

Machine-Level Programming I: Basics

Introduction to Computer Systems
4th Lecture, Sep. 23, 2021

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Today: Machine Programming I: Basics

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

Intel x86 Processors

- **Dominate laptop/desktop/server market**
- **Evolutionary design**
 - Backwards compatible up until 8086, introduced in 1978
 - Added more features as time goes on
 - Now 3 volumes, about 5,000 pages of documentation
- **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.

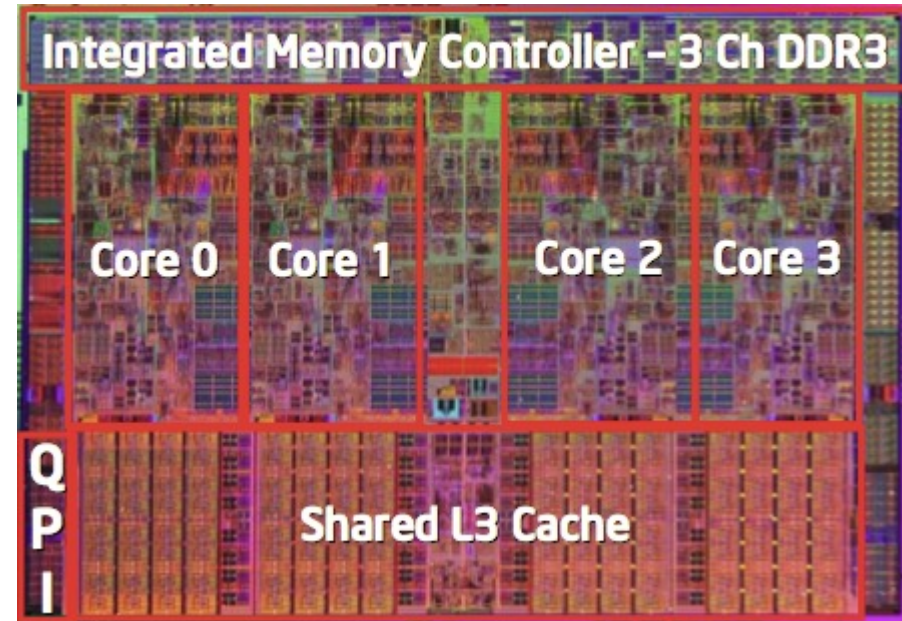
Intel x86 Evolution: Milestones

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

Intel x86 Processors, cont.

■ Machine Evolution

■ 386	1985	0.3M
■ Pentium	1993	3.1M
■ Pentium/MMX	1997	4.5M
■ Pentium Pro	1995	6.5M
■ Pentium 4	2000	42M
■ Core 2 Duo	2006	291M
■ Core i7	2008	731M
■ Core i7 Skylake	2015	1.9B
■ Xeon Skylake-SP	2017	8B



