

# Machine-Level Programming I: Basics

15-213/18-213: Introduction to Computer Systems  
5<sup>th</sup> Lecture, September 13, 2016

**Instructor:**

Phil Gibbons

# Today: Machine Programming I: Basics

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

# Intel x86 Processors

- **Dominate laptop/desktop/server market**
  
- **Evolutionary design**
  - Backwards compatible up until 8086, introduced in 1978
  - Added more features as time goes on
  
- **Complex instruction set computer (CISC)**
  - Many different instructions with many different formats
    - But, only small subset encountered with Linux programs
  - Hard to match performance of Reduced Instruction Set Computers (RISC)
  - But, Intel has done just that!
    - In terms of speed. Less so for low power.

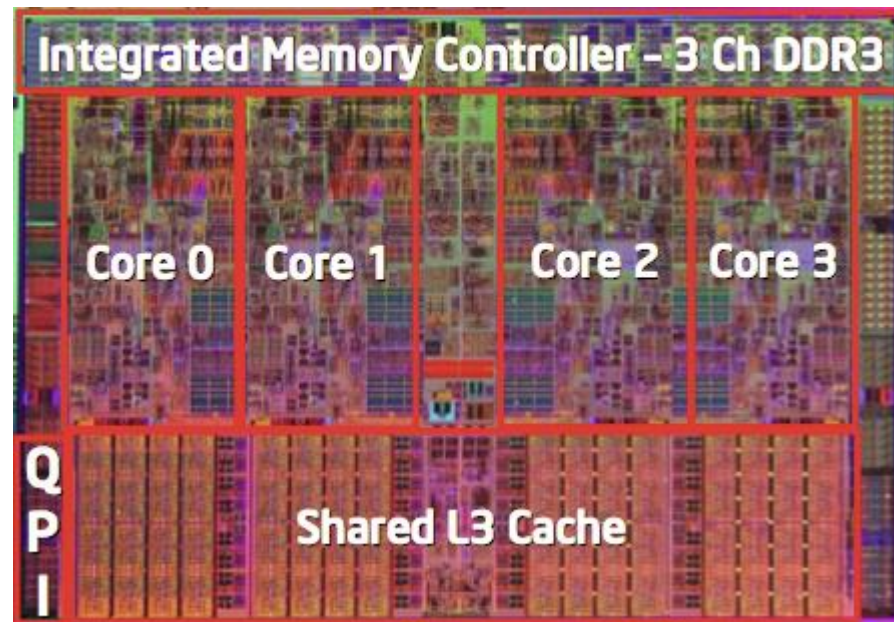
# Intel x86 Evolution: Milestones

<i>Name</i>	<i>Date</i>	<i>Transistors</i>	<i>MHz</i>
■ <b>8086</b>	<b>1978</b>	<b>29K</b>	<b>5-10</b>
<ul style="list-style-type: none"> <li>▪ First 16-bit Intel processor. Basis for IBM PC &amp; DOS</li> <li>▪ 1MB address space</li> </ul>			
■ <b>386</b>	<b>1985</b>	<b>275K</b>	<b>16-33</b>
<ul style="list-style-type: none"> <li>▪ First 32 bit Intel processor , referred to as IA32</li> <li>▪ Added “flat addressing”, capable of running Unix</li> </ul>			
■ <b>Pentium 4E</b>	<b>2004</b>	<b>125M</b>	<b>2800-3800</b>
<ul style="list-style-type: none"> <li>▪ First 64-bit Intel x86 processor, referred to as x86-64</li> </ul>			
■ <b>Core 2</b>	<b>2006</b>	<b>291M</b>	<b>1060-3333</b>
<ul style="list-style-type: none"> <li>▪ First multi-core Intel processor</li> </ul>			
■ <b>Core i7</b>	<b>2008</b>	<b>731M</b>	<b>1600-4400</b>
<ul style="list-style-type: none"> <li>▪ Four cores (our shark machines)</li> </ul>			

# Intel x86 Processors, cont.

## ■ Machine Evolution

■ 386	1985	0.3M
■ Pentium	1993	3.1M
■ Pentium/MMX	1997	4.5M
■ PentiumPro	1995	6.5M
■ Pentium III	1999	8.2M
■ Pentium 4	2000	42M
■ Core 2 Duo	2006	291M
■ Core i7	2008	731M



## ■ Added Features

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

# Intel x86 Processors, cont.

## ■ Past Generations

### Process technology

- |                               |      |        |
|-------------------------------|------|--------|
| ■ 1 <sup>st</sup> Pentium Pro | 1995 | 600 nm |
| ■ 1 <sup>st</sup> Pentium III | 1999 | 250 nm |
| ■ 1 <sup>st</sup> Pentium 4   | 2000 | 180 nm |
| ■ 1 <sup>st</sup> Core 2 Duo  | 2006 | 65 nm  |

