CS429: Computer Organization and Architecture
Instruction Set Architecture II

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Topics of this Slideset

- Assembly Programmer’s Execution Model
- Accessing Information
- Registers
- Memory
- Arithmetic operations

BTW: We’re through with Y86 for a while, and starting the x86. We’ll come back to the Y86 later for pipelining.
x86 processors totally dominate the laptop/desktop/server market.

**Evolutionary Design**
- Starting in 1978 with 8086
- Added more features over time.

**Complex Instruction Set Computer (CISC)**
- Still support many old, now obsolete, features.
- There are many different instructions with many different formats, but only a small subset are encountered with Linux programs.
- Hard to match performance of Reduced Instruction Set Computers (RISC), though Intel has done just that!
Machine Evolution

<table>
<thead>
<tr>
<th>Model</th>
<th>Date</th>
<th>Trans.</th>
</tr>
</thead>
<tbody>
<tr>
<td>386</td>
<td>1985</td>
<td>0.3M</td>
</tr>
<tr>
<td>Pentium</td>
<td>1993</td>
<td>3.1M</td>
</tr>
<tr>
<td>Pentium/MMX</td>
<td>1997</td>
<td>4.5M</td>
</tr>
<tr>
<td>Pentium Pro</td>
<td>1995</td>
<td>6.5M</td>
</tr>
<tr>
<td>Pentium III</td>
<td>1999</td>
<td>8.2M</td>
</tr>
<tr>
<td>Pentium 4</td>
<td>2001</td>
<td>42M</td>
</tr>
<tr>
<td>Core 2 Duo</td>
<td>2006</td>
<td>291M</td>
</tr>
<tr>
<td>Core i7</td>
<td>2008</td>
<td>731M</td>
</tr>
<tr>
<td>Core i7-8086K</td>
<td>2018</td>
<td>3B</td>
</tr>
</tbody>
</table>

Added Features

- Instructions to support multimedia operations
- Instructions to enable more efficient conditional operations
- Transition from 32 to 64 bits
- More cores
Historically
- AMD has followed behind Intel
- A little bit slower, a lot cheaper

Then
- Recruited top circuit designers from Digital Equipment Corp. (DEC) 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 manufacturers
**Transmeta**
Radically different approach to implementation.
- Translate x86 code into “very long instruction word” (VLIW) code.
- Very high degree of parallelism.

**Centaur / Via**
- Continued evolution from Cyrix, the 3rd x86 vendor. Low power, design team in Austin.
- 32-bit processor family.
  - At 2 GHz, around 2 watts; at 600 MHz around 0.5 watt.
- 64-bit processor family, used by HP, Lenovo, OLPC, IBM.
  - Very low power, only a few watts at 1.2 GHz.
  - Full virtualization and SSE support.
Definitions:

**Architecture:** (also ISA or instruction set architecture). The parts of a processor design one needs in order to understand or write assembly/machine code.

- Examples: instruction set specification, registers

**Microarchitecture:** implementation of the architecture.

- Examples: cache sizes and core frequency

**Code Forms:**

- Machine code: the byte-level programs that a processor executes
- Assembly code: a human-readable textual representation of machine code

**Example ISAs:**

- Intel: x86, IA32, Itanium, x86-64
- ARM: used in almost all mobile phones
Abstract vs. Concrete Machine Models

Machine Models

```
Memory ---------> Processor
              ^           |
              | C          |
              |           |
              | Mem Proc   |
```

Data
1) char
2) int, float
3) double
4) struct, array
5) pointer

Control
1) loops
2) conditionals
3) switch
4) proc. call
5) proc. return

Assembly

```
Memory ---------> Processor
              ^           |
              | Regs ALU   |
              |           |
              | Stack c-codes |
```

1) byte
2) 2-byte word
3) 4-byte long word
4) 8-byte quad word
5) contiguous byte allocation
6) address of initial byte

1) branch/jump
2) call
3) ret

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**Programmer Visible State**

- **PC (Program Counter):** address of next instruction. Called `%rip` in x86-64.
- **Condition codes:**
  - Store status info about most recent arithmetic operation.
  - Used for conditional branching.
- **Register file:** heavily used program data.
- **Memory**
  - Byte addressable array.
  - Code, user data, (some) OS data.
  - Includes stack.
ISA Principles

- Contract between programmer and the hardware.
  - Defines visible state of the system.
  - Defines how state changes in response to instructions.
- For Programmer: ISA is model of how a program will execute.
- For Hardware Designer: ISA is formal definition of the correct way to execute a program.
  - With a stable ISA, SW doesn’t care what the HW looks like under the hood.
  - Hardware implementations can change drastically.
  - As long as the HW implements the same ISA, all prior SW should still run.
  - Example: x86 ISA has spanned many chips; instructions have been added but the SW for prior chips still runs.
- ISA specification: the binary encoding of the instruction set.
Instruction formats
Instruction types
Addressing modes

Instruction
Op | Mode | Ra | Rb

Memory

Before State

Data type
Operations
Interrupts / Events

After State

Memory

Regs

Machine State
Memory organization
Register organization
**Architecture:** defines *what* a computer system does in response to a program and set of data.

