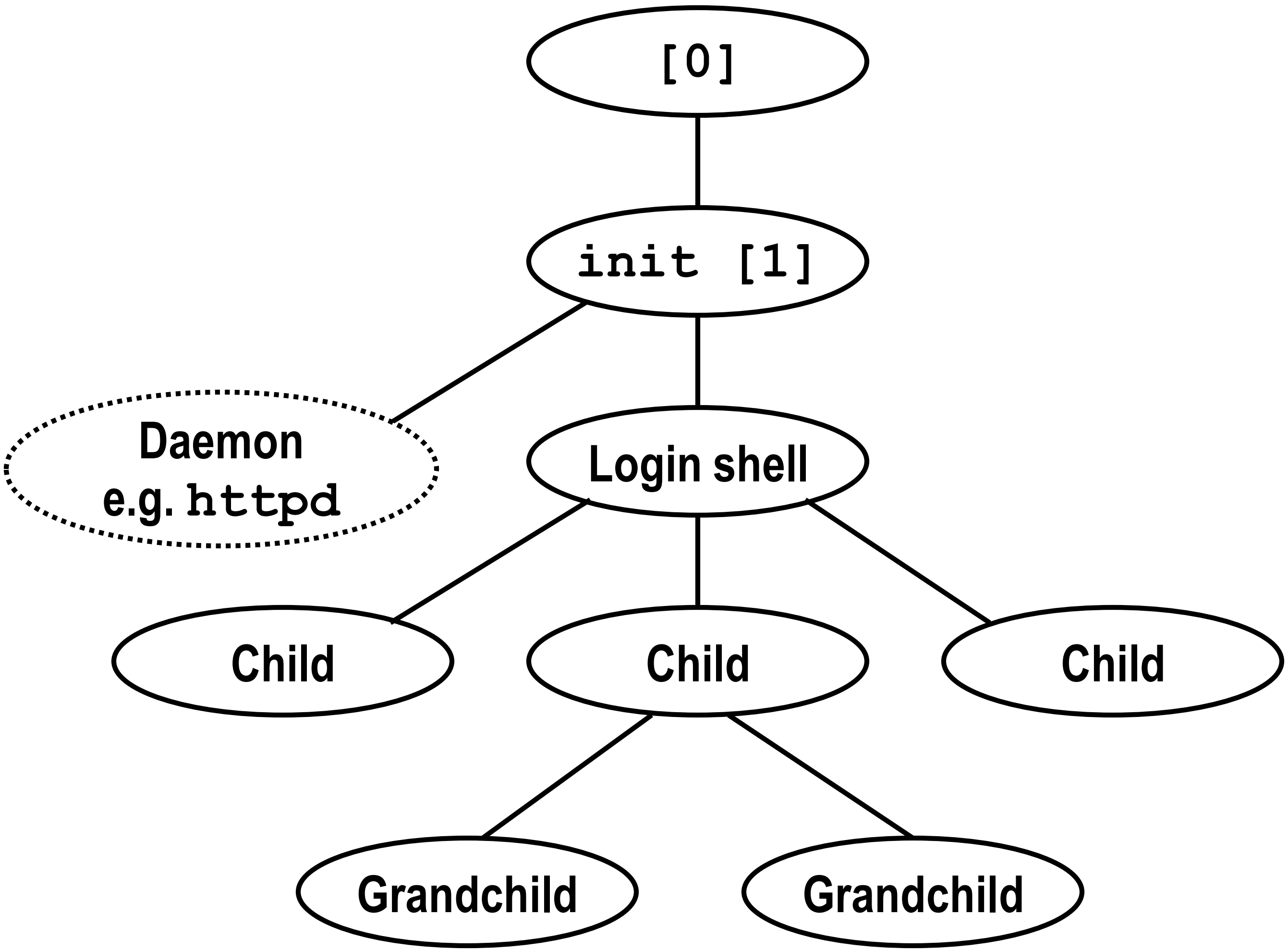
The World of Multitasking

- **System runs many processes concurrently**
- **Process: executing program**
  - State includes memory image + register values + program counter
- **Regularly switches from one process to another**
  - Suspend process when it needs I/O resource or timer event occurs
  - Resume process when I/O available or given scheduling priority
- **Appears to user(s) as if all processes executing simultaneously**
  - Even though most systems can only execute one process at a time
  - Except possibly with lower performance than if running alone

Programmer's Model of Multitasking

- **Basic functions**
  - **`fork`** spawns new process
    - Called once, returns twice
  - **`exit`** terminates own process
    - Called once, never returns
    - Puts it into "zombie" status
  - **`wait`** and **`waitpid`** wait for and reap terminated children
  - **`execve`** runs new program in existing process
    - Called once, (normally) never returns

Unix Process Hierarchy



Shell Programs

- A *shell* is an application program that runs programs on behalf of the user.
  - **`sh`** Original Unix shell (Stephen Bourne, AT&T Bell Labs, 1977)
  - **`csh`** BSD Unix C shell (**`tcsh`**: enhanced `csh` at CMU and elsewhere)
  - **`bash`** "Bourne-Again" Shell

```
int main() {
    char cmdline[MAXLINE];

    while (1) {
        /* read */
        printf("> ");
        Fgets(cmdline, MAXLINE, stdin);
        if (feof(stdin))
            exit(0);

        /* evaluate */
        eval(cmdline);
    }
}
```

Execution is a sequence of read/evaluate steps

Simple Shell `eval` Function

```
void eval(char *cmdline) {
    char *argv[MAXARGS]; /* argv for execve() */
    int bg;              /* should the job run in bg or fg? */
    pid_t pid;           /* process id */

    bg = parseline(cmdline, argv);
    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }

        if (!bg) {   /* parent waits for fg job to terminate */
            int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error");
        }
        else         /* otherwise, don't wait for bg job */
            printf("%d %s", pid, cmdline);
    }
}
```

What Is a "Background Job"?

- **Users generally run one command at a time**
  - Type command, read output, type another command

- **Some programs run "for a long time"**
  - Example: "delete this file in two hours"

```
unix> sleep 7200; rm /tmp/junk  # shell stuck for 2 hours
```

- **A "background" job is a process we don't want to wait for**

```
unix> (sleep 7200 ; rm /tmp/junk) &
[1] 907
unix> # ready for next command
```

Problem with Simple Shell Example

- **Our example shell correctly waits for and reaps foreground jobs**

- **But what about background jobs?**
  - Will become zombies when they terminate
  - Will never be reaped because shell (typically) will not terminate
  - Will create a memory leak that could run the kernel out of memory
  - Modern Unix: once you exceed your process quota, your shell can't run any new commands for you: fork() returns -1

```
unix> limit maxproc            # csh syntax
maxproc       202752
unix> ulimit -u                # bash syntax
202752
```

ECF to the Rescue!

- **Problem**
  - The shell doesn't know when a background job will finish
  - By nature, it could happen at any time
  - The shell's regular control flow can't reap exited background processes in a timely fashion
  - Regular control flow is “wait until running job completes, then reap it”

- **Solution: Exceptional control flow**
  - The kernel will interrupt regular processing to alert us when a background process completes
  - In Unix, the alert mechanism is called a ***signal***

Today

- Multitasking, shells
- **Signals**
- Nonlocal jumps

Signals

- **A *signal* is a small message that notifies a process that an event of some type has occurred in the system**
  - akin to exceptions and interrupts
  - sent from the kernel (sometimes at the request of another process) to a process
  - signal type is identified by small integer ID's (1-30)
  - only information in a signal is its ID and the fact that it arrived

ID	*Name*	*Default Action*	*Corresponding Event*
2	SIGINT	Terminate	Interrupt (e.g., ctl-c from keyboard)
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
11	SIGSEGV	Terminate & Dump	Segmentation violation
14	SIGALRM	Terminate	Timer signal
17	SIGCHLD	Ignore	Child stopped or terminated

Sending a Signal

- **Kernel *sends* (delivers) a signal to a *destination process* by updating some state in the context of the destination process**

- **Kernel sends a signal for one of the following reasons:**
  - Kernel has detected a system event such as divide-by-zero (SIGFPE) or the termination of a child process (SIGCHLD)
  - Another process has invoked the **`kill`** system call to explicitly request the kernel to send a signal to the destination process

Receiving a Signal

- **A destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal**

- **Three possible ways to react:**
  - ***Ignore*** the signal (do nothing)
  - ***Terminate*** the process (with optional core dump)
  - ***Catch*** the signal by executing a user-level function called ***signal handler***
    - Akin to a hardware exception handler being called in response to an asynchronous interrupt

Pending and Blocked Signals

- **A signal is *pending* if sent but not yet received**
  - There can be at most one pending signal of any particular type
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded

- **A process can *block* the receipt of certain signals**
  - Blocked signals can be delivered, but will not be received until the signal is unblocked

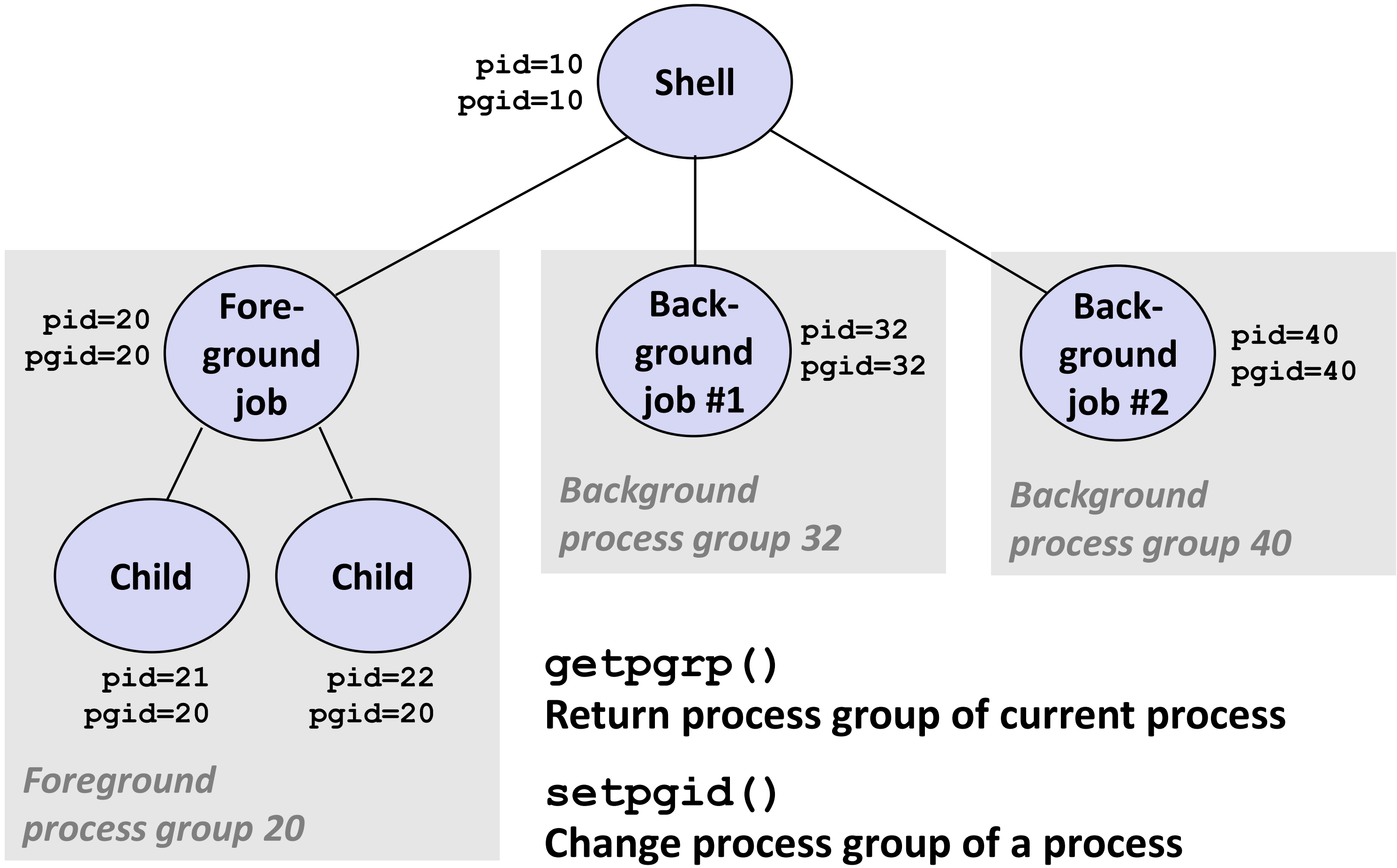
- **A pending signal is received at most once**

Signal Concepts

- **Kernel maintains `pending` and `blocked` bit vectors in the context of each process**
  - **`pending`**: represents the set of pending signals
    - Kernel sets bit k in **`pending`** when a signal of type k is delivered
    - Kernel clears bit k in **`pending`** when a signal of type k is received
  - **`blocked`**: represents the set of blocked signals
    - Can be set and cleared by using the **`sigprocmask`** function