■ 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

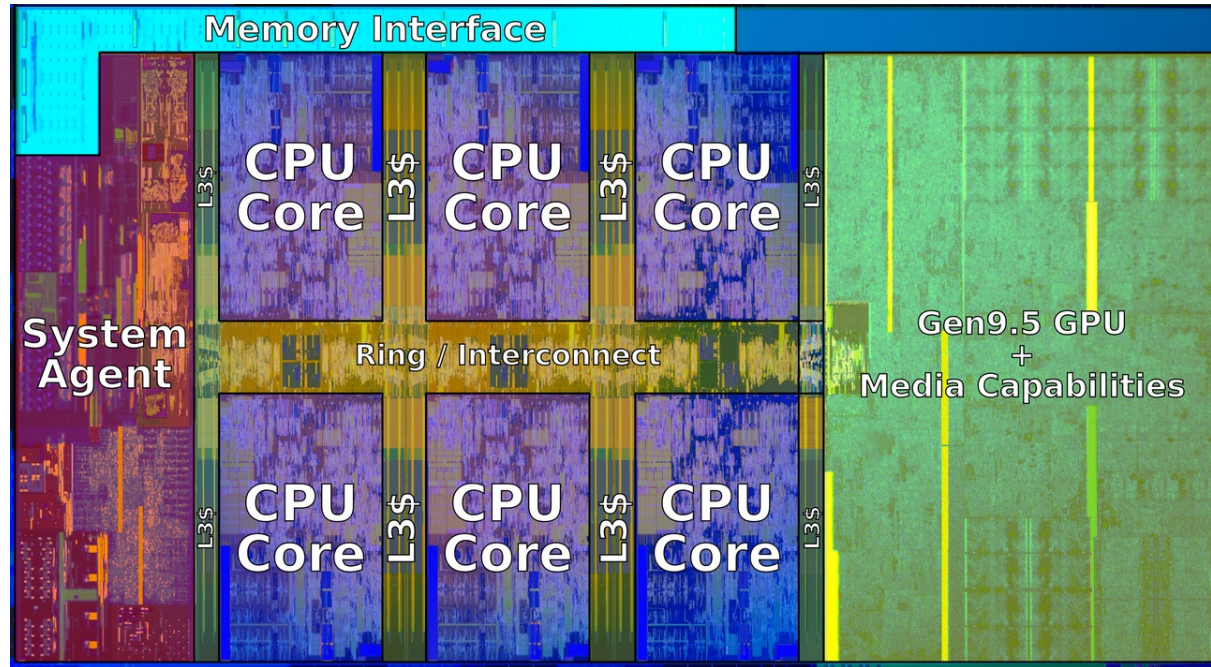
■ 1 st Pentium Pro	1995	600 nm
■ 1 st Pentium III	1999	250 nm
■ 1 st Pentium 4	2000	180 nm
■ 1 st Core 2 Duo	2006	65 nm

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

■ Recent & Upcoming 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
7.	Kaby Lake	2016	14 nm
8.	Coffee Lake	2017	14 nm
9.	Cannon Lake	2018	10 nm
10.	Ice Lake	2019	10 nm
11.	Tiger Lake	2020	10 nm

2018 State of the Art: Coffee Lake



■ Mobile Model: Core i7

- 2.2-3.2 GHz
- 45 W

■ Desktop Model: Core i7

- Integrated graphics
- 2.4-4.0 GHz
- 35-95 W

■ Server Model: Xeon E

- Integrated graphics
- Multi-socket enabled
- 3.3-3.8 GHz
- 80-95 W

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
 - 1995-2011: Lead semiconductor “fab” in world
 - 2018: #2 largest by \$\$ (#1 is Samsung)
 - 2019: reclaimed #1
- AMD fell behind
 - Relies on external semiconductor manufacturer GlobalFoundries
 - ca. 2019 CPUs (e.g., Ryzen) are competitive again

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 this course: RIP, Fall 2016