- *Programmer visible* elements of computer system.

**Implementation (microarchitecture):** defines *how* a computer does it.

- Sequence of steps to complete operations.
- Time to execute each operation.
- Hidden “bookkeeping” function.

*If the architecture changes, some programs may no longer run or return the same answer. If the implementation changes, some programs may run faster/slower/better, but the answers won’t change.*
Examples

Which of the following are part of the architecture and which are part of the implementation? Hint: if the programmer can see/use it (directly) in a program, it’s part of the architecture.

- Number/names of general purpose registers
- Width of memory bus
- Binary representation of each instruction
- Number of cycles to execute a FP instruction
- Condition code bits set by a move instruction
- Size of the instruction cache
- Type of FP format
Turning C into Object Code

- Code in files: `p1.c`, `p2.c`
- For minimal optimization, compile with command:
  ```
gcc -Og p1.c p2.c -o p
  ```
- Use optimization (`-Og`); new to recent versions of gcc
- Put resulting binary in file `p`

```
C program (p1.c p2.c)
  \downarrow
  Compiler (gcc)

Asm program (p1.s p2.s)
  \downarrow
  Assembler (gcc or as)

Object program (p1.o p2.o)
  \downarrow
  Linker (gcc or lo)

Executable program (p)
  \downarrow
  Static libraries (.a)
```
C Code (sum.c):

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

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

Run command: `gcc -Og -S sum.c`
produces file `sum.s`.

```
sumstore:
    pushq %rbx # save %rbx
    movq %rdx, %rbx # temp ←— dest
call plus
    movq %rax, (%rbx) # *dest ←— t
    popq %rbx # restore %rbx
    ret
```

**Warning:** you may get different results due to variations in gcc and compiler settings.
Assembly Characteristics

**Minimal Data Types**
- “Integer” data of 1, 2, 4 or 8 bytes
- 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

**Primitive Operations**
- Perform arithmetic functions 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
Assembler
- Translates .s into .o
- Binary encoding of each inst.
- 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 (just before execution)
Machine Instruction Example

*C dest = t;*

movq %rax, (%rbx)

C Code
- Store value t where designated by dest

Assembly
- Move 8-byte value to memory (quad word in x86 parlance).
- Operands:
  - t: Register %rax
  - dest: Register %rbx
  - *dest: Memory M[%rbx]

Object Code
- 3-byte instruction
- Stored at address 0x40059e
Disassembling Object Code

This is disassembly of the .o file (no main routine). Offsets are relative.

> objdump -d sumstore.o

sumstore.o: file format elf64-x86-64
Disassembly of section .text:
0000000000000000 <sumstore>:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>53</td>
<td>push %rbx</td>
</tr>
<tr>
<td>1</td>
<td>48 89 d3</td>
<td>mov %rdx,%rbx</td>
</tr>
<tr>
<td>4</td>
<td>e8 00 00 00 00</td>
<td>callq 9 &lt;sumstore+0x9&gt;</td>
</tr>
<tr>
<td>9</td>
<td>48 89 03</td>
<td>mov %rax,(%rbx)</td>
</tr>
<tr>
<td>c</td>
<td>5b</td>
<td>pop %rbx</td>
</tr>
<tr>
<td>d</td>
<td>c3</td>
<td>retq</td>
</tr>
</tbody>
</table>

- 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
This is disassembly of the .o file (no main routine). Offsets are relative.

Dump of assembler code for function sumstore:

- \(0x0000000000000000\) <+0>: push %rbx
- \(0x0000000000000001\) <+1>: mov %rdx,%rbx
- \(0x0000000000000004\) <+4>: callq 0x9 <sumstore+9>
- \(0x0000000000000009\) <+9>: mov %rax,(%rbx)
- \(0x000000000000000c\) <+12>: pop %rbx
- \(0x000000000000000d\) <+13>: retq

End of assembler dump.

Within gdb debugger:

```
   gdb sum
   disassemble sumstore
   x/14xb sumstore
```

Examine the 14 bytes starting at sumstore.
What Can be Disassembled?