Process Groups

- Every process belongs to exactly one process group



`getpgrp()`
Return process group of current process

`setpgid()`
Change process group of a process

Sending Signals with /bin/`kill` Program

- `/bin/kill` program sends arbitrary signal to a process or process group

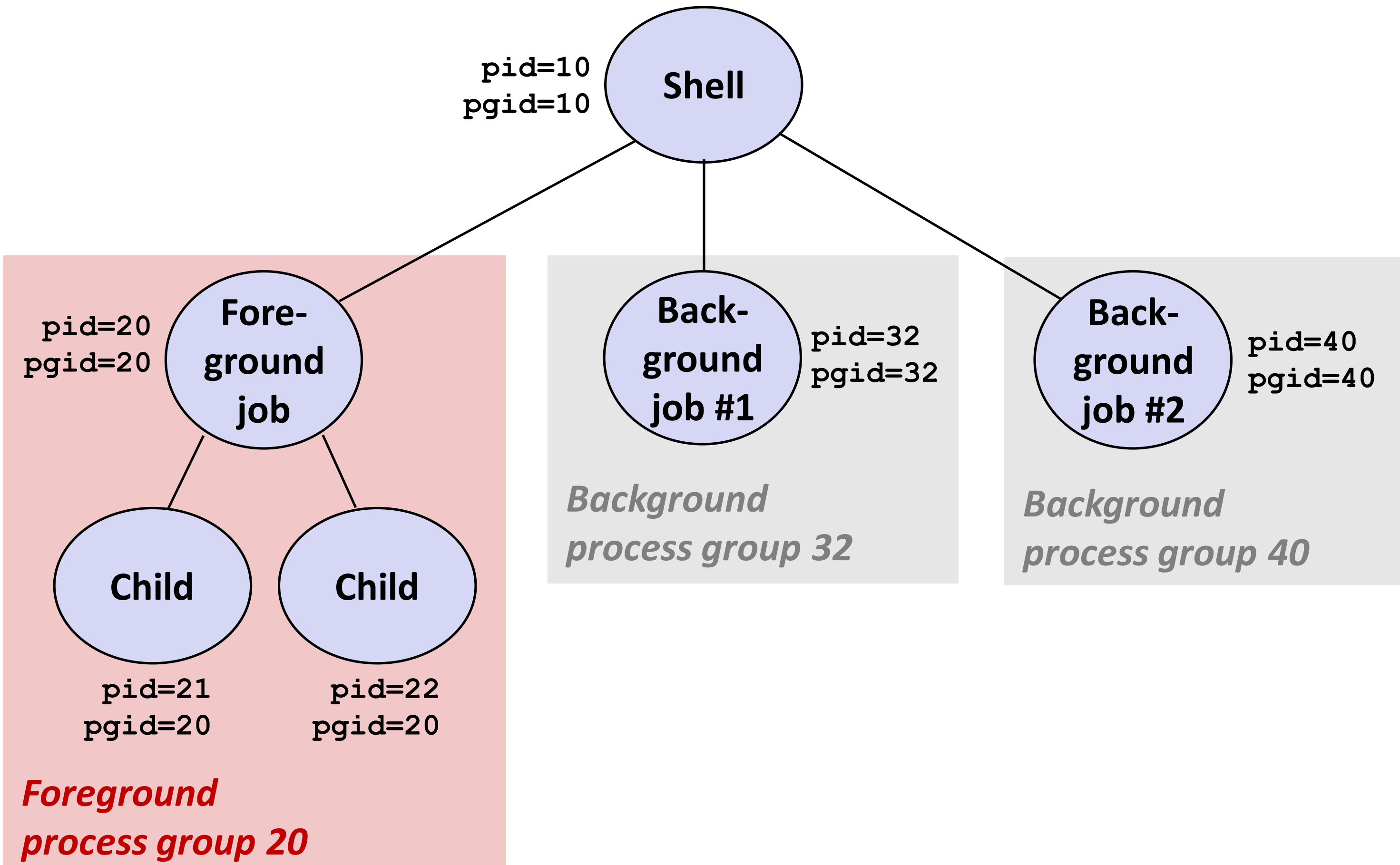
- Examples
  - `/bin/kill -9 24818`
    Send SIGKILL to process 24818
  - `/bin/kill -9 -24817`
    Send SIGKILL to every process in process group 24817

```
linux> ./forks 16
Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24818 pts/2    00:00:02 forks
24819 pts/2    00:00:02 forks
24820 pts/2    00:00:00 ps
linux> /bin/kill -9 -24817
linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24823 pts/2    00:00:00 ps
linux>
```

Sending Signals from the Keyboard

- **Typing ctrl-c (ctrl-z) sends a SIGINT (SIGTSTP) to every job in the foreground process group.**
  - SIGINT – default action is to terminate each process
  - SIGTSTP – default action is to stop (suspend) each process



Example of `ctrl-c` and `ctrl-z`

```
bluefish> ./forks 17
Child: pid=28108 pgrp=28107
Parent: pid=28107 pgrp=28107
<types ctrl-z>
Suspended
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
27699 pts/8    Ss     0:00 -tcsh
28107 pts/8    T      0:01 ./forks 17
28108 pts/8    T      0:01 ./forks 17
28109 pts/8    R+     0:00 ps w
bluefish> fg
./forks 17
<types ctrl-c>
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
27699 pts/8    Ss     0:00 -tcsh
28110 pts/8    R+     0:00 ps w
```

STAT (process state) Legend:

First letter:

S: sleeping

T: stopped

R: running

Second letter:

s: session leader

+: foreground proc group

See "man ps" for more details

Sending Signals with `kill` Function

```
void fork12()
{
    pid_t pid[N];
    int i, child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            while(1); /* Child infinite loop */

    /* Parent terminates the child processes */
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    /* Parent reaps terminated children */
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

Receiving Signals

- **Suppose kernel is returning from an exception handler and is ready to pass control to process *p***

- **Kernel computes `pnb = pending & ~blocked`**
  - The set of pending nonblocked signals for process *p*

- **If `(pnb == 0)`**
  - Pass control to next instruction in the logical flow for *p*
- **Else**
  - Choose least nonzero bit *k* in **`pnb`** and force process *p* to ***receive*** signal *k*
  - The receipt of the signal triggers some ***action*** by *p*
  - Repeat for all nonzero *k* in **`pnb`**
  - Pass control to next instruction in logical flow for *p*

Default Actions

- **Each signal type has a predefined *default action*, which is one of:**
  - The process terminates
  - The process terminates and dumps core
  - The process stops until restarted by a SIGCONT signal
  - The process ignores the signal

Installing Signal Handlers

- **The `signal` function modifies the default action associated with the receipt of signal `signum`:**
  - `handler_t *signal(int signum, handler_t *handler)`

- **Different values for `handler`:**
  - SIG_IGN: ignore signals of type **`signum`**
  - SIG_DFL: revert to the default action on receipt of signals of type **`signum`**
  - Otherwise, **`handler`** is the address of a ***signal handler***
    - Called when process receives signal of type **`signum`**
    - Referred to as ***"installing"*** the handler
    - Executing handler is called ***"catching"*** or ***"handling"*** the signal
    - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal

Signal Handling Example

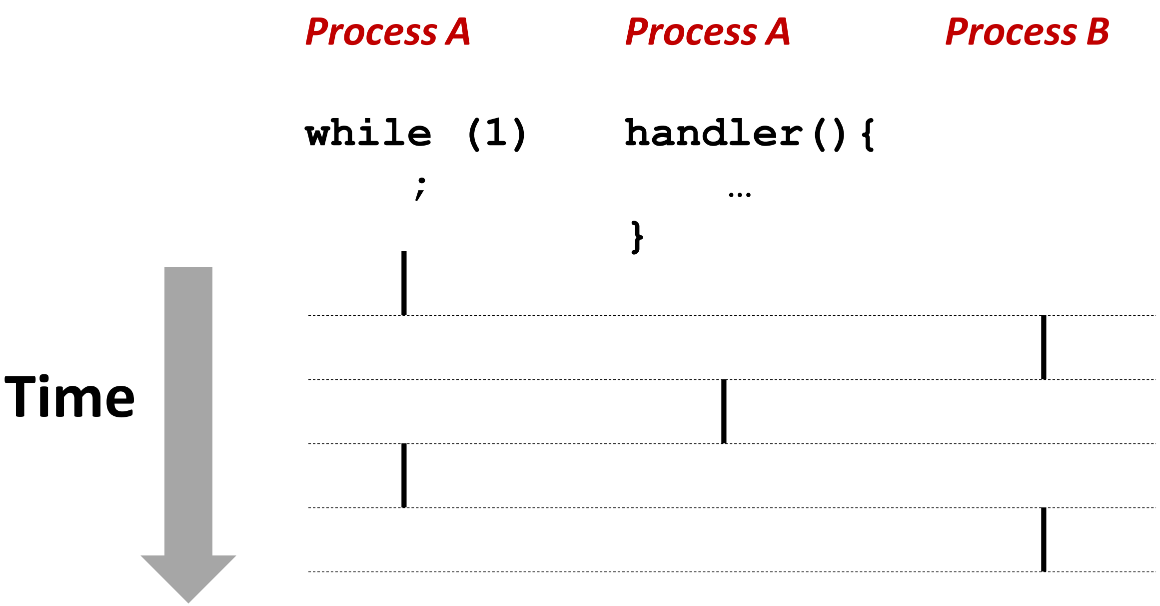
```
void int_handler(int sig) {
    safe_printf("Process %d received signal %d\n", getpid(), sig);
    exit(0);
}

void fork13() {
    pid_t pid[N];
    int i, child_status;
    signal(SIGINT, int_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            while(1); /* child infinite loop
        }
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

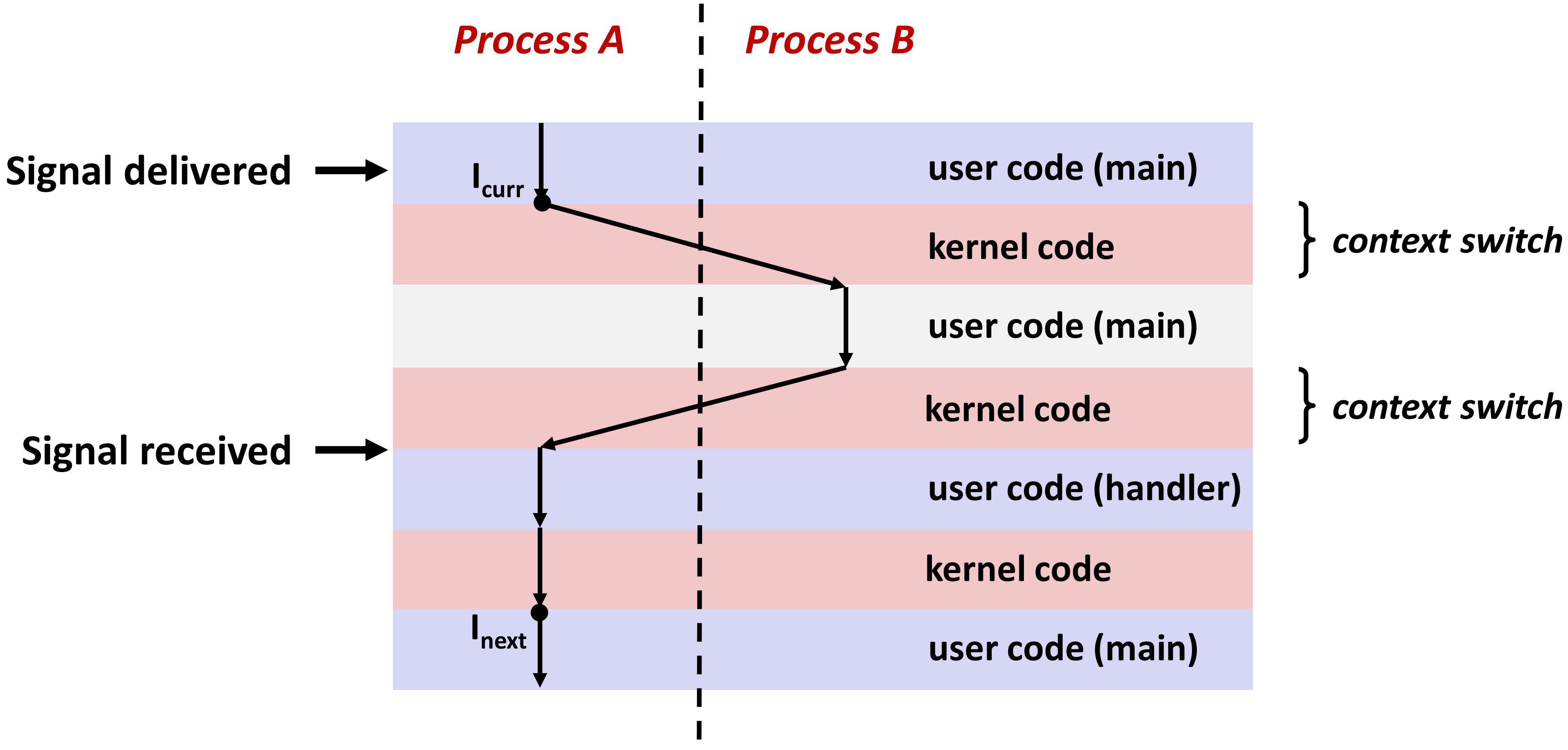
```
linux> ./forks 13
Killing process 25417
Killing process 25418
Killing process 25419
Killing process 25420
Killing process 25421
Process 25417 received signal 2
Process 25418 received signal 2
Process 25420 received signal 2
Process 25421 received signal 2
Process 25419 received signal 2
Child 25417 terminated with exit status 0
Child 25418 terminated with exit status 0
Child 25420 terminated with exit status 0
Child 25419 terminated with exit status 0
Child 25421 terminated with exit status 0
linux>
```