## ■ Recent Generations

- |    |              |      |       |
|----|--------------|------|-------|
| 1. | Nehalem      | 2008 | 45 nm |
| 2. | Sandy Bridge | 2011 | 32 nm |
| 3. | Ivy Bridge   | 2012 | 22 nm |
| 4. | Haswell      | 2013 | 22 nm |
| 5. | Broadwell    | 2014 | 14 nm |
| 6. | Skylake      | 2015 | 14 nm |

## ■ Upcoming Generations

- |   |            |       |       |
|---|------------|-------|-------|
| ■ | Kaby Lake  | 2016? | 14 nm |
| ■ | Cannonlake | 2017? | 10 nm |

**Process technology dimension  
= width of narrowest wires  
(10 nm  $\approx$  100 atoms wide)**

# 2016 State of the Art: Skylake

## ■ Mobile Model: Core i7

- 2.6-2.9 GHz
- 45 W

## ■ Desktop Model: Core i7

- Integrated graphics
- 2.8-4.0 GHz
- 35-91 W

## ■ Server Model: Xeon

- Integrated graphics
- Multi-socket enabled
- 2-3.7 GHz
- 25-80 W

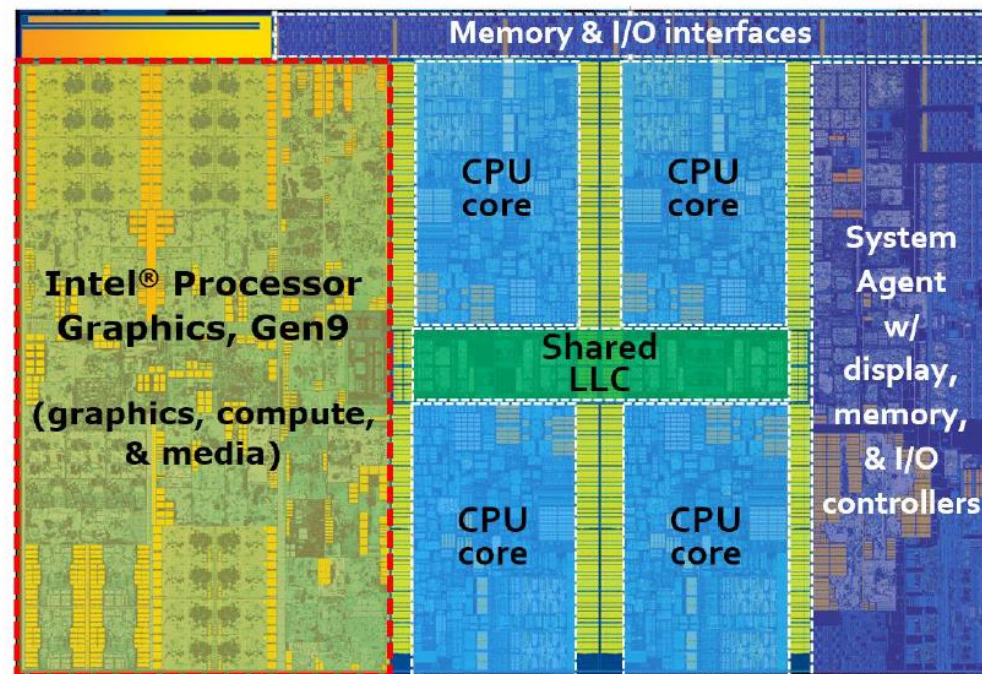


Figure 1: Architecture components layout for an Intel® Core™ i7 processor 6700K for desktop systems. This SoC contains 4 CPU cores, outlined in blue dashed boxes. Outlined in the red dashed box, is an Intel® HD Graphics 530. It is a one-slice instantiation of Intel processor graphics gen9 architecture.

# x86 Clones: Advanced Micro Devices (AMD)

## ■ Historically

- AMD has followed just behind Intel
- A little bit slower, a lot cheaper

## ■ Then

- Recruited top circuit designers from Digital Equipment Corp. and other downward trending companies
- Built Opteron: tough competitor to Pentium 4
- Developed x86-64, their own extension to 64 bits

## ■ Recent Years

- Intel got its act together
  - Leads the world in semiconductor technology
- AMD has fallen behind
  - Relies on external semiconductor manufacturer



# Intel's 64-Bit History

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

# Our Coverage

## ■ IA32

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

## ■ x86-64

- The standard
- `shark> gcc hello.c`
- `shark> gcc -m64 hello.c`

## ■ Presentation

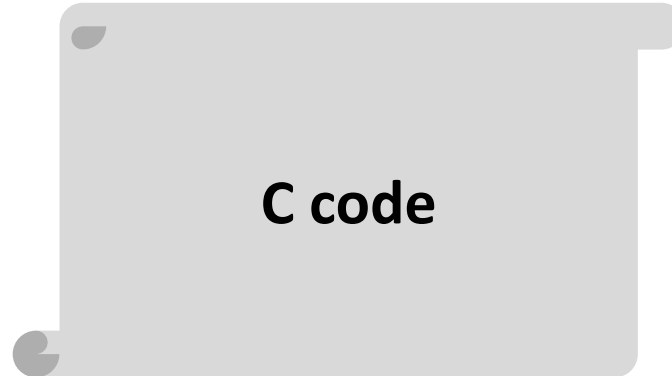
- Book covers x86-64
- Web aside on IA32
- We will only cover x86-64