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

% 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 $0x304cd91
Which Assembler?

Intel/Microsoft Format

\[
\begin{align*}
\text{lea} & \quad \text{rax}, \ [\text{rcx}+\text{rcx} \times 4] \\
\text{sub} & \quad \text{rsp}, \ 8 \\
\text{cmp} & \quad \text{quad ptr} [\text{ebp} - 8], \ 0 \\
\text{mov} & \quad \text{rax}, \ \text{quad ptr} [\text{rax} \times 4 + 10h] \\
\end{align*}
\]

GAS/Gnu Format

\[
\begin{align*}
\text{lea} & \quad (\%\text{rcx},\%\text{rcx},4), \ \%\text{rax} \\
\text{subq} & \quad $8,\%\text{rsp} \\
\text{cmpq} & \quad $0,-8(\%\text{rbp}) \\
\text{movq} & \quad $0x10,(\,%\text{rax},4),\%\text{rax} \\
\end{align*}
\]

Intel/Microsoft Differs from GAS

- Operands are listed in opposite order:
  - `mov Dest, Src`  \quad `movq Src, Dest`
- Constants not preceded by '$$'; denote hex with 'h' at end.
  - `10h $0x10`
- Operand size indicated by operands rather than operator suffix.
  - `sub`  \quad `subq`
- Addressing format shows effective address computation.
  - `[\text{rax} \times 4 + 10h] $0x10(,%\text{rax},4)`

From now on we’ll always use GAS assembler format.
For each of the 64-bit registers, the LS 4 bytes are named 32-bit registers.

<table>
<thead>
<tr>
<th>Reg.</th>
<th>LS 4 bytes</th>
<th>Reg.</th>
<th>LS 4 bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rax</td>
<td>%eax</td>
<td>%r8</td>
<td>%r8d</td>
</tr>
<tr>
<td>%rbx</td>
<td>%ebx</td>
<td>%r9</td>
<td>%r9d</td>
</tr>
<tr>
<td>%rcx</td>
<td>%ecx</td>
<td>%r10</td>
<td>%r10d</td>
</tr>
<tr>
<td>%rdx</td>
<td>%edx</td>
<td>%r11</td>
<td>%r11d</td>
</tr>
<tr>
<td>%rsi</td>
<td>%esi</td>
<td>%r12</td>
<td>%r12d</td>
</tr>
<tr>
<td>%rdi</td>
<td>%edi</td>
<td>%r13</td>
<td>%r13d</td>
</tr>
<tr>
<td>%rsp</td>
<td>%esp</td>
<td>%r14</td>
<td>%r14d</td>
</tr>
<tr>
<td>%rbp</td>
<td>%ebp</td>
<td>%r15</td>
<td>%r15d</td>
</tr>
</tbody>
</table>

You can also reference the LS 16-bits (2 bytes) and LS 8-bits (1 byte). For the numbered registers (%r8–%r15) the components are named e.g., %r8d (32-bits), %r8w (16-bits), %r8b (8-bits).
Decomposing the %rax Register

All of the x86’s 64-bit registers have 32-bit, 16-bit and 8-bit accessible internal structure. It varies slightly among the different registers. Example, only %rax, %rbx, %rcx, %rdx allow direct access to byte 1 (%ah).

\[
\begin{array}{ccc}
%rax (64) & \quad & %eax (32) \\
\quad & \quad & \%
\end{array}
\]

\[
%ax (16)
\]

%ah %al
<table>
<thead>
<tr>
<th>32-bit reg</th>
<th>16-bit reg</th>
<th>8-bit reg</th>
<th>8-bit Reg</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>%eax</td>
<td>%ax</td>
<td>%ah</td>
<td>%al</td>
<td>accumulator</td>
</tr>
<tr>
<td>%ecx</td>
<td>%cx</td>
<td>%ch</td>
<td>%cl</td>
<td>counter</td>
</tr>
<tr>
<td>%edx</td>
<td>%dx</td>
<td>%dh</td>
<td>%dl</td>
<td>data</td>
</tr>
<tr>
<td>%ebx</td>
<td>%bx</td>
<td>%bh</td>
<td>%bl</td>
<td>base</td>
</tr>
<tr>
<td>%esi</td>
<td>%si</td>
<td></td>
<td>%sil*</td>
<td>source index</td>
</tr>
<tr>
<td>%edi</td>
<td>%di</td>
<td></td>
<td>%dil*</td>
<td>dest. index</td>
</tr>
<tr>
<td>%esp</td>
<td>%sp</td>
<td></td>
<td>%spl*</td>
<td>stack pointer</td>
</tr>
<tr>
<td>%ebp</td>
<td>%bp</td>
<td></td>
<td>%bpl*</td>
<td>base pointer</td>
</tr>
</tbody>
</table>