Signals Handlers as Concurrent Flows

- **A signal handler is a separate logical flow (not process) that runs concurrently with the main program**
  - "concurrently" in the "not sequential" sense



Another View of Signal Handlers as Concurrent Flows



Signal Handler Funkiness

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    safe_printf(
           "Received signal %d from process %d\n",
           sig, pid);
}

void fork14()
{
    pid_t pid[N];
    int i, child_status;
    ccount = N;
    signal(SIGCHLD, child_han
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            sleep(1); /* deschedule child */
            exit(0);  /* Child: Exit */
        }
    while (ccount > 0)
        pause(); /* Suspend until signal occurs */
}
```

```
linux> ./forks 14
Received SIGCHLD signal 17 for process 21344
Received SIGCHLD signal 17 for process 21345
```

- **Pending signals are not queued**
  - For each signal type, just have single bit indicating whether or not signal is pending
  - Even if multiple processes have sent this signal

Living With Nonqueuing Signals

- **Must check for all terminated jobs**
  - Typically loop with **`wait`**

```
void child_handler2(int sig)
{
    int child_status;
    pid_t pid;
    while ((pid = waitpid(-1, &child_status, WNOHANG)) > 0) {
        ccount--;
        safe_printf("Received signal %d from process %d\n",
                    sig, pid);
    }
}

void fork15()
{
    . . .
    signal(SIGC
    . . .
}
```

```
greatwhite> forks 15
Received signal 17 from process 27476
Received signal 17 from process 27477
Received signal 17 from process 27478
Received signal 17 from process 27479
Received signal 17 from process 27480
greatwhite>
```

More Signal Handler Funkiness

- **Signal arrival during long system calls (say a `read`)**
- **Signal handler interrupts `read` call**
  - Linux: upon return from signal handler, the **`read`** call is restarted automatically
  - Some other flavors of Unix can cause the **`read`** call to fail with an **`EINTER`** error number (**`errno`**)
    in this case, the application program can restart the slow system call

- **Subtle differences like these complicate the writing of portable code that uses signals**
  - Consult your textbook for details

A Program That Reacts to Externally Generated Events (Ctrl-c)

```
#include <stdlib.h>
#include <stdio.h>
#include <signal.h>

void handler(int sig) {
  safe_printf("You think hitting ctrl-c will stop the bomb?\n");
  sleep(2);
  safe_printf("Well...");
  sleep(1);
  printf("OK\n");
  exit(0);
}

main() {
  signal(SIGINT, handler); /* installs ctl-c handler */
  while(1) {
  }
}
```

```
linux> ./external
<ctrl-c>
You think hitting ctrl-c will stop
the bomb?
Well...OK
linux>
```

external.c

A Program That Reacts to Internally Generated Events

```
#include <stdio.h>
#include <signal.h>

int beeps = 0;

/* SIGALRM handler */
void handler(int sig) {
  safe_printf("BEEP\n");

  if (++beeps < 5)
    alarm(1);
  else {
    safe_printf("BOOM!\n");
    exit(0);
  }
}
```

internal.c

```
main() {
  signal(SIGALRM, handler);
  alarm(1); /* send SIGALRM in
               1 second */

  while (1) {
    /* handler returns here */
  }
}
```

```
linux> ./internal
BEEP
BEEP
BEEP
BEEP
BEEP
BOOM!
bass>
```

Async-Signal-Safety

- Function is *async-signal-safe* if either reentrant (all variables stored on stack frame, CS:APP2e 12.7.2) or non-interruptible by signals.
- Posix guarantees 117 functions to be async-signal-safe
  - `write` is on the list, `printf` is not
- One solution: async-signal-safe wrapper for `printf`:

```
void safe_printf(const char *format, ...) {
    char buf[MAXS];
    va_list args;

    va_start(args, format);                    /* reentrant */
    vsnprintf(buf, sizeof(buf), format, args); /* reentrant */
    va_end(args);                              /* reentrant */
    write(1, buf, strlen(buf));                /* async-signal-safe */
}
```

safe_printf.c

Today

- Multitasking, shells
- Signals
- **Nonlocal jumps**

Nonlocal Jumps: `setjmp/longjmp`

- **Powerful (but dangerous) user-level mechanism for transferring control to an arbitrary location**
  - Controlled to way to break the procedure call / return discipline
  - Useful for error recovery and signal handling

- **`int setjmp(jmp_buf j)`**
  - Must be called before longjmp
  - Identifies a return site for a subsequent longjmp
  - Called once, returns one or more times

- **Implementation:**
  - Remember where you are by storing the current ***register context***, ***stack pointer***, and ***PC value*** in `jmp_buf`
  - Return 0

`setjmp/longjmp` (cont)

- `void longjmp(jmp_buf j, int i)`
  - Meaning:
    - return from the `setjmp` remembered by jump buffer `j` again ...
    - ... this time returning `i` instead of 0
  - Called after `setjmp`
  - Called once, but never returns

- **`longjmp` Implementation:**
  - Restore register context (stack pointer, base pointer, PC value) from jump buffer `j`
  - Set `%eax` (the return value) to `i`
  - Jump to the location indicated by the PC stored in jump buf `j`

setjmp/longjmp Example

```
#include <setjmp.h>
jmp_buf buf;

main() {
   if (setjmp(buf) != 0) {
      printf("back in main due to an error\n");
   else
      printf("first time through\n");
   p1(); /* p1 calls p2, which calls p3 */
}
...
p3() {
   <error checking code>
   if (error)
      longjmp(buf, 1)
}
```

Limitations of Nonlocal Jumps

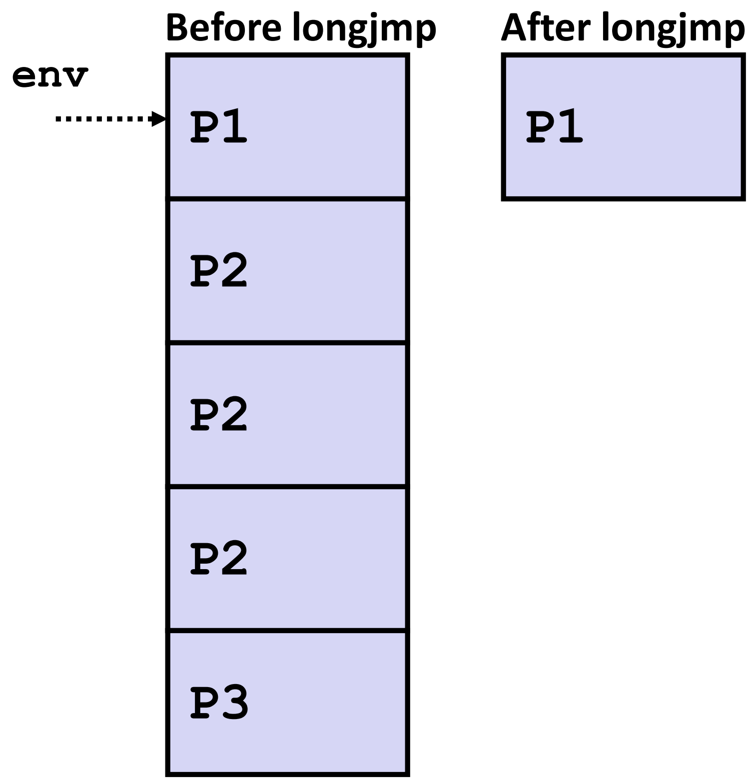
- **Works within stack discipline**
  - Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;

P1()
{
  if (setjmp(env)) {
    /* Long Jump to here */
  } else {
    P2();
  }
}

P2()
{ . . . P2(); . . . P3(); }

P3()
{
  longjmp(env, 1);
}
```



Limitations of Long Jumps (cont.)

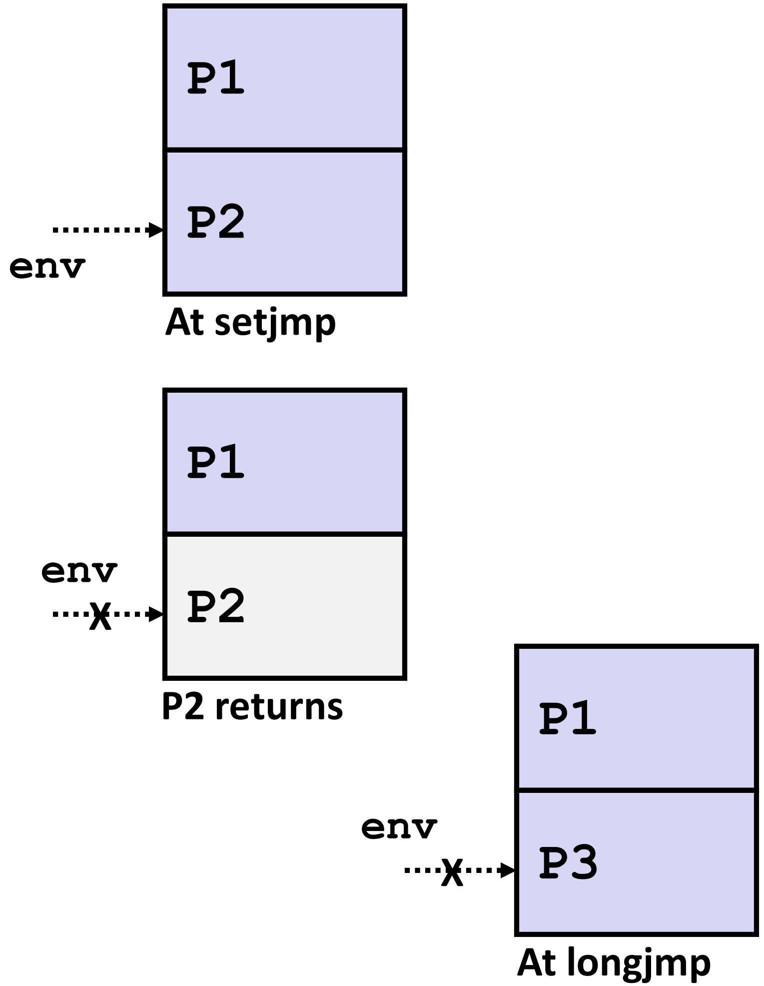
- **Works within stack discipline**
  - Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;

P1()
{
  P2(); P3();
}

P2()
{
   if (setjmp(env)) {
    /* Long Jump to here */
  }
}

P3()
{
  longjmp(env, 1);
}
```



Putting It All Together: A Program That Restarts Itself When `ctrl-c`'d

```
#include <stdio.h>
#include <signal.h>
#include <setjmp.h>

sigjmp_buf buf;

void handler(int sig) {
  siglongjmp(buf, 1);
}

main() {
  signal(SIGINT, handler);

  if (!sigsetjmp(buf, 1))
    printf("starting\n");
  else
    printf("restarting\n");