# Today: Machine Programming I: Basics

- History of Intel processors and architectures
- **Assembly Basics: Registers, operands, move**
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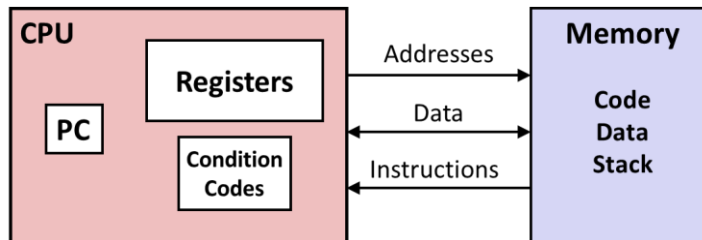
# Levels of Abstraction

C programmer



Nice clean layers,  
but beware...

Assembly programmer



Computer Designer

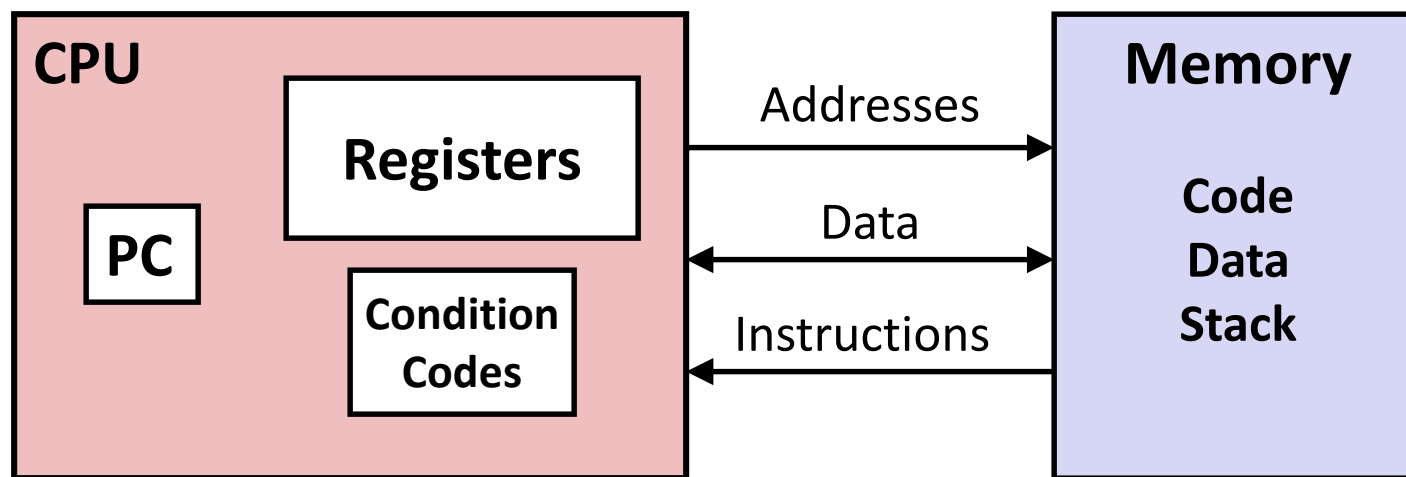
Caches, clock freq, layout, ...

**Of course, you know that: It's why you are taking this course.**

# Definitions

- **Architecture:** (also ISA: instruction set architecture) The parts of a processor design that one needs to understand for writing assembly/machine code.
  - Examples: instruction set specification, registers
- **Microarchitecture: Implementation of the architecture**
  - Examples: cache sizes and core frequency
- **Code Forms:**
  - **Machine Code:** The byte-level programs that a processor executes
  - **Assembly Code:** A text representation of machine code
- **Example ISAs:**
  - Intel: x86, IA32, Itanium, x86-64
  - ARM: Used in almost all mobile phones