■ x86-64

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

■ Presentation

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

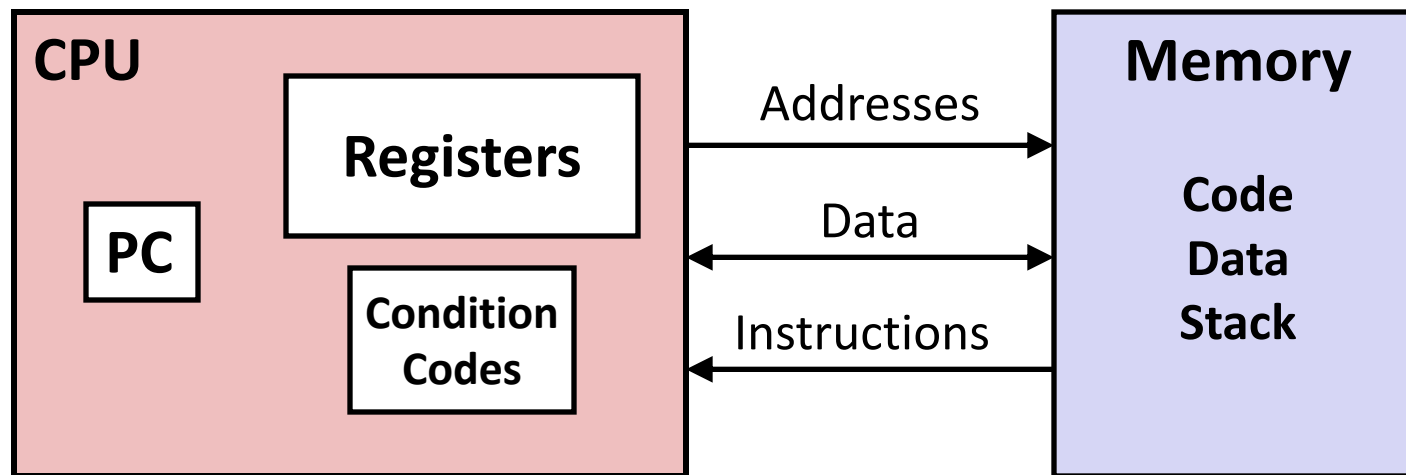
Today: Machine Programming I: Basics

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

Definitions

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

Assembly/Machine Code View

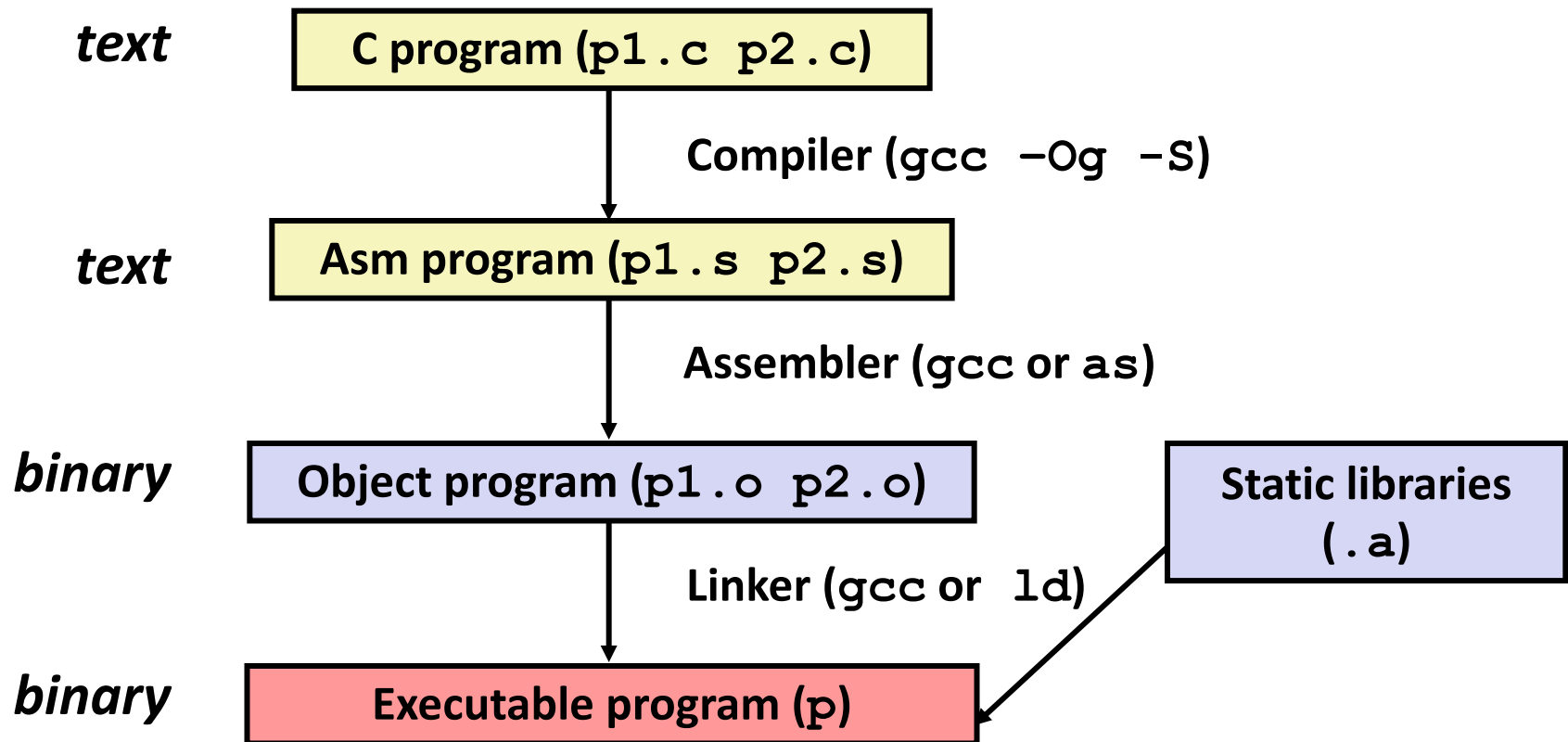


Programmer-Visible State

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

Turning C into Object Code

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



Compiling Into Assembly

C Code (sum.c)