  while(1) {
     sleep(1);
     printf("processing...\n");
  }
}
```

restart.c

```
greatwhite> ./restart
starting
processing...
processing...
processing...
restarting
processing...
processing...
restarting
processing...
processing...
processing...
```

Ctrl-c

Ctrl-c

Summary

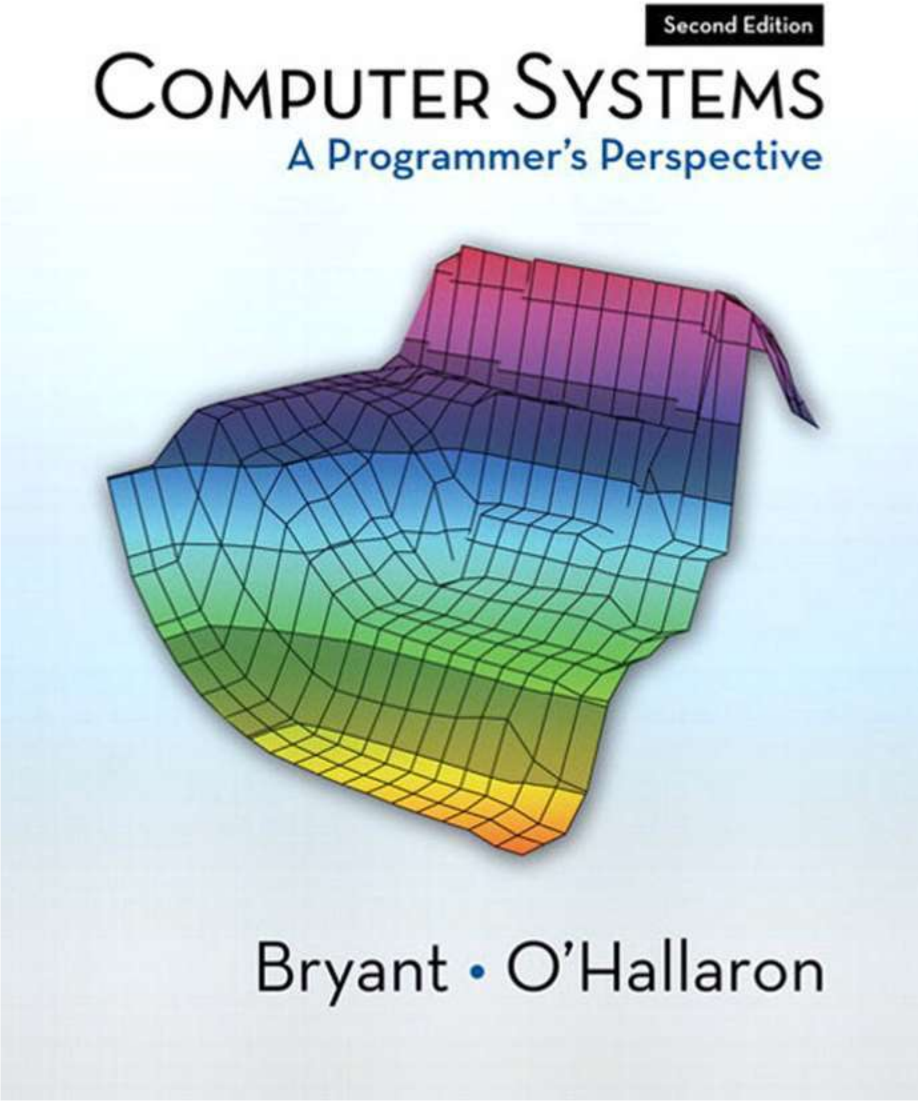
- **Signals provide process-level exception handling**
  - Can generate from user programs
  - Can define effect by declaring signal handler
- **Some caveats**
  - Very high overhead
    - >10,000 clock cycles
    - Only use for exceptional conditions
  - Don’t have queues
    - Just one bit for each pending signal type
- **Nonlocal jumps provide exceptional control flow within process**
  - Within constraints of stack discipline

BBM341 Systems Programming

Kayhan İmre

Overview

- Course theme
- Five realities

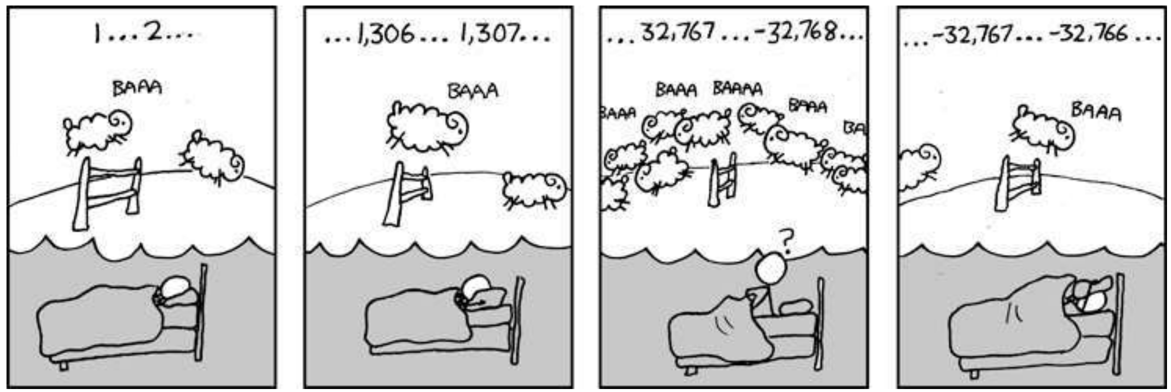


Course Theme: Abstraction Is Good But Don't Forget Reality

- **Most CS and CE courses emphasize abstraction**
  - Abstract data types
  - Asymptotic analysis
- **These abstractions have limits**
  - Especially in the presence of bugs
  - Need to understand details of underlying implementations
- **Useful outcomes**
  - Become more effective programmers
    - Able to find and eliminate bugs efficiently
    - Able to understand and tune for program performance
  - Prepare for later "systems" classes in CS & ECE
    - Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems

Great Reality #1:
Ints are not Integers, Floats are not Reals

- **Example 1: Is $x^2 \geq 0$?**
  - Float's: Yes!



  - Int's:
    - 40000 * 40000 → 1600000000
    - 50000 * 50000 → ??
- **Example 2: Is (x + y) + z = x + (y + z)?**
  - Unsigned & Signed Int's: Yes!
  - Float's:
    - (1e20 + -1e20) + 3.14 --> 3.14
    - 1e20 + (-1e20 + 3.14) --> ??

Source: xkcd.com/571

Great Reality #2:
You've Got to Know Assembly

- **Chances are, you'll never write programs in assembly**
  - Compilers are much better & more patient than you are
- **But: Understanding assembly is key to machine-level execution model**
  - Behavior of programs in presence of bugs
    - High-level language models break down
  - Tuning program performance
    - Understand optimizations done / not done by the compiler
    - Understanding sources of program inefficiency
  - Implementing system software
    - Compiler has machine code as target
    - Operating systems must manage process state
  - Creating / fighting malware
    - x86 assembly is the language of choice!

Great Reality #3: Memory Matters

Random Access Memory Is an Unphysical Abstraction

- **Memory is not unbounded**
  - It must be allocated and managed
  - Many applications are memory dominated
- **Memory referencing bugs especially pernicious**
  - Effects are distant in both time and space
- **Memory performance is not uniform**
  - Cache and virtual memory effects can greatly affect program performance
  - Adapting program to characteristics of memory system can lead to major speed improvements

Memory Referencing Errors

- **C and C++ do not provide any memory protection**
  - Out of bounds array references
  - Invalid pointer values
  - Abuses of malloc/free
- **Can lead to nasty bugs**
  - Whether or not bug has any effect depends on system and compiler
  - Action at a distance
    - Corrupted object logically unrelated to one being accessed
    - Effect of bug may be first observed long after it is generated
- **How can I deal with this?**
  - Program in Java, Ruby or ML
  - Understand what possible interactions may occur
  - Use or develop tools to detect referencing errors (e.g. Valgrind)

Memory System Performance Example