# Assembly/Machine Code View



## Programmer-Visible State

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

## ▪ Memory

- Byte addressable array
- Code and user data
- Stack to support procedures

# Assembly Characteristics: Data Types

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

# x86-64 Integer Registers

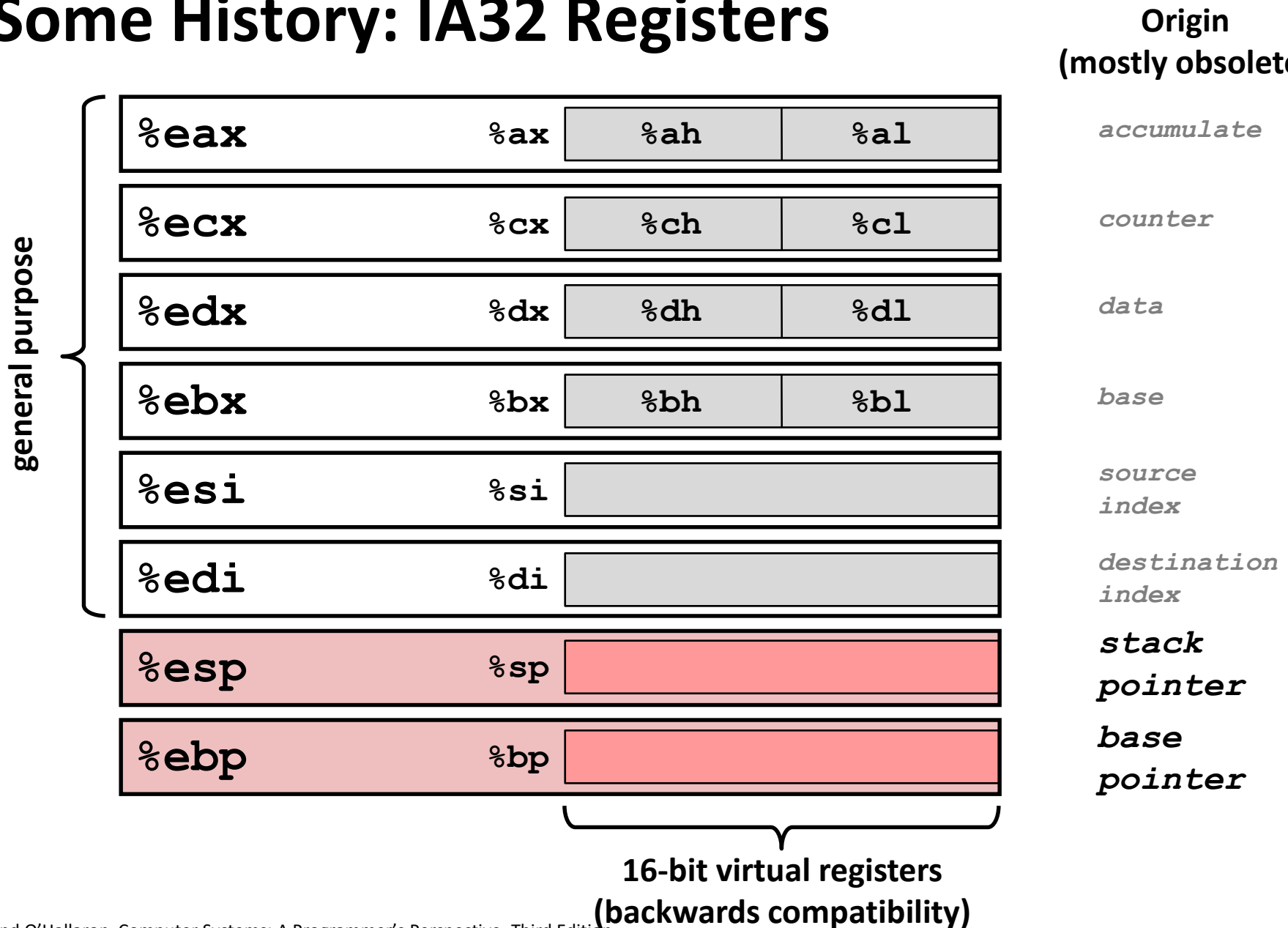
<code>%rax</code>	<code>%eax</code>
<code>%rbx</code>	<code>%ebx</code>
<code>%rcx</code>	<code>%ecx</code>
<code>%rdx</code>	<code>%edx</code>
<code>%rsi</code>	<code>%esi</code>
<code>%rdi</code>	<code>%edi</code>
<code>%rsp</code>	<code>%esp</code>
<code>%rbp</code>	<code>%ebp</code>

<code>%r8</code>	<code>%r8d</code>
<code>%r9</code>	<code>%r9d</code>
<code>%r10</code>	<code>%r10d</code>
<code>%r11</code>	<code>%r11d</code>
<code>%r12</code>	<code>%r12d</code>
<code>%r13</code>	<code>%r13d</code>
<code>%r14</code>	<code>%r14d</code>
<code>%r15</code>	<code>%r15d</code>

- Can reference low-order 4 bytes (also low-order 1 & 2 bytes)
- Not part of memory (or cache)



# Some History: IA32 Registers



# Assembly Characteristics: Operations

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

# Moving Data

## ■ Moving Data

`movq Source, Dest`

## ■ Operand Types

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

`%rax`

`%rcx`

`%rdx`

`%rbx`

`%rsi`

`%rdi`

`%rsp`

`%rbp`

`%rN`

**Warning: Intel docs use  
`mov Dest, Source`**

# movq Operand Combinations

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

**Cannot do memory-memory transfer with a single instruction**

# Simple Memory Addressing Modes

## ■ Normal (R) Mem[Reg[R]]

- Register R specifies memory address
- Aha! Pointer dereferencing in C

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

## ■ Displacement D(R) Mem[Reg[R]+D]

- Register R specifies start of memory region
- Constant displacement D specifies offset