*These are only available in 64-bit mode.*
Simple Addressing Modes (Same as Y86)

- **Immediate**: value
  
  \[
  \text{movq } \$0xab, \%rbx
  \]

- **Register**: Reg[R]

  \[
  \text{movq } \%rcx, \%rbx
  \]

- **Normal (R)**: Mem[Reg[R]]
  
  - Register R specifies memory address.
  - This is often called *indirect* addressing.
  - Aha! Pointer dereferencing in C

  \[
  \text{movq } (\%rcx), \%rax
  \]

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

  \[
  \text{movq } 8(\%rcb), \%rdx
  \]
Moving Data:

- **Form:** `movq Source, Dest`
- Moves 8-byte “long” word
- Lots of these in typical code

### Operand Types

- **Immediate:** Constant integer data
  - Like C constant, but prefixed with ‘$’
  - E.g., $0x400, $-533
  - Encoded with 1, 2, or 4 bytes

- **Register:** One of 16 integer registers
  - Example: `%rax, %r13`
  - But `%rsp` is reserved for special use
  - Others have special uses for particular instructions

- **Memory:** Source/dest is first address of block
  - Example: `%rax, 0x20(%rbx)`
  - Various “addressing modes”
Unlike the Y86, we don’t distinguish the operator depending on the operand addressing modes.

<table>
<thead>
<tr>
<th>Source</th>
<th>Dest.</th>
<th>Assembler</th>
<th>C Analog</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate</td>
<td>Register</td>
<td><code>movq $0x4,%rax</code></td>
<td><code>temp = 0x4;</code></td>
</tr>
<tr>
<td>Immediate</td>
<td>Memory</td>
<td><code>movq $-147,(%rax)</code></td>
<td><code>*p = -147;</code></td>
</tr>
<tr>
<td>Register</td>
<td>Register</td>
<td><code>movq %rax,%rdx</code></td>
<td><code>temp2 = temp1;</code></td>
</tr>
<tr>
<td>Register</td>
<td>Memory</td>
<td><code>movq %rax,(%rdx)</code></td>
<td><code>*p = temp;</code></td>
</tr>
<tr>
<td>Memory</td>
<td>Register</td>
<td><code>movq (%rax),%rdx</code></td>
<td><code>temp = *p</code></td>
</tr>
</tbody>
</table>

Direct memory-memory transfers are not supported.
C programming model is close to machine language.

- Machine language manipulates memory addresses.
  - For address computation;
  - To store addresses in registers or memory.

- C employs pointers, which are just addresses of primitive data elements or data structures.

Examples of operators * and &:

```
int a, b; /* declare integers a and b */
int *a_ptr; /* a is a pointer to an integer */
a_ptr = a; /* illegal, types don’t match*/
a_ptr = &a; /* a_ptr holds address of a */
b = *a_ptr; /* dereference a_ptr and assign value to b */
```
Using Simple Addressing Modes

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

```assembly
swap:
    movq (%rdi), %rax
    movq (%rsi), %rdx
    movq %rdx, (%rdi)
    movq %rax, (%rsi)
    ret
```
```c
void swap(long *xp, long *yp) {
    long t0 = *xp;
    long t1 = *yp;
    *xp = t1;
    *yp = t0;
}
```

### Register Value Table

<table>
<thead>
<tr>
<th>Register</th>
<th>Value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rdi</td>
<td>xp</td>
<td>points into memory</td>
</tr>
<tr>
<td>%rsi</td>
<td>yp</td>
<td>points into memory</td>
</tr>
<tr>
<td>%rax</td>
<td>t0</td>
<td>temporary storage</td>
</tr>
<tr>
<td>%rdx</td>
<td>t1</td>
<td>temporary storage</td>
</tr>
</tbody>
</table>

### Assembly Code

```
swap:
    movq (%rdi), %rax
    movq (%rsi), %rdx
    movq %rdx, (%rdi)
    movq %rax, (%rsi)
    ret
```
Understanding Swap (2)

swap:

\[
\begin{align*}
\text{movq} \quad & (% \text{rdi}), \quad %\text{rax} \quad \# \quad t0 = *x_p \\
\text{movq} \quad & (% \text{rsi}), \quad %\text{rdx} \quad \# \quad t1 = *y_p \\
\text{movq} \quad & %\text{rdx}, \quad (% \text{rdi}) \quad \# \quad *x_p = t1 \\
\text{movq} \quad & %\text{rax}, \quad (% \text{rsi}) \quad \# \quad *y_p = t0 \\
\text{ret} & 
\end{align*}
\]