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

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

Generated x86-64 Assembly

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

Obtain (on our server machine) with command

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

Produces file `sum.s`

Warning: Will get very different results on our server 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
.type   sumstore, @function

sumstore:
.LFB35:
    .cfi_startproc
pushq   %rbx
.cfi_def_cfa_offset 16
.cfi_offset 3, -16
movq    %rdx, %rbx
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movq    %rax, (%rbx)
popq    %rbx
.cfi_def_cfa_offset 8
ret
.cfi_endproc

.LFE35:
.size   sumstore, .-sumstore
```

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

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**
- **(SIMD vector data types of 8, 16, 32 or 64 bytes)**
- **Code: Byte sequences encoding series of instructions**
- **No aggregate types such as arrays or structures**
 - Just contiguously allocated bytes in memory

Assembly Characteristics: Operations

- **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
 - Indirect 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

Object

0x0400595:

0x53

0x48

0x89

0xd3

0xe8

0xf2

0xff

0xff

0xff

0x48

0x89

0x03

0x5b

0xc3

Disassembled

Dump of assembler code for function sumstore:

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

■ Within gdb Debugger

`gdb sum`

`disassemble sumstore`

■ Disassemble procedure

`x/14xb sumstore`

■ Examine the 14 bytes starting at `sumstore`

What Can be Disassembled?

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

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

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

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

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

```
30001000:
```

```
30001001:
```

```
30001003:
```

```
30001005:
```

```
3000100a:
```

**Reverse engineering forbidden by
Microsoft End User License Agreement**

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

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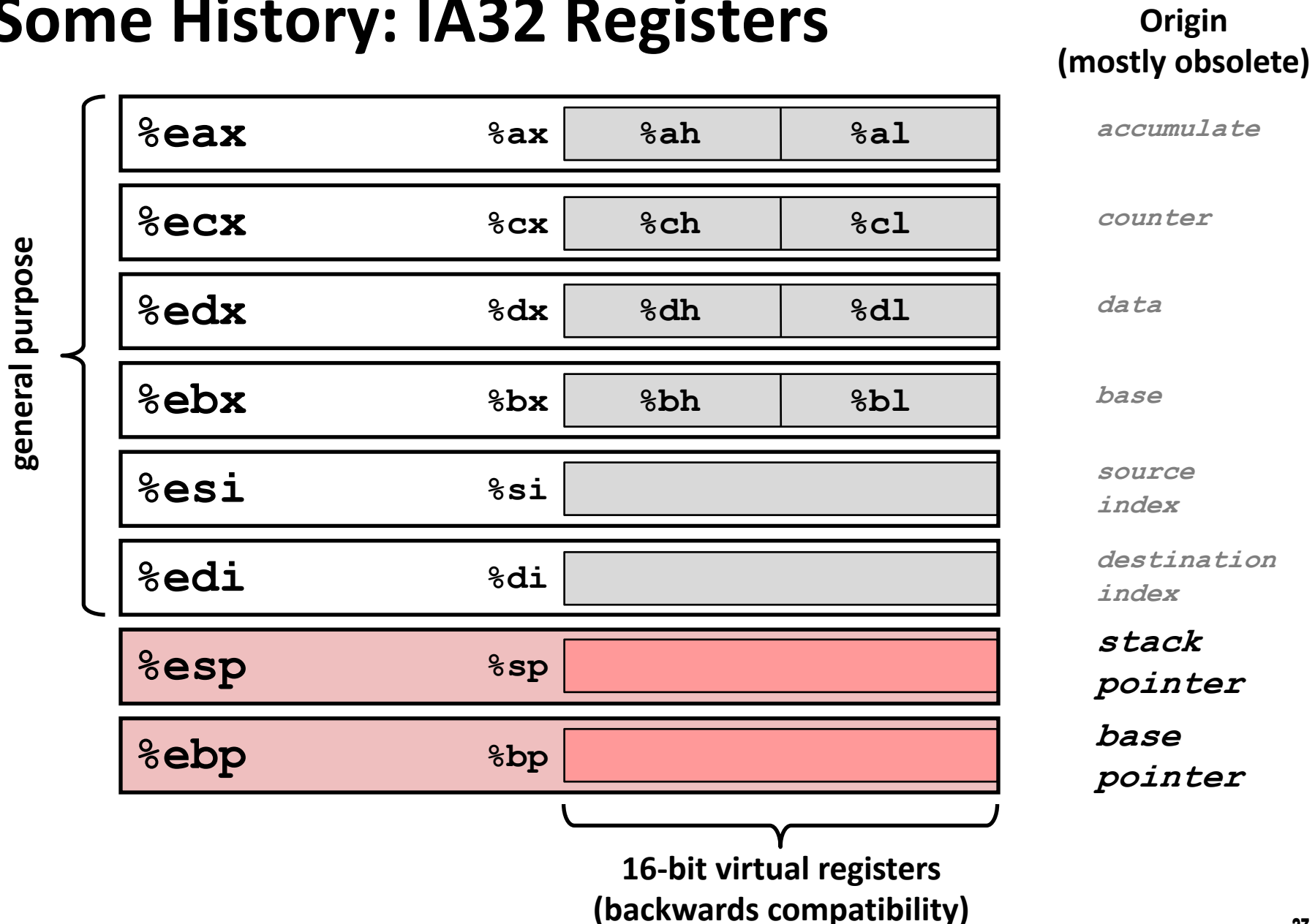
x86-64 Integer Registers

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

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

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

Some History: IA32 Registers



Moving Data

■ Moving Data

`movq Source, Dest:`

■ Operand Types

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

`%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 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
```