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

# Example of Simple Addressing Modes

```
void  
whatAmI (<type> a, <type> b)  
{  
    ????  
}
```

`%rdi`

`%rsi`

`whatAmI:`

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

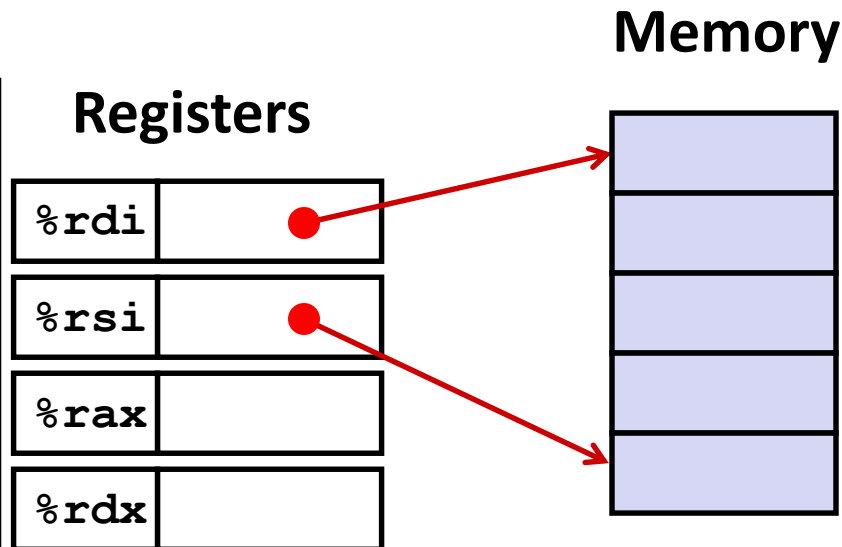
# Example of Simple Addressing Modes

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

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

# Understanding Swap()

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



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

swap:

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



# Understanding Swap()

## Registers

<code>%rdi</code>	<code>0x120</code>
<code>%rsi</code>	<code>0x100</code>
<code>%rax</code>	
<code>%rdx</code>	

## Memory

	Address
123	<code>0x120</code>
	<code>0x118</code>
	<code>0x110</code>
	<code>0x108</code>
456	<code>0x100</code>

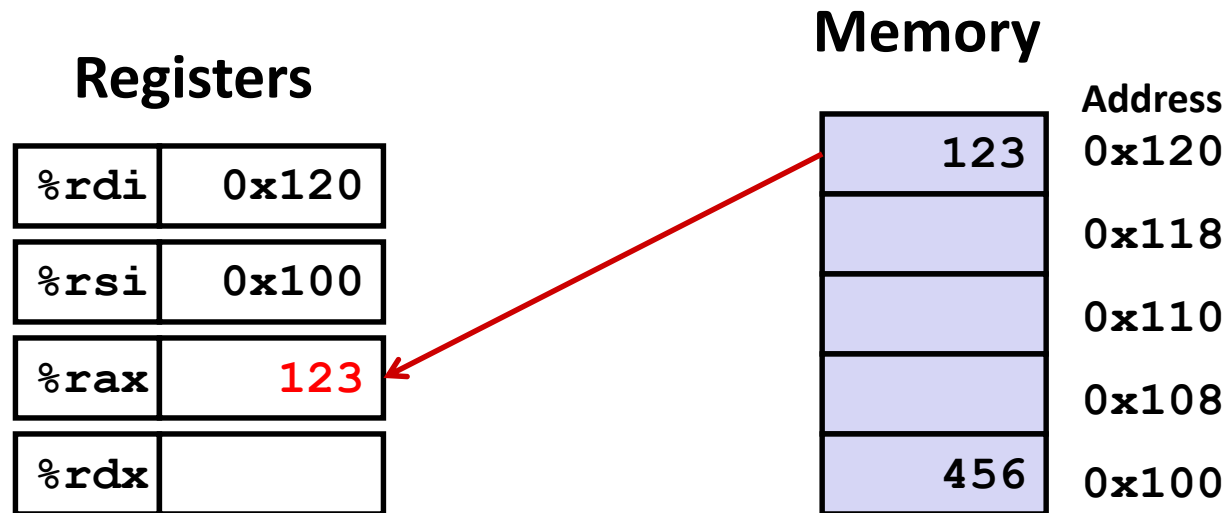
`swap:`

```

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