```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

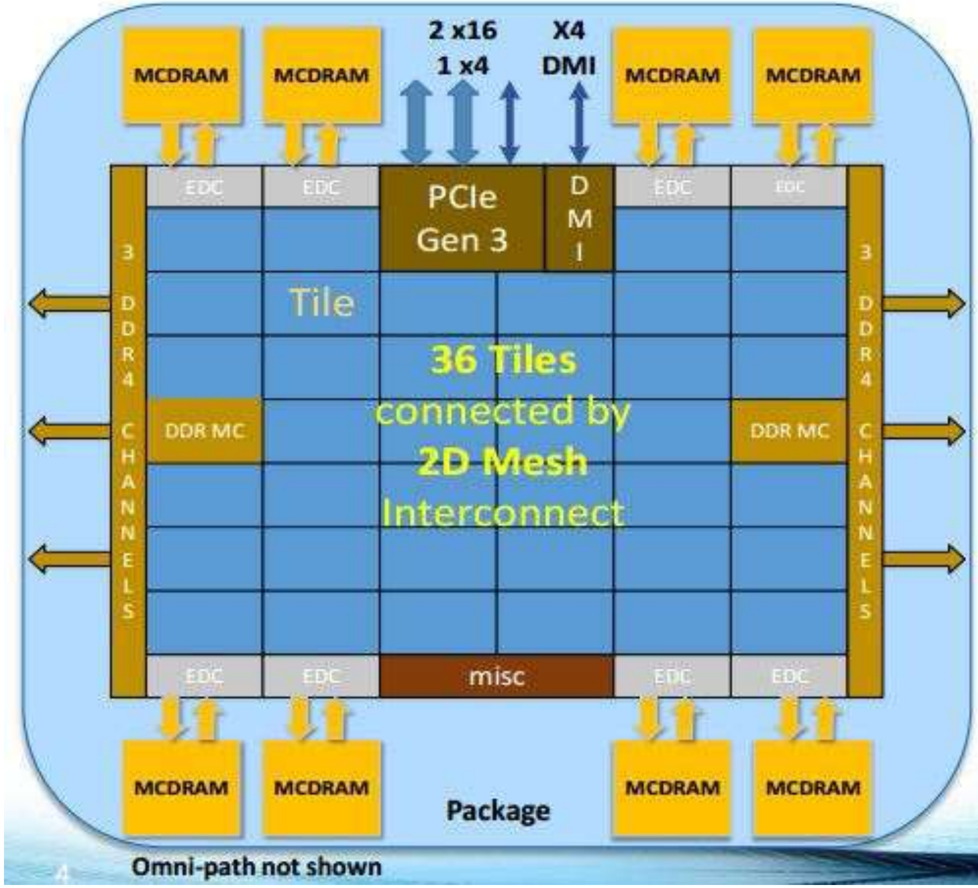
```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

21 times slower
(Pentium 4)

- **Hierarchical memory organization**
- **Performance depends on access patterns**
  - Including how step through multi-dimensional array

Knights Landing Overview

TILE



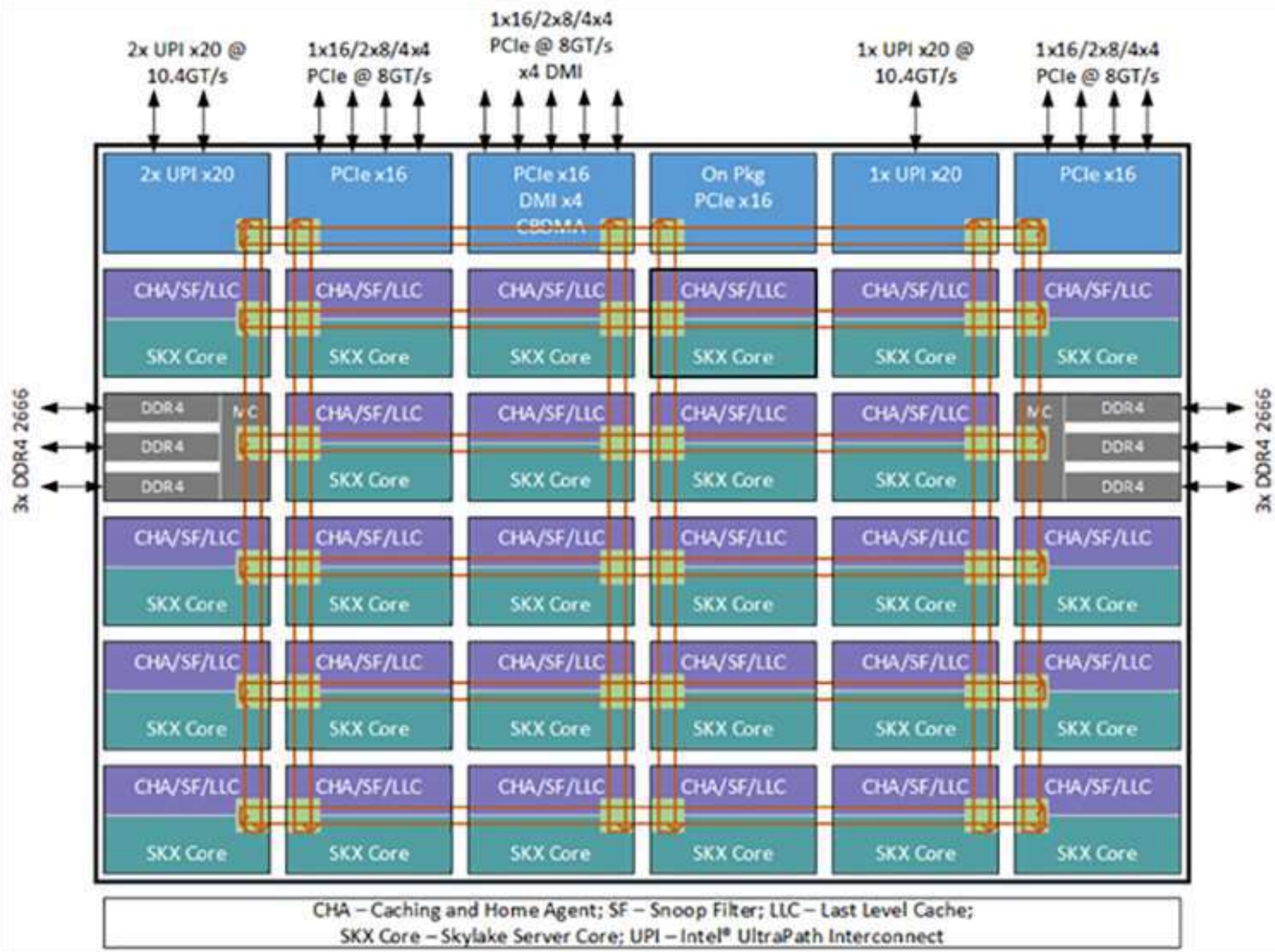
Chip: 36 Tiles interconnected by **2D Mesh**
Tile: 2 Cores + 2 VPU/core + 1 MB L2

Memory: MCDRAM: 16 GB on-package; High BW
DDR4: 6 channels @ 2400 up to 384GB
IO: 36 lanes PCIe Gen3. 4 lanes of DMI for chipset
Node: 1-Socket only
Fabric: Omni-Path on-package (not shown)

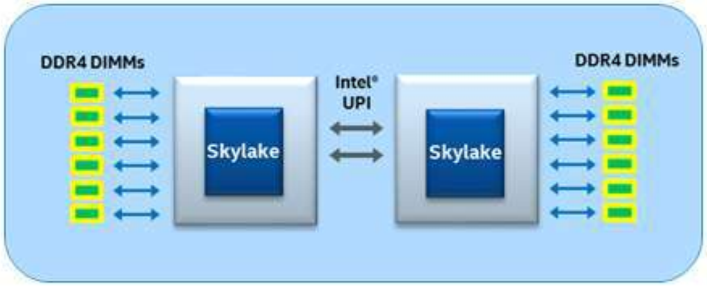
Vector Peak Perf: 3+TF DP and 6+TF SP Flops
Scalar Perf: ~3x over Knights Corner
Streams Triad (GB/s): MCDRAM : 400+; DDR: 90+

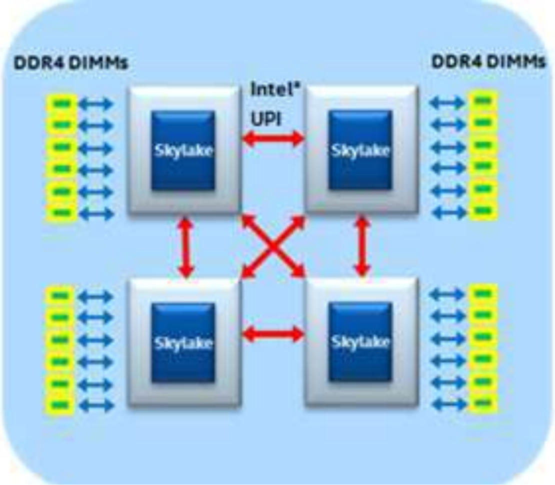
Source Intel: All products, computer systems, dates and figures specified are preliminary based on current expectations, and are subject to change without notice. KNL data are preliminary based on current expectations and are subject to change without notice. 1Binary Compatible with Intel Xeon processors using Haswell Instruction Set [illegible]. 2Bandwidth numbers are based on STREAM-like memory access pattern when MCDRAM [illegible] memory. Results have been estimated based on internal Intel analysis [illegible] purposes only. Any difference in system [illegible] actual performance.

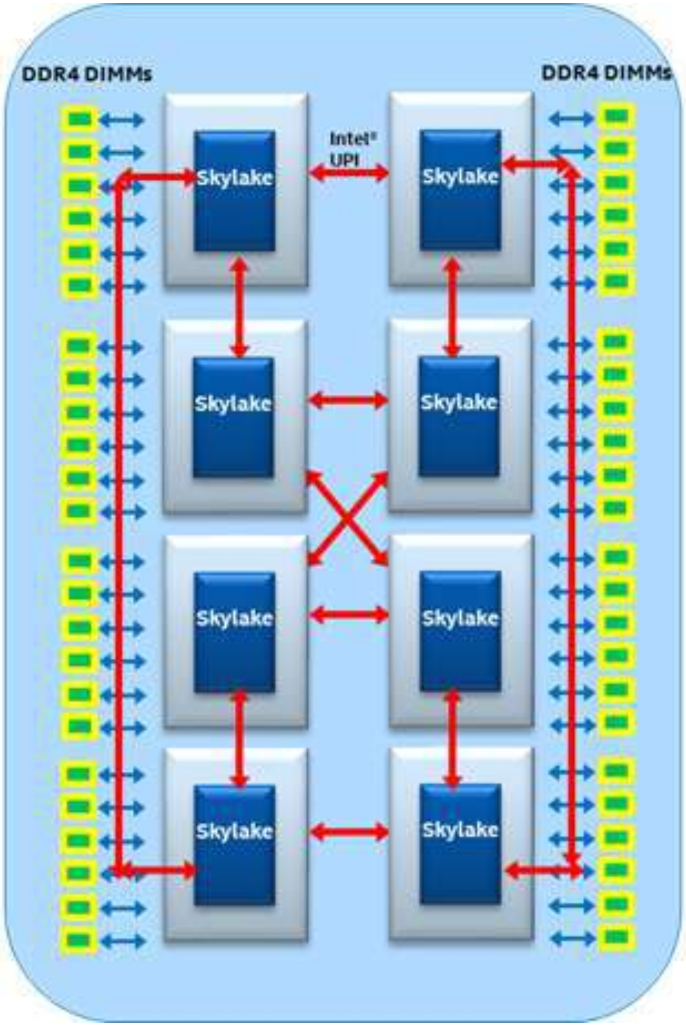
Intel® Xeon® Processor Scalable (2018)



Intel® Xeon® Processor Scalable (2018)



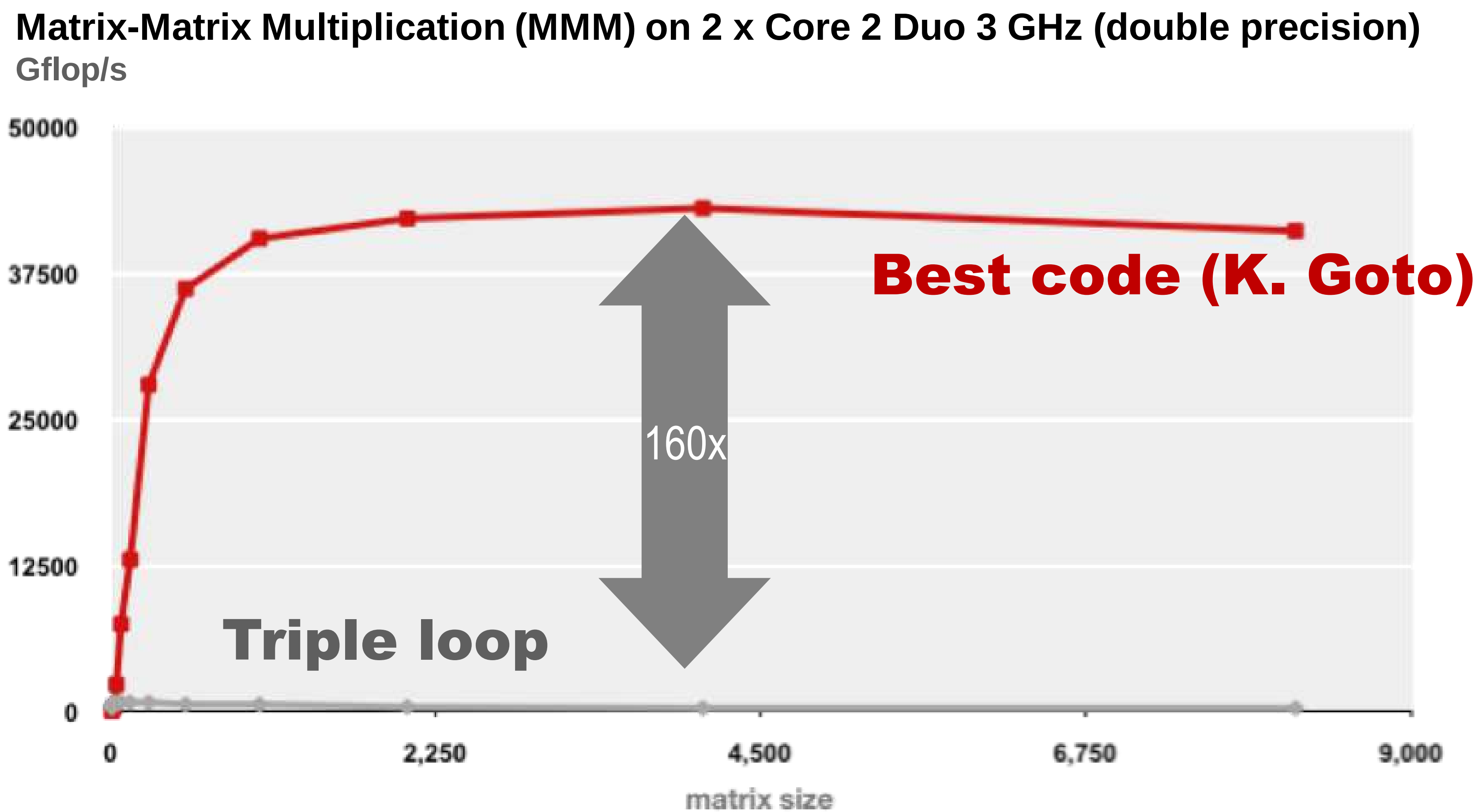




Great Reality #4: There's more to performance than asymptotic complexity

- **Constant factors matter too!**
- **And even exact op count does not predict performance**
  - Easily see 10:1 performance range depending on how code written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- **Must understand system to optimize performance**
  - How programs compiled and executed
  - How to measure program performance and identify bottlenecks
  - How to improve performance without destroying code modularity and generality

Example Matrix Multiplication



- Standard desktop computer, vendor compiler, using optimization flags
- Both implementations have exactly the same operations count ($2n^3$)
- What is going on?

Great Reality #5: Computers do more than execute programs

- **They need to get data in and out**
  - I/O system critical to program reliability and performance

- **They communicate with each other over networks**
  - Many system-level issues arise in presence of network
    - Concurrent operations by autonomous processes
    - Coping with unreliable media
    - Cross platform compatibility
    - Complex performance issues

Course Perspective

- **Most Systems Courses are Builder-Centric**
  - Computer Architecture
    - Design pipelined processor in Verilog
  - Operating Systems
    - Implement large portions of operating system
  - Compilers
    - Write compiler for simple language
  - Networking
    - Implement and simulate network protocols

Course Perspective (Cont.)

- **Our Course is Programmer-Centric**
  - Purpose is to show how by knowing more about the underlying system, one can be more effective as a programmer
  - Enable you to
    - Write programs that are more reliable and efficient
    - Incorporate features that require hooks into OS
      - E.g., concurrency, signal handlers
  - Not just a course for dedicated hackers
    - We bring out the hidden hacker in everyone
  - Cover material in this course that you won’t see elsewhere

Textbooks

- **Randal E. Bryant and David R. O'Hallaron,**
  - "Computer Systems: A Programmer's Perspective, Second Edition" (CS:APP2e), Prentice Hall, 2011
  - http://csapp.cs.cmu.edu/2e/home.html
  - This book really matters for the course!
    - How to solve labs
    - Practice problems typical of exam problems

- **Brian Kernighan and Dennis Ritchie,**
  - "The C Programming Language, Second Edition", Prentice Hall, 1988

Programs and Data

- **Topics**
  - Bits operations, arithmetic, assembly language programs
  - Representation of C control and data structures
  - Includes aspects of architecture and compilers

The Memory Hierarchy

- **Topics**
  - Memory technology, memory hierarchy, caches, disks, locality
  - Includes aspects of architecture and OS

Performance

- **Topics**
  - Co-optimization (control and data), measuring time on a computer
  - Includes aspects of architecture, compilers, and OS

Exceptional Control Flow

- **Topics**
  - Hardware exceptions, processes, process control, Unix signals, nonlocal jumps
  - Includes aspects of compilers, OS, and architecture

Virtual Memory

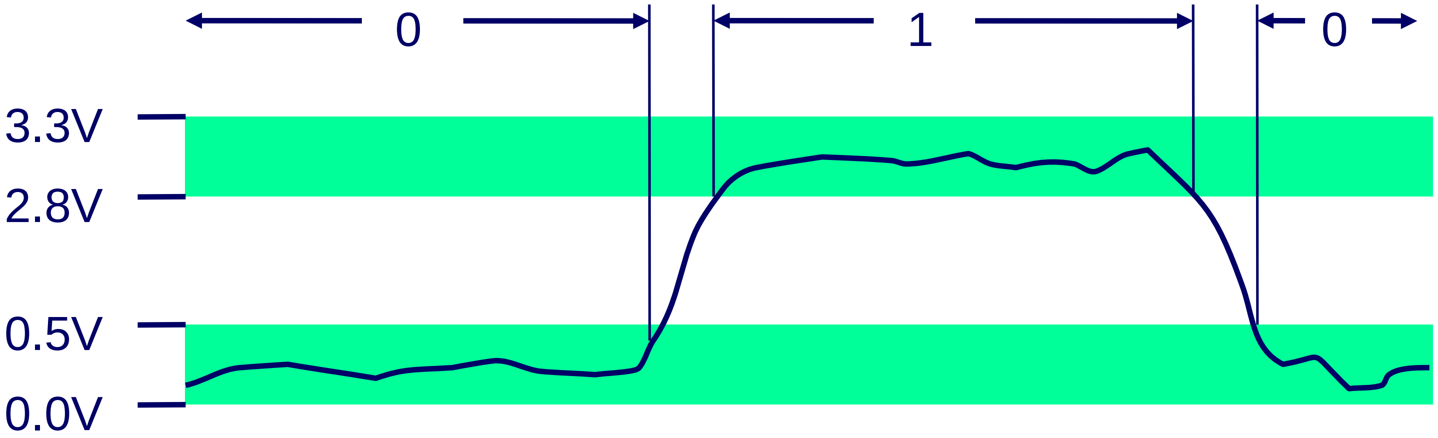
- **Topics**
  - Virtual memory, address translation, dynamic storage allocation
  - Includes aspects of architecture and OS

Bits, Bytes, and Integers

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

Binary Representations

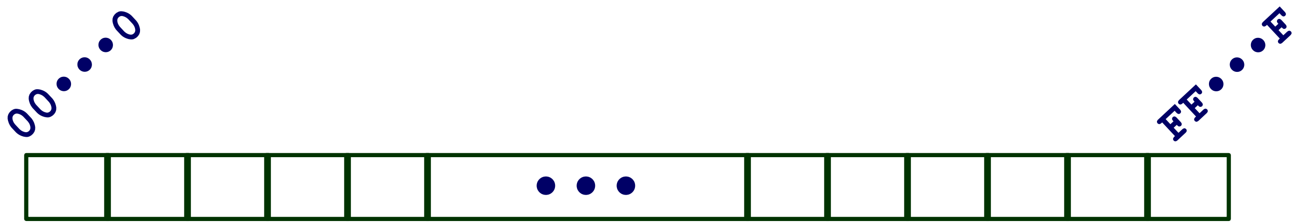


Encoding Byte Values

- **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

Byte-Oriented Memory Organization



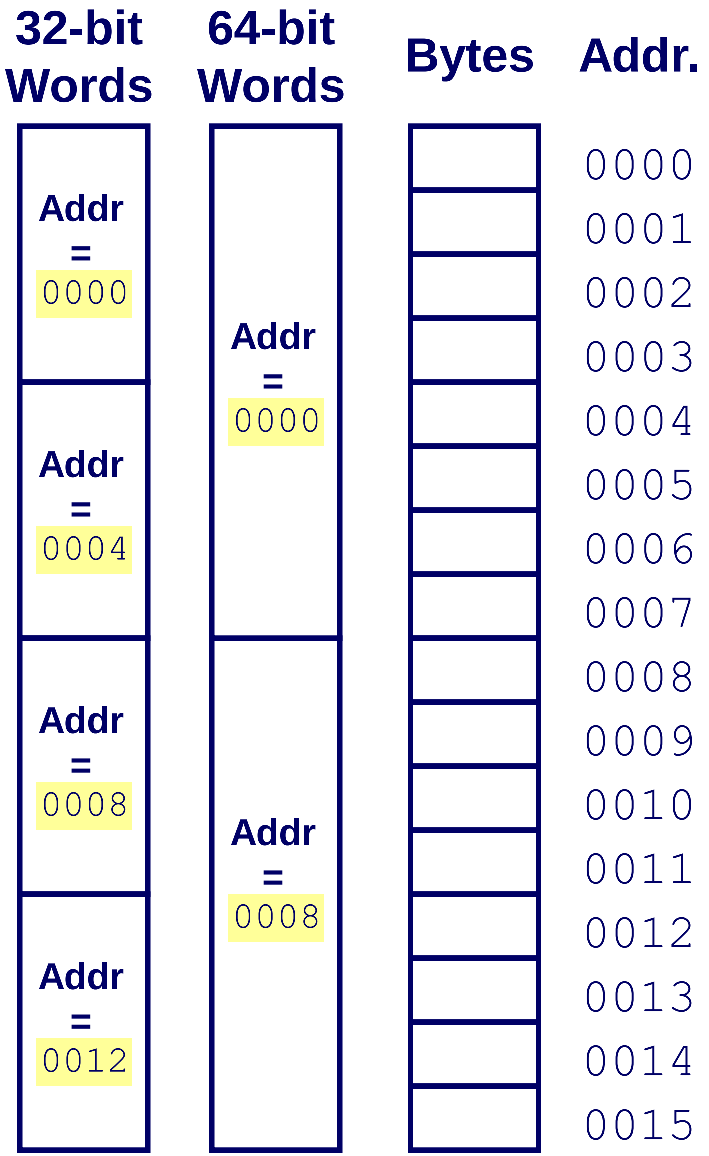
- **Programs Refer to Virtual Addresses**
  - Conceptually very large array of bytes
  - Actually implemented with hierarchy of different memory types
  - System provides address space private to particular "process"
    - Program being executed
    - Program can clobber its own data, but not that of others
- **Compiler + Run-Time System Control Allocation**
  - Where different program objects should be stored
  - All allocation within single virtual address space

Machine Words

- **Machine Has "Word Size"**
  - Nominal size of integer-valued data
    - Including addresses
  - Most current machines use 32 bits (4 bytes) words
    - Limits addresses to 4GB
    - Becoming too small for memory-intensive applications
  - High-end systems use 64 bits (8 bytes) words
    - Potential address space ≈ 1.8×10^{19} bytes
    - x86-64 machines support 48-bit addresses: 256 Terabytes
  - Machines 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)



Data Representations

C Data Type	Typical 32-bit	Intel IA32	x86-64
char	1	1	1
short	2	2	2
int	4	4	4
long	4	4	8
long long	8	8	8
float	4	4	4
double	8	8	8
long double	8	10/12	10/16
pointer	4	4	8

Byte Ordering

- **How should bytes within a multi-byte word be ordered in memory?**
- **Conventions**
  - Big Endian: Sun, PPC Mac, Internet
    - Least significant byte has highest address
  - Little Endian: x86
    - Least significant byte has lowest address

Byte Ordering Example

- **Big Endian**
  - Least significant byte has highest address
- **Little Endian**
  - Least significant byte has lowest address
- **Example**
  - Variable x has 4-byte representation 0x01234567
  - Address given by &x is 0x100

Big Endian

		0x100	0x101	0x102	0x103		
		01	23	45	67		

Little Endian

		0x100	0x101	0x102	0x103		
		67	45	23	01		

Reading Byte-Reversed Listings

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

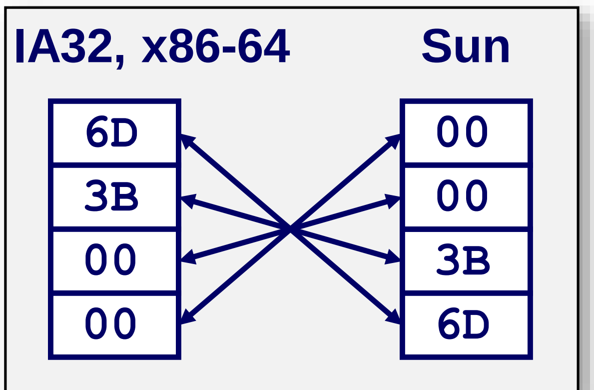
Address	Instruction Code	Assembly Rendition	
`8048365:`	`5b`	`pop`	`%ebx`
`8048366:`	`81 c3 ab 12 00 00`	`add`	`$0x12ab,%ebx`
`804836c:`	`83 bb 28 00 00 00 00`	`cmpl`	`$0x0,0x28(%ebx)`

- **Deciphering Numbers**
  - Value: 0x12ab
  - Pad to 32 bits: 0x000012ab
  - Split into bytes: 00 00 12 ab
  - Reverse: ab 12 00 00

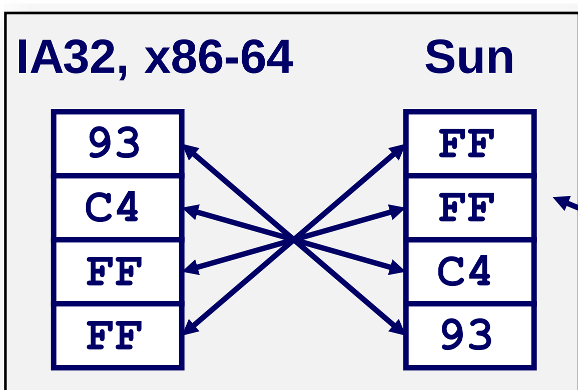
Representing Integers

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

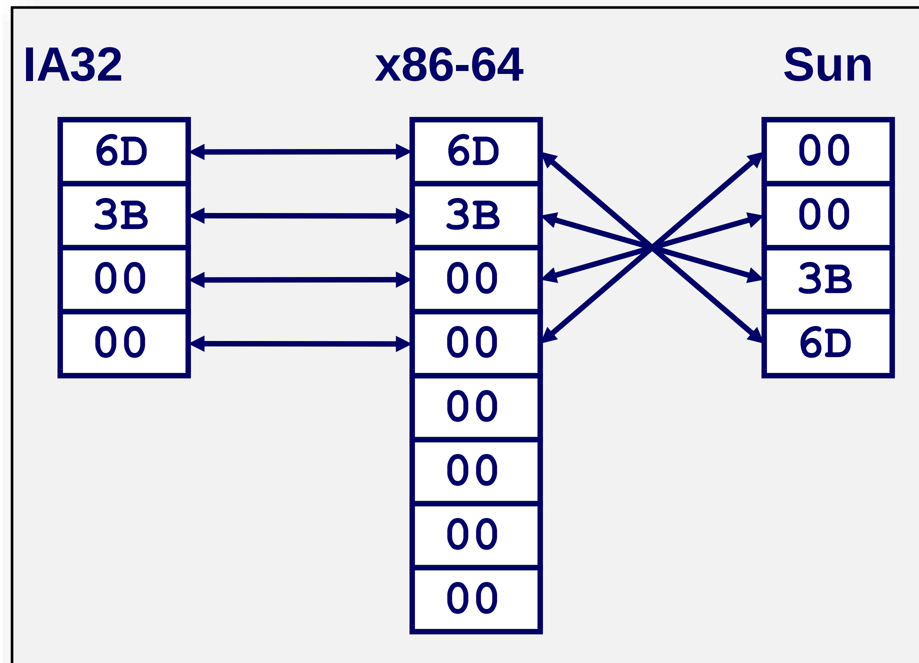
int A = 15213;



int B = -15213;



long int C = 15213;

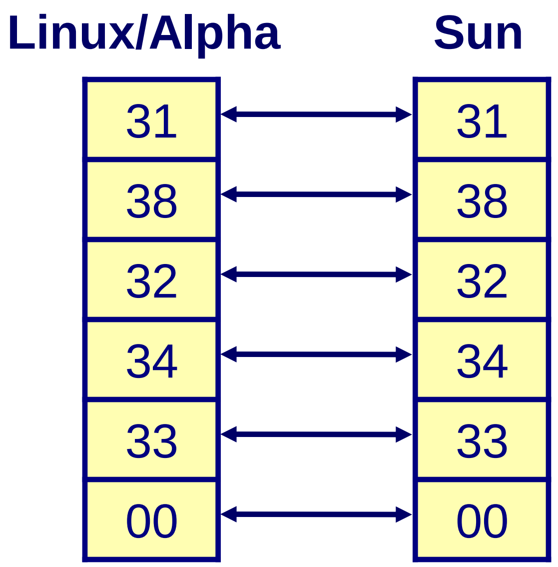


Two's complement representation
(Covered later)

Representing Strings