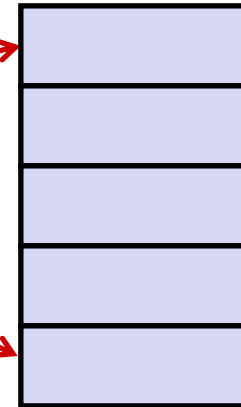
Understanding Swap()

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

Registers

%rdi	
%rsi	
%rax	
%rdx	

Memory



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

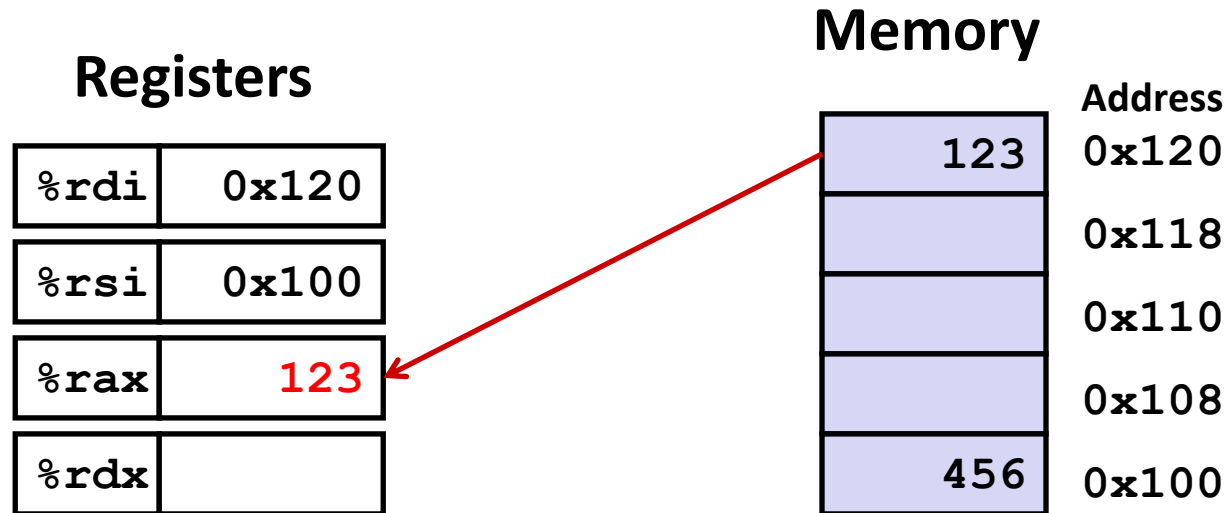
`swap:`

```

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