```

# Understanding Swap()



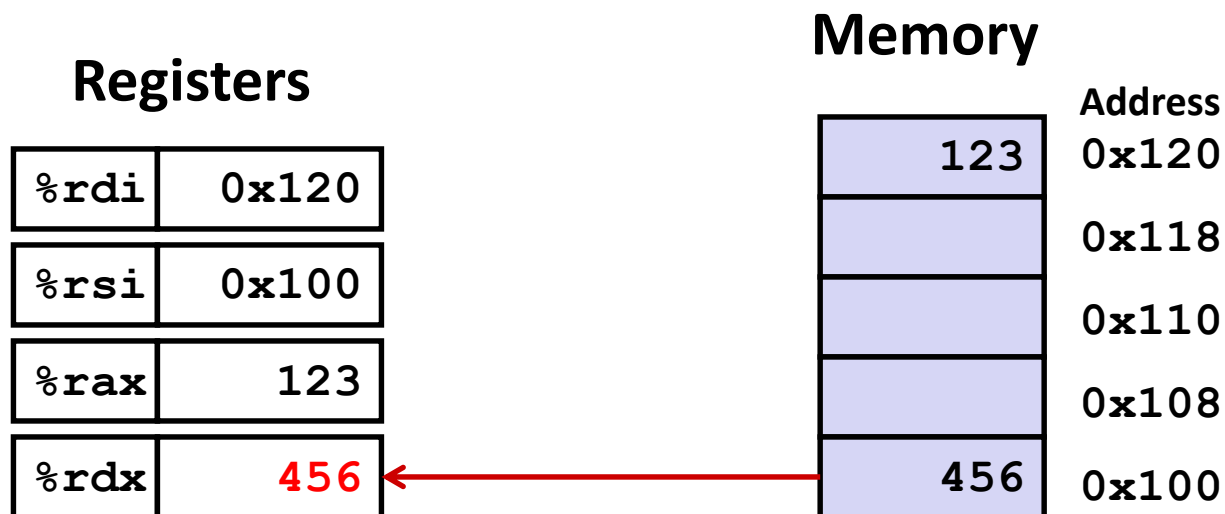
**swap:**

```

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

```

# Understanding Swap()



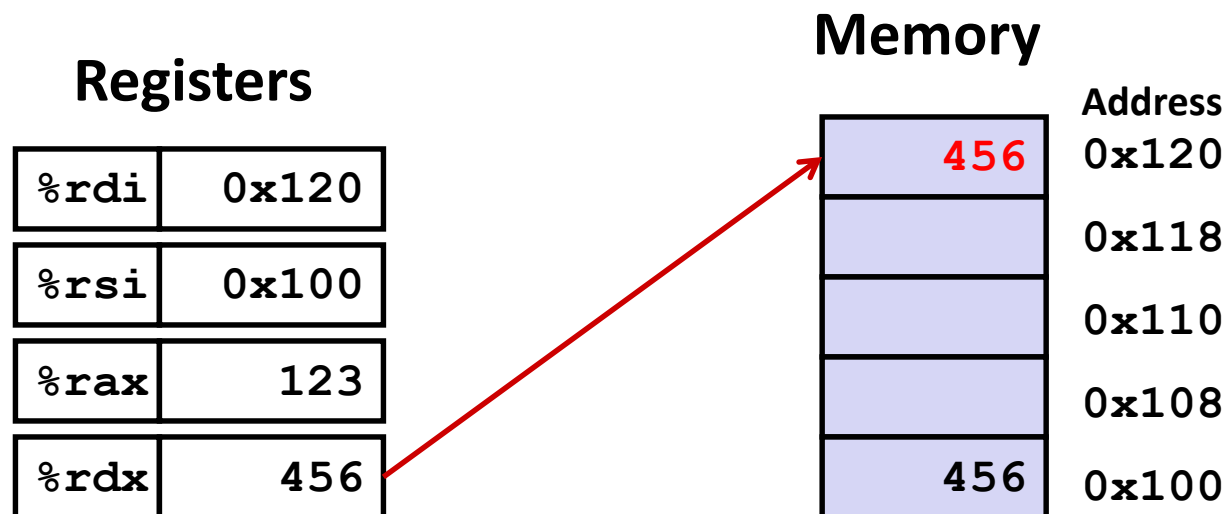
**swap:**

```

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

```

# Understanding Swap()



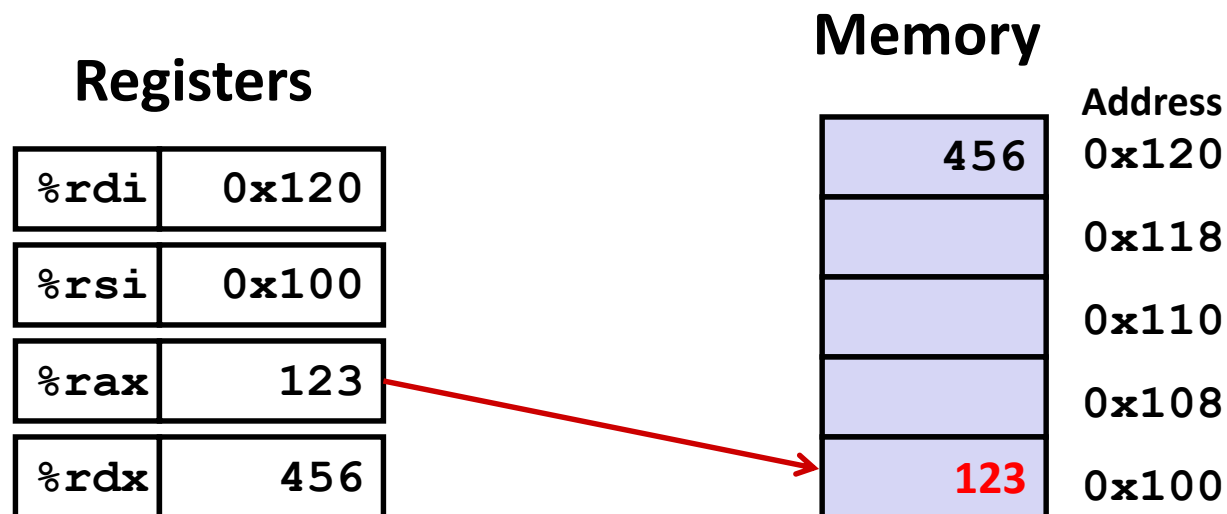
**swap:**

```

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