```
char S[6] = "18243";
```

- **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



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

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**

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
    - $\sim 01000001_2 = 10111110_2$
  - ~0x00 = 0xFF
    - $\sim 00000000_2 = 11111111_2$
  - 0x69 & 0x55 = 0x41
    - $01101001_2 \,\&\, 01010101_2 = 01000001_2$
  - 0x69 | 0x55 = 0x7D
    - $01101001_2 \mid 01010101_2 = 01111101_2$

Contrast: Logic Operations in C

- **Contrast to Logical Operators**
  - &&, ||, !
    - View 0 as "False"
    - Anything nonzero as "True"
    - Always return 0 or 1
    - Early termination
- **Examples (char data type)**
  - !0x41 = 0x00
  - !0x00 = 0x01
  - !!0x41 = 0x01
  - 0x69 && 0x55 = 0x01
  - 0x69 || 0x55 = 0x01

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 right
- **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

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

Encoding Integers

Unsigned

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

Two's Complement

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

Sign Bit

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

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

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

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

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**

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

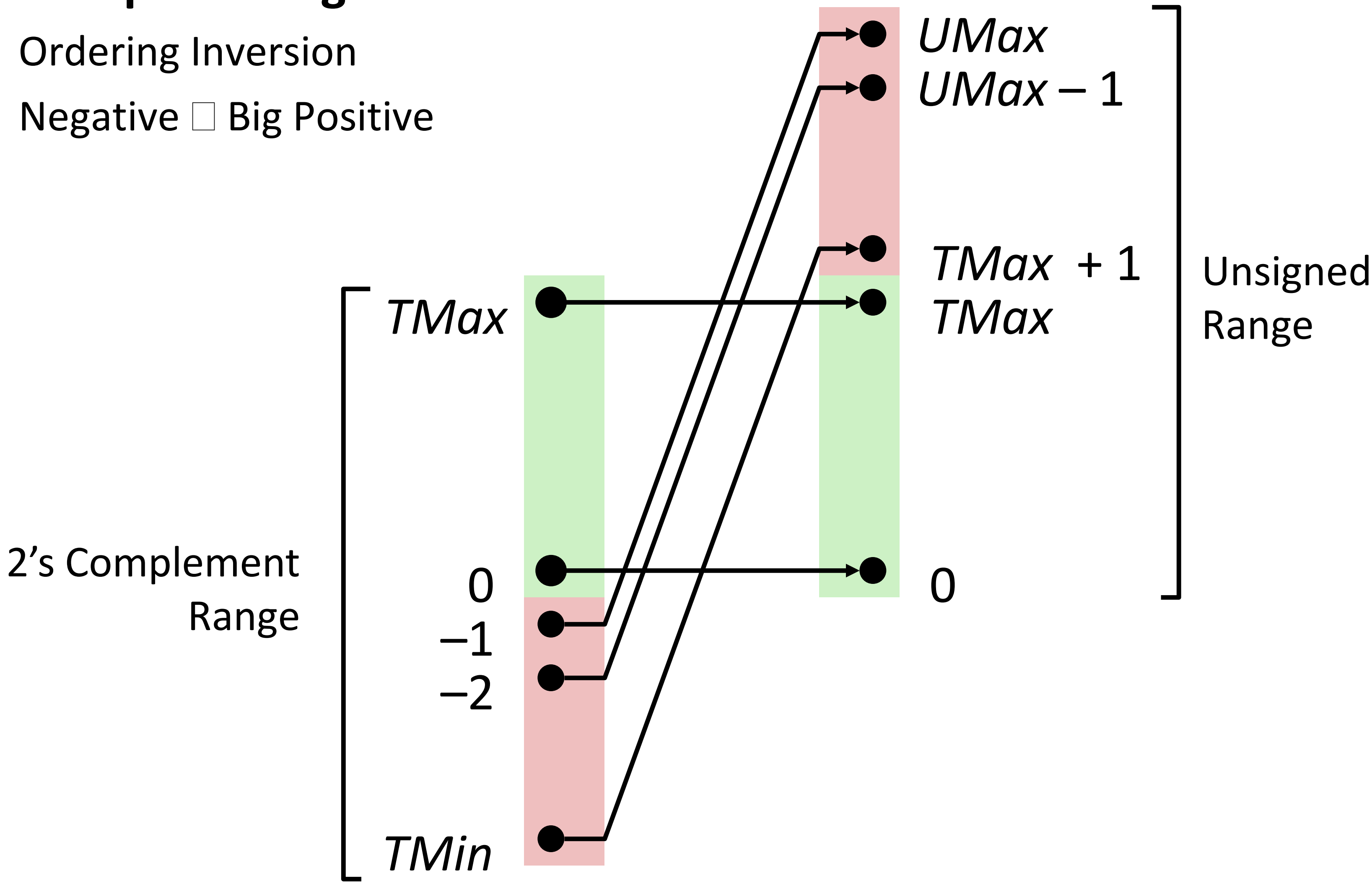
- **C Programming**
  - #include <limits.h>
  - Declares constants, e.g.,
    - ULONG_MAX
    - LONG_MAX
    - LONG_MIN
  - Values platform specific

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

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**

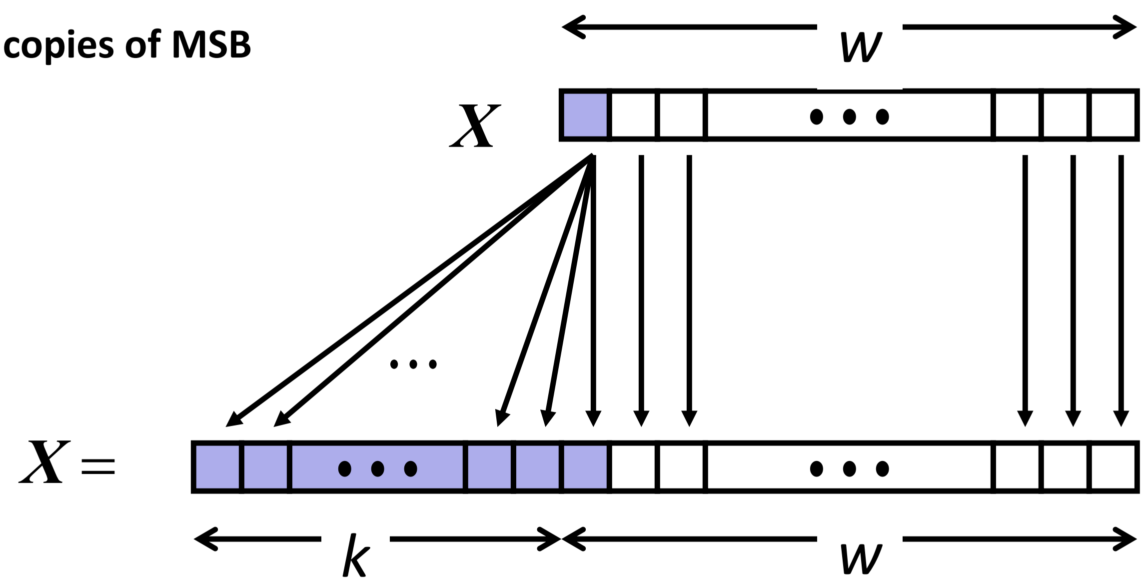
- **Expression containing signed and unsigned int**
  - `int` is cast to `unsigned`!!

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

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 behaviour

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

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

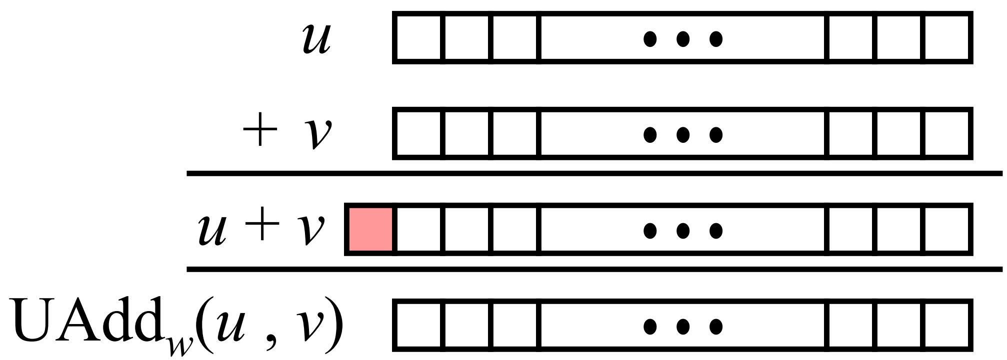
	Decimal	Hex	Binary
`0`	0	`00 00`	`00000000 00000000`
`~0`	-1	`FF FF`	`11111111 11111111`
`~0+1`	0	`00 00`	`00000000 00000000`

Unsigned Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



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

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

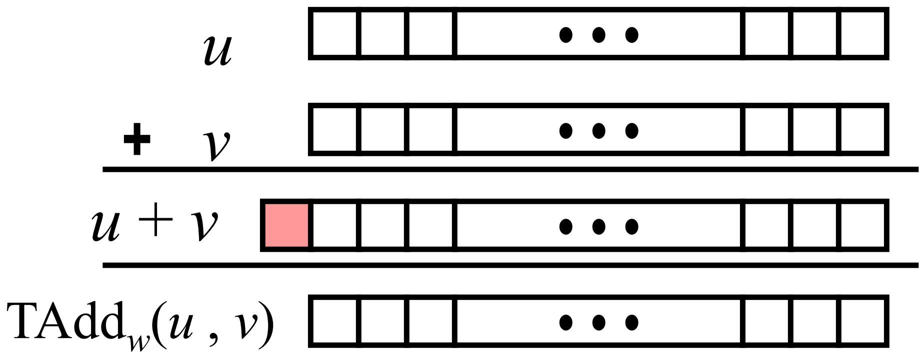
$$UAdd_w(u,v) = \begin{cases} u+v & u+v < 2^w \\ u+v-2^w & u+v \geq 2^w \end{cases}$$

Two’s Complement Addition

Operands: *w* bits

True Sum: *w*+1 bits

Discard Carry: *w* bits



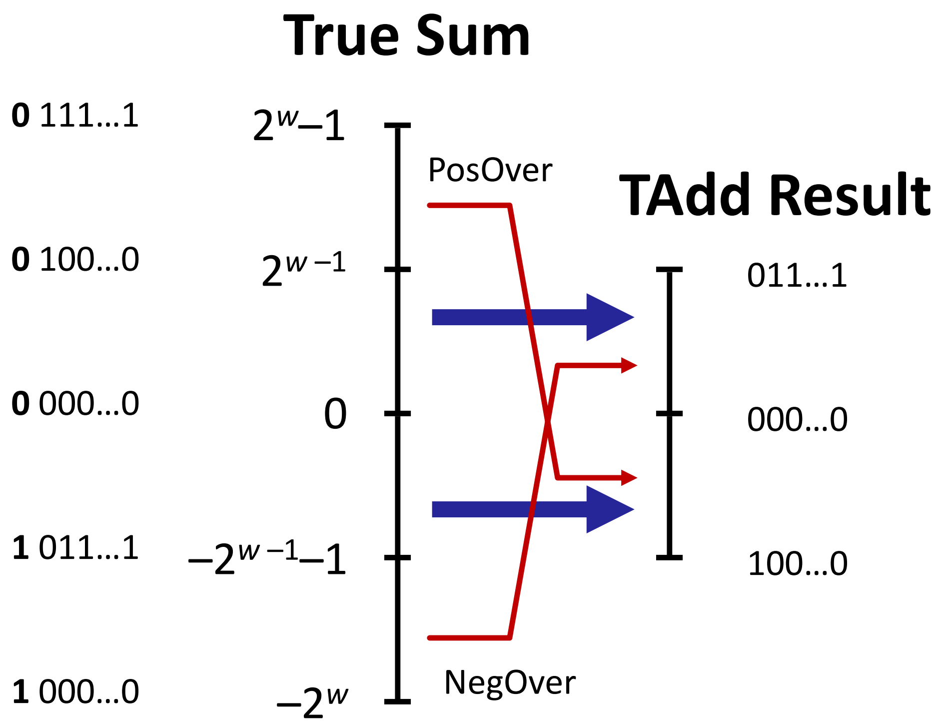
- **TAdd and UAdd have Identical Bit-Level Behavior**
  - Signed vs. unsigned addition in C:

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

  - Will give `s == t`

TAdd Overflow

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



Multiplication

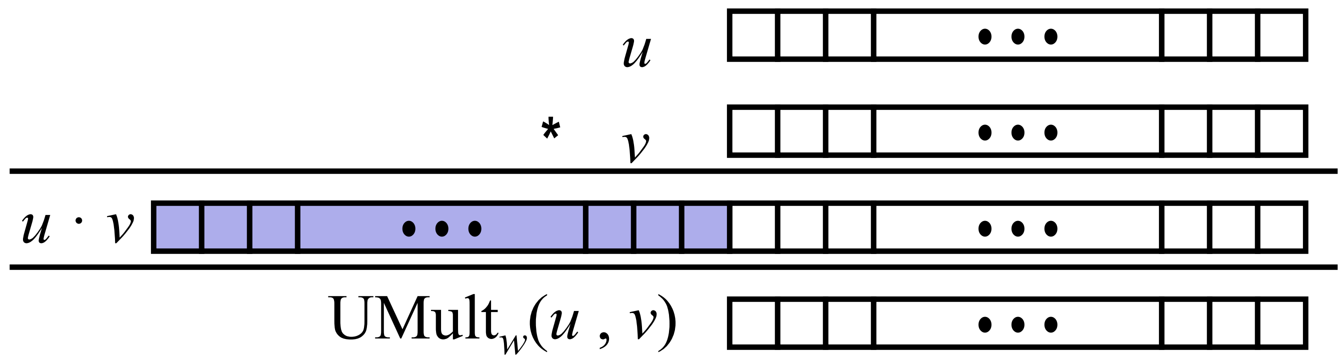
- **Computing Exact Product of *w*-bit numbers *x*, *y***
  - Either signed or unsigned
- **Ranges**
  - Unsigned: $0 \leq x * y \leq (2^w - 1)^2 = 2^{2w} - 2^{w+1} + 1$
    - Up to $2w$ bits
  - Two's complement min: $x * y \geq (-2^{w-1})*(2^{w-1}-1) = -2^{2w-2} + 2^{w-1}$
    - Up to $2w-1$ bits
  - Two's complement max: $x * y \leq (-2^{w-1})^2 = 2^{2w-2}$
    - Up to $2w$ bits, but only for $(TMin_w)^2$
- **Maintaining Exact Results**
  - Would need to keep expanding word size with each product computed
  - Done in software by "arbitrary precision" arithmetic packages

Unsigned Multiplication in C

Operands: *w* bits

True Product: 2**w* bits

Discard *w* bits: *w* bits



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

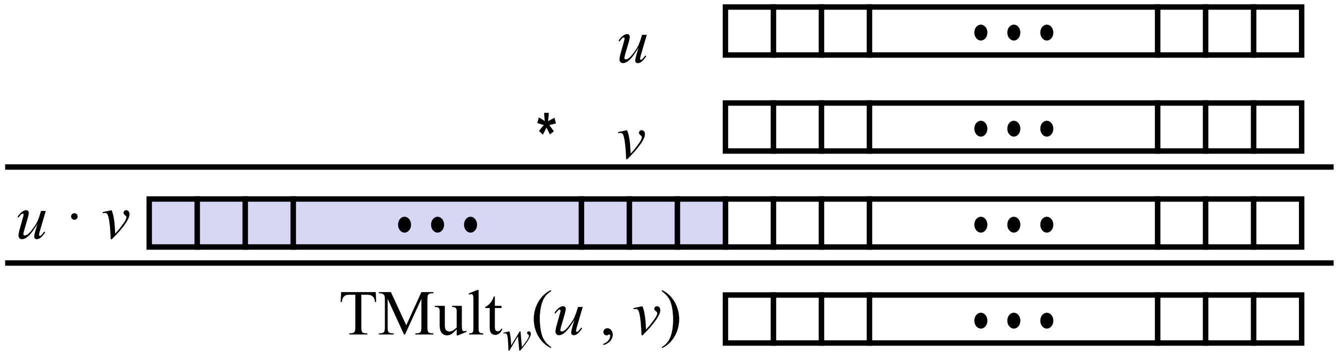
  $\text{UMult}_w(u, v) = u \cdot v \bmod 2^w$

Signed Multiplication in C

Operands: *w* bits

True Product: 2**w* bits

Discard *w* bits: *w* bits



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

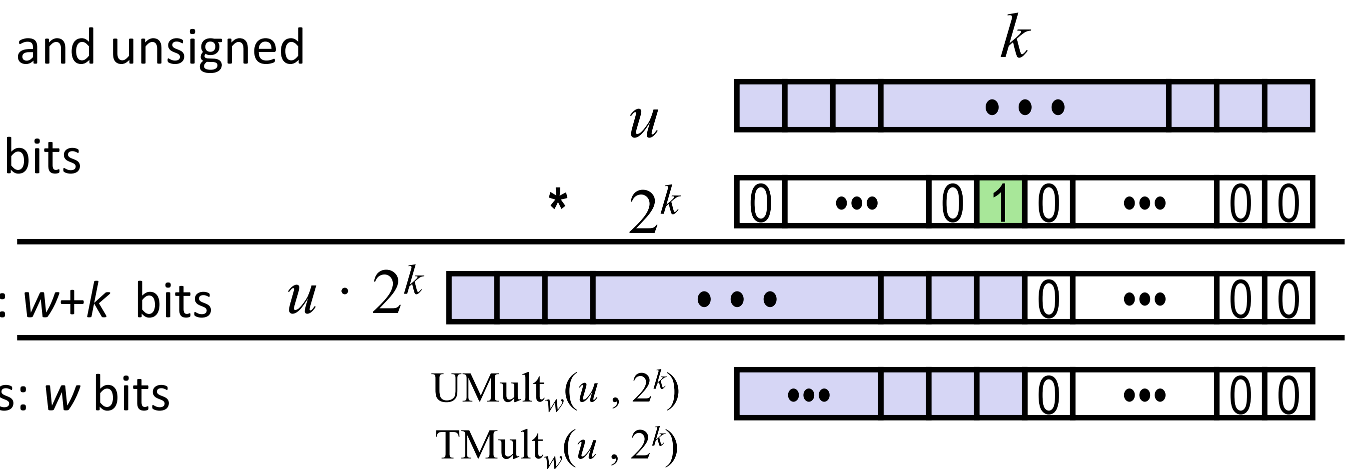
Power-of-2 Multiply with Shift

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

Operands: *w* bits

True Product: *w*+*k* bits

Discard *k* bits: *w* bits



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

Compiled Multiplication Code

C Function

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

Compiled Arithmetic Operations