```

Understanding Swap()



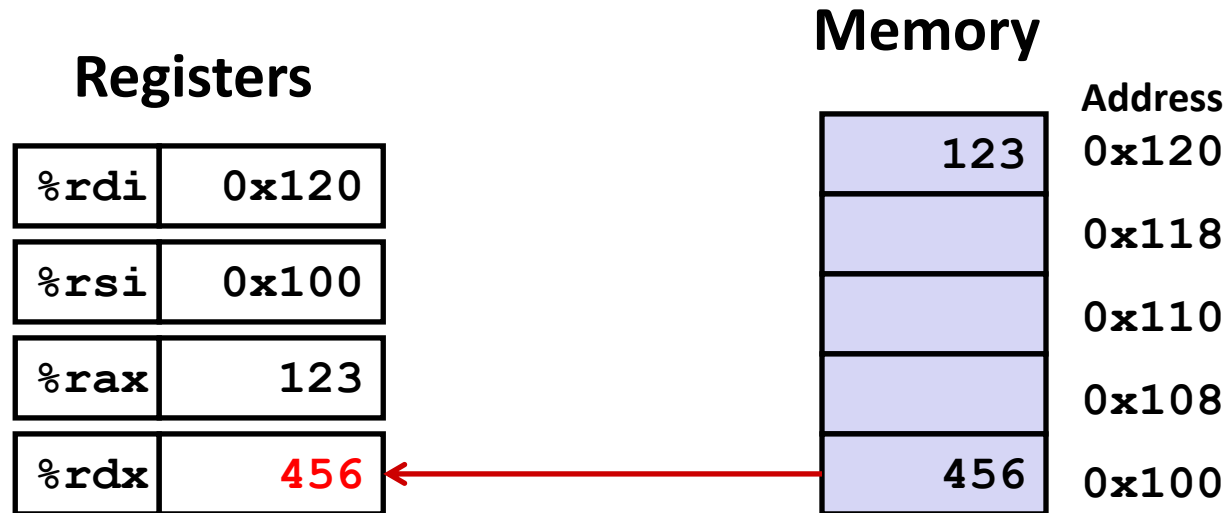
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```

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

```

Understanding Swap()



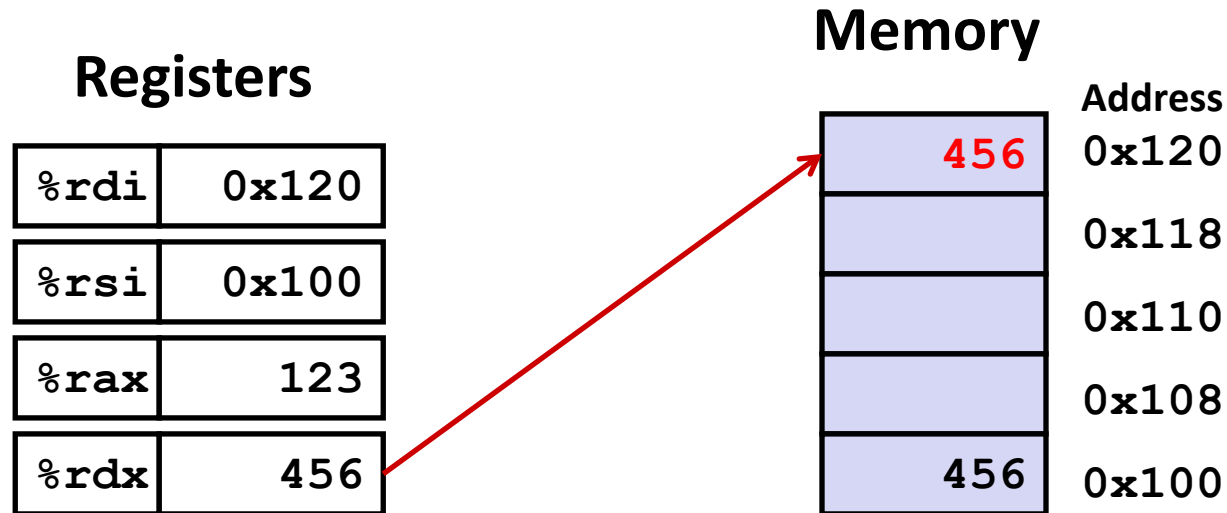
swap:

```

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

```

Understanding Swap()



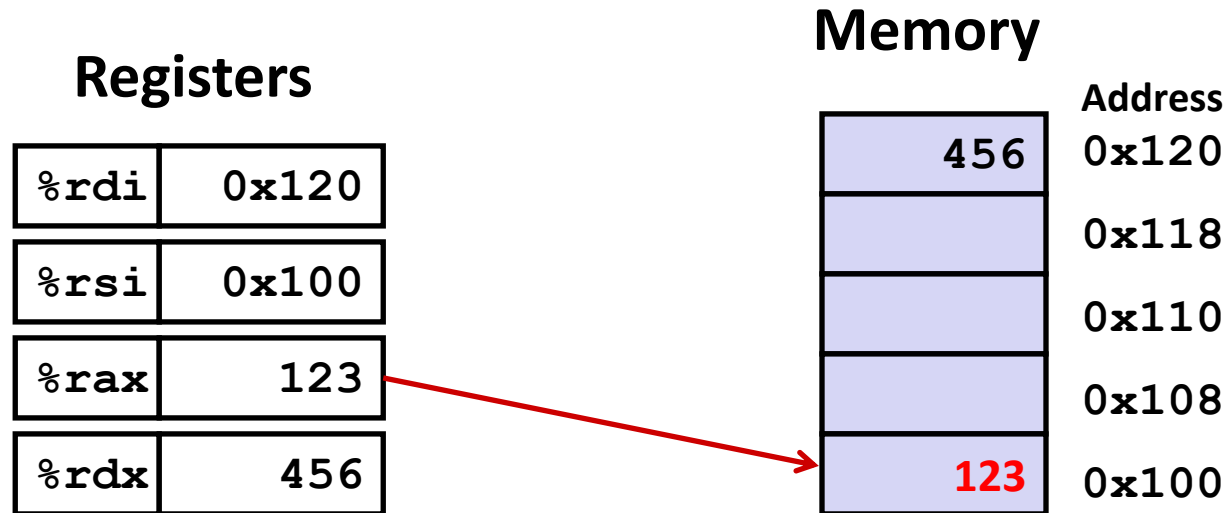
swap:

```

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

```

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■ 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
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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>

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- **Arithmetic & logical operations**

Address Computation Instruction

- leaq Src, Dst

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

■ Uses

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

■ Example

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

Converted to ASM by compiler:

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

Some Arithmetic Operations

■ Two Operand Instructions:

Format	Computation		
<code>addq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} + \text{Src}$	
<code>subq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} - \text{Src}$	
<code>imulq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} * \text{Src}$	
<code>salq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} \ll \text{Src}$	Also called <code>shlq</code>
<code>sarq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} \gg \text{Src}$	Arithmetic
<code>shrq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} \gg \text{Src}$	Logical
<code>xorq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} \wedge \text{Src}$	
<code>andq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} \& \text{Src}$	
<code>orq</code>	<code>Src, Dest</code>	$\text{Dest} = \text{Dest} \text{Src}$	

■ Watch out for argument order!

- (Warning: Intel docs use “*op Dest, Src*”)

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

Some Arithmetic Operations

■ One Operand Instructions

<code>incq</code>	<code>Dest</code>	$\text{Dest} = \text{Dest} + 1$
<code>decq</code>	<code>Dest</code>	$\text{Dest} = \text{Dest} - 1$
<code>negq</code>	<code>Dest</code>	$\text{Dest} = -\text{Dest}$
<code>notq</code>	<code>Dest</code>	$\text{Dest} = \sim\text{Dest}$

■ See book for more instructions

Arithmetic Expression Example

```

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

```

```

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

```

Interesting Instructions

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

Understanding Arithmetic Expression

Example

```

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

```

```

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

```

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

Machine Programming I: Summary

■ History of Intel processors and architectures

- Evolutionary design leads to many quirks and artifacts

■ C, assembly, machine code

- New forms of visible state: program counter, registers, ...
- Compiler must transform statements, expressions, procedures into low-level instruction sequences

■ Assembly Basics: Registers, operands, move

- The x86-64 move instructions cover wide range of data movement forms

■ Arithmetic

- C compiler will figure out different instruction combinations to carry out computation