```

# Understanding Swap()



**swap:**

```

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

```

# Simple Memory Addressing Modes

## ■ Normal (R) Mem[Reg[R]]

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movq (%rcx), %rax
```

## ■ Displacement D(R) Mem[Reg[R]+D]

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

# Complete Memory Addressing Modes

## ■ Most General Form

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

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

## ■ Special Cases

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

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

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

# Address Computation Examples

<code>%rdx</code>	<code>0xf000</code>
<code>%rcx</code>	<code>0x0100</code>

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



# Today: Machine Programming I: Basics

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

# Address Computation Instruction

## ■ `leaq Src, Dst`

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

## ■ Uses

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

## ■ Example

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

## Converted to ASM by compiler:

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

# Some Arithmetic Operations

## ■ Two Operand Instructions:

### *Format*

### *Computation*

addq     *Src, Dest*     Dest = Dest + Src

subq     *Src, Dest*     Dest = Dest – Src

imulq    *Src, Dest*     Dest = Dest \* Src

salq     *Src, Dest*     Dest = Dest << Src

sarq     *Src, Dest*     Dest = Dest >> Src

shrq     *Src, Dest*     Dest = Dest >> Src

xorq     *Src, Dest*     Dest = Dest ^ Src

andq     *Src, Dest*     Dest = Dest & Src

orq      *Src, Dest*     Dest = Dest | Src

*Also called shlq*

*Arithmetic*

*Logical*

## ■ Watch out for argument order! *Src, Dest* (Warning: Intel docs use “op *Dest, Src*”)

## ■ No distinction between signed and unsigned int (why?)

# Some Arithmetic Operations

## ■ One Operand Instructions

`incq`     *Dest*      $Dest = Dest + 1$

`decq`     *Dest*      $Dest = Dest - 1$

`negq`     *Dest*      $Dest = -Dest$

`notq`     *Dest*      $Dest = \sim Dest$

## ■ See book for more instructions

# Arithmetic Expression Example

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

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

## Interesting Instructions

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

# Understanding Arithmetic Expression

## Example

```

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

```

```

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

```

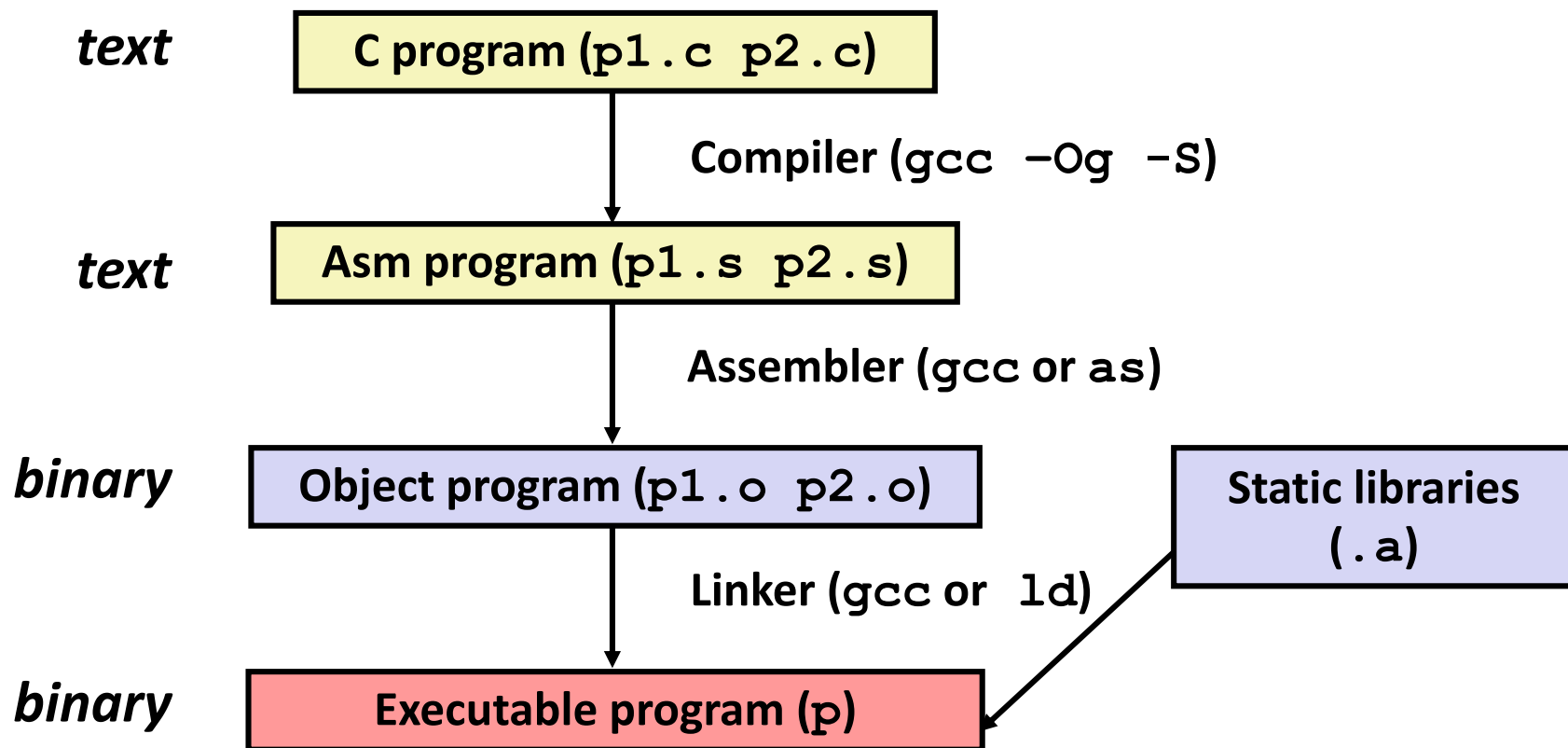
Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rdx	Argument <b>z</b> , <b>t4</b>
%rax	<b>t1</b> , <b>t2</b> , <b>rval</b>
%rcx	<b>t5</b>

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- **C, assembly, machine code**

# Turning C into Object Code

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





# Compiling Into Assembly

## C Code (sum.c)

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

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

## Generated x86-64 Assembly

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

Obtain (on shark machine) with command