```
  leal (%eax,%eax,2), %eax
  sall $2, %eax
```

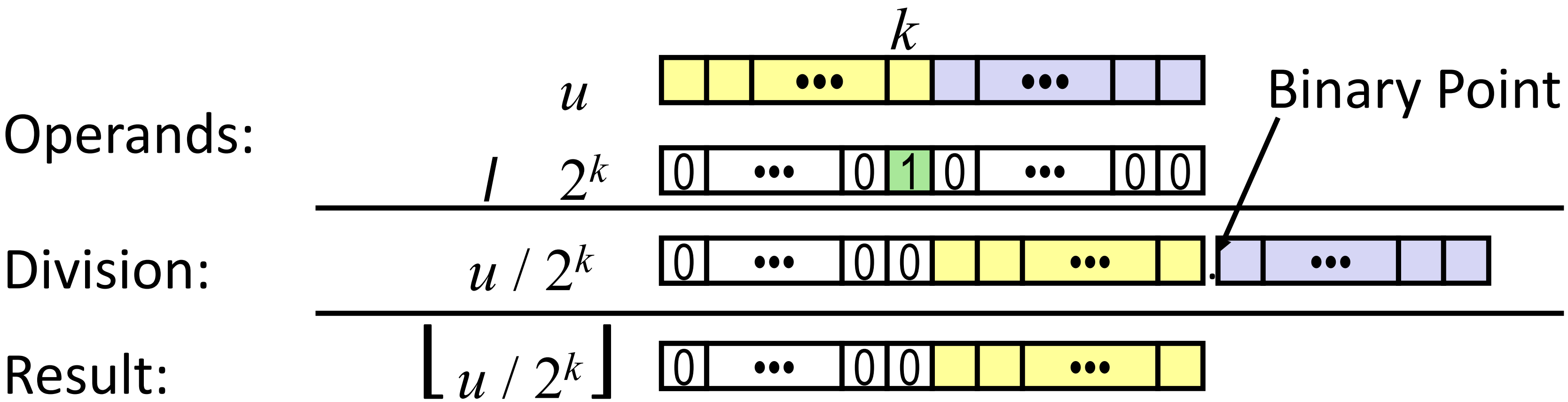
Explanation

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

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

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`

Compiled Unsigned Division Code

C Function

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

Compiled Arithmetic Operations