```
gcc -Og -S sum.c
```

Produces file `sum.s`

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

# What it really looks like

```
        .globl  sumstore
        .type   sumstore, @function
sumstore:
.LFB35:
        .cfi_startproc
pushq   %rbx
        .cfi_def_cfa_offset 16
        .cfi_offset 3, -16
movq    %rdx, %rbx
call    plus
movq    %rax, (%rbx)
popq    %rbx
        .cfi_def_cfa_offset 8
ret
        .cfi_endproc
.LFE35:
        .size   sumstore, .-sumstore
```

# What it really looks like

Things that look weird and are preceded by a “ are generally directives.

```

        .globl  sumstore
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sumstore:
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        .cfi_startproc
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sumstore:
    pushq   %rbx
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    popq    %rbx
    ret

```

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

# Object Code

## Code for `sumstore`

0x0400595:

0x53

0x48

0x89

0xd3

0xe8

0xf2

0xff

0xff

0xff

0x48

0x89

0x03

0x5b

0xc3

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

## ■ 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

```
*dest = t;
```

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

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

## ■ C Code

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

## ■ Assembly

- Move 8-byte value to memory
  - Quad words in x86-64 parlance
- Operands:
  - `t`: Register `%rax`
  - `dest`: Register `%rbx`
  - `*dest`: Memory `M[%rbx]`

## ■ Object Code

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

# Disassembling Object Code

## Disassembled

```

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

```

## ■ Disassembler

`objdump -d sum`

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



# Alternate Disassembly

## Disassembled

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

- **Within gdb Debugger**
    - Disassemble procedure
- ```
gdb sum  
disassemble sumstore
```

# Alternate Disassembly

Object  
Code

0x0400595:

0x53

0x48

0x89

0xd3

0xe8

0xf2

0xff

0xff

0xff

0x48

0x89

0x03

0x5b

0xc3

Disassembled

Dump of assembler code for function `sumstore`:

```
0x000000000400595 <+0>: push    %rbx
0x000000000400596 <+1>: mov     %rdx,%rbx
0x000000000400599 <+4>: callq  0x400590 <plus>
0x00000000040059e <+9>: mov     %rax, (%rbx)
0x0000000004005a1 <+12>: pop    %rbx
0x0000000004005a2 <+13>: retq
```

## ■ Within gdb Debugger

- Disassemble procedure

```
gdb sum
```

```
disassemble sumstore
```

- Examine the 14 bytes starting at `sumstore`

```
x/14xb sumstore
```

# What Can be Disassembled?

```
% objdump -d WINWORD.EXE
```

```
WINWORD.EXE: file format pei-i386
```

```
No symbols in "WINWORD.EXE".
```

```
Disassembly of section .text:
```

```
30001000 <.text>:
```

```
30001000:
```

```
30001001:
```

```
30001003:
```

```
30001005:
```

```
3000100a:
```

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

# Machine Programming I: Summary

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