```
  shrl $3, %eax
```

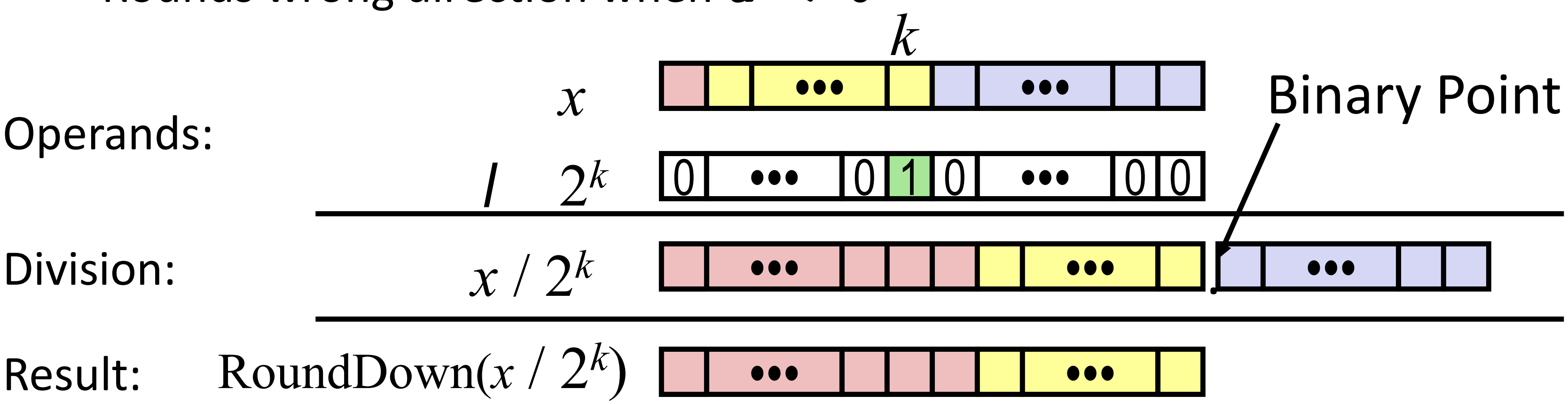
Explanation

```
  # 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`

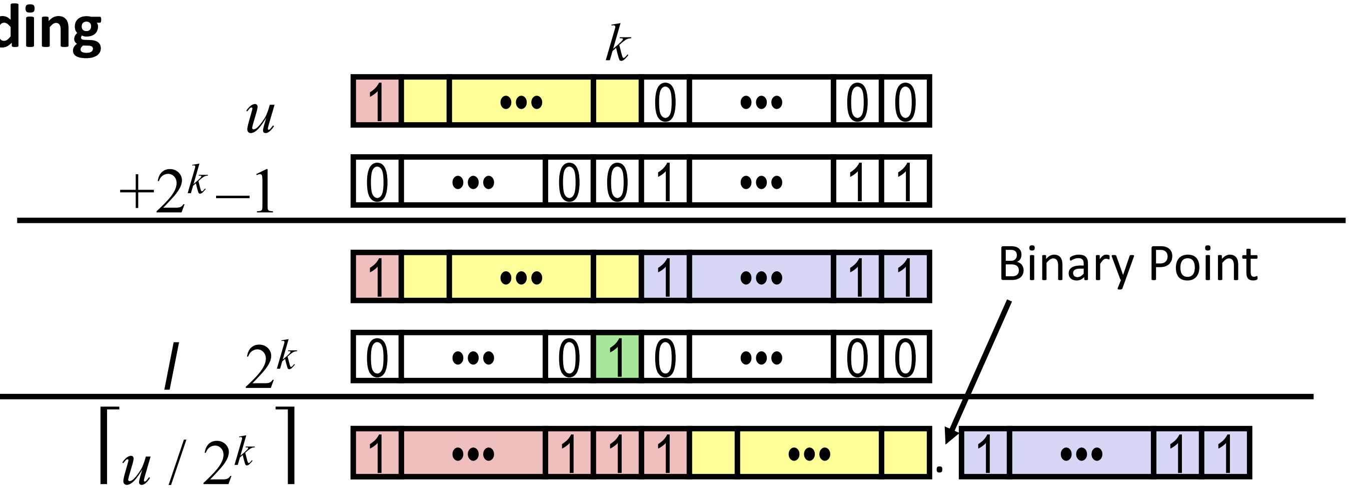
Correct Power-of-2 Divide

- **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

Dividend:

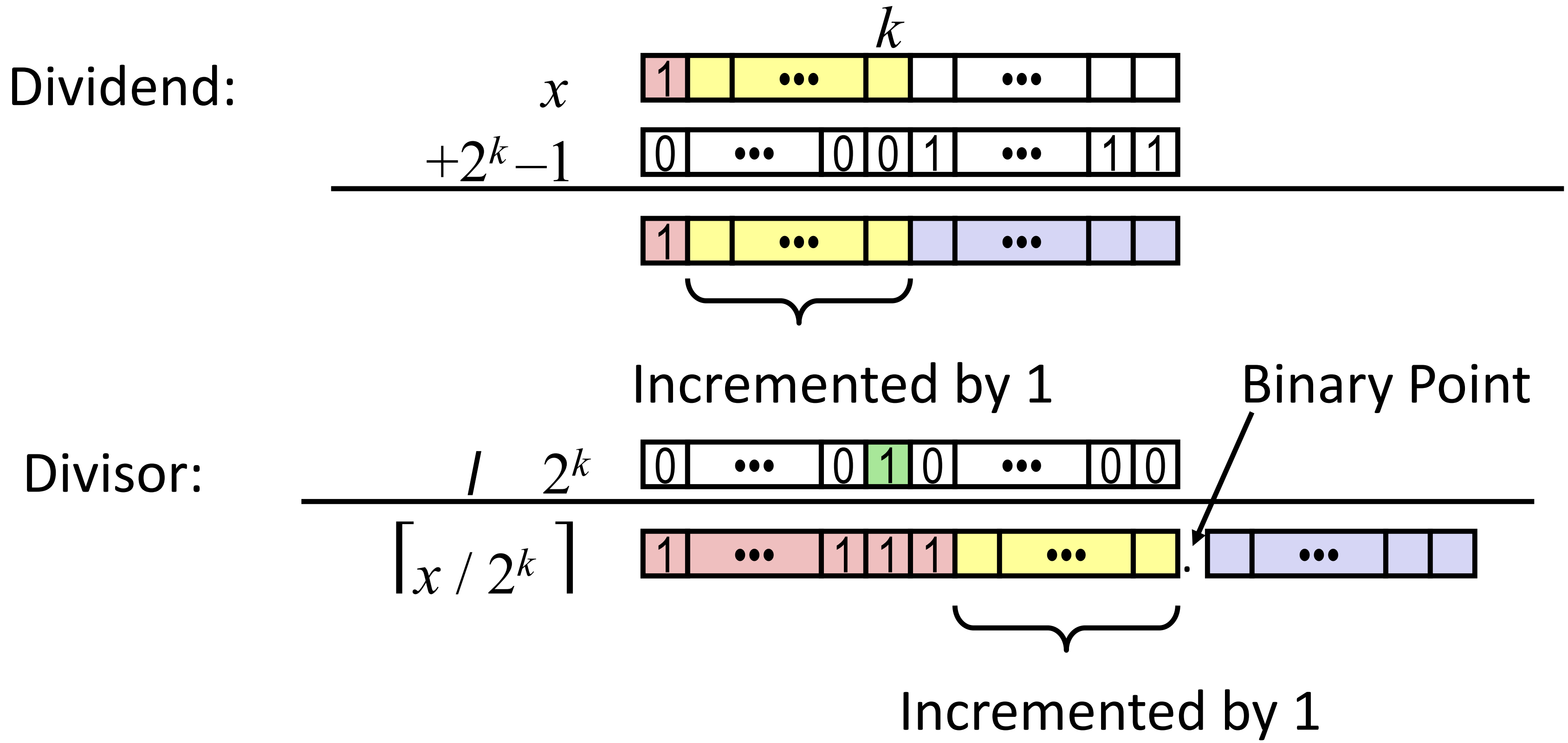
Divisor:



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

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

Compiled Arithmetic Operations

```
  testl %eax, %eax
  js    L4
L3:
  sarl $3, %eax
  ret
L4:
  addl $7, %eax
  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 >>

Today: Integers

- Representation: unsigned and signed
- Conversion, casting
- Expanding, truncating
- Addition, negation, multiplication, shifting
- Summary