Initial State:

**Registers**

<table>
<thead>
<tr>
<th>%rdi</th>
<th>0x120</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rsi</td>
<td>0x100</td>
</tr>
<tr>
<td>%rax</td>
<td></td>
</tr>
<tr>
<td>%rdx</td>
<td></td>
</tr>
</tbody>
</table>

**Memory**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>123</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0x120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x118</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x108</td>
</tr>
<tr>
<td></td>
<td>456</td>
<td>0x100</td>
</tr>
</tbody>
</table>
Understanding Swap (3)

\textbf{swap:}
\begin{align*}
\text{movq} &\quad (% r d i ) , \% r a x \quad # t0 = \ast xp , \leftarrow \quad \text{PC here} \\
\text{movq} &\quad (% r s i ) , \% r d x \quad # t1 = \ast yp \\
\text{movq} &\quad \% r d x , (\% r d i ) \quad # \ast xp = t1 \\
\text{movq} &\quad \% r a x , (\% r s i ) \quad # \ast yp = t0 \\
\text{ret} &
\end{align*}

\textbf{Registers}

<table>
<thead>
<tr>
<th>Register</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rdi</td>
<td>0x120</td>
</tr>
<tr>
<td>%rsi</td>
<td>0x100</td>
</tr>
<tr>
<td>%rax</td>
<td>123</td>
</tr>
<tr>
<td>%rdx</td>
<td></td>
</tr>
</tbody>
</table>

\textbf{Memory}

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x120</td>
<td>123</td>
</tr>
<tr>
<td>0x118</td>
<td></td>
</tr>
<tr>
<td>0x110</td>
<td></td>
</tr>
<tr>
<td>0x108</td>
<td></td>
</tr>
<tr>
<td>0x100</td>
<td>456</td>
</tr>
</tbody>
</table>
### Understanding Swap (4)

#### Registers

<table>
<thead>
<tr>
<th>Register</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rdi</td>
<td>0x120</td>
</tr>
<tr>
<td>%rsi</td>
<td>0x100</td>
</tr>
<tr>
<td>%rax</td>
<td>123</td>
</tr>
<tr>
<td>%rdx</td>
<td>456</td>
</tr>
</tbody>
</table>

#### Memory

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x120</td>
<td>123</td>
</tr>
<tr>
<td>0x118</td>
<td></td>
</tr>
<tr>
<td>0x110</td>
<td></td>
</tr>
<tr>
<td>0x108</td>
<td></td>
</tr>
<tr>
<td>0x100</td>
<td>456</td>
</tr>
</tbody>
</table>
swap:

\[
\begin{align*}
\text{movq} & \quad (%rdi), %rax \quad \# t0 = *xp \\
\text{movq} & \quad (%rsi), %rdx \quad \# t1 = *yp \\
\text{movq} & \quad %rdx, (%rdi) \quad \# *xp = t1, \leftarrow \text{PC here} \\
\text{movq} & \quad %rax, (%rsi) \quad \# *yp = t0 \\
\text{ret} & 
\end{align*}
\]

Registers

<table>
<thead>
<tr>
<th>Register</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rdi</td>
<td>0x120</td>
</tr>
<tr>
<td>%rsi</td>
<td>0x100</td>
</tr>
<tr>
<td>%rax</td>
<td>123</td>
</tr>
<tr>
<td>%rdx</td>
<td>456</td>
</tr>
</tbody>
</table>

Memory

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<tr>
<td>0x118</td>
<td>0x118</td>
</tr>
<tr>
<td>0x120</td>
<td>456</td>
</tr>
</tbody>
</table>

\[456 \quad 0x100\]
swap:
  movq (%rdi), %rax # t0 = *xp
  movq (%rsi), %rdx # t1 = *yp
  movq %rdx, (%rdi) # *xp = t1
  movq %rax, (%rsi) # *yp = t0, <-- PC here
  ret

Registers

<table>
<thead>
<tr>
<th>%rdi</th>
<th>0x120</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rsi</td>
<td>0x100</td>
</tr>
<tr>
<td>%rax</td>
<td>123</td>
</tr>
<tr>
<td>%rdx</td>
<td>456</td>
</tr>
</tbody>
</table>

Memory

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>456</td>
<td>0x120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x118</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0x110</td>
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<tr>
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<td></td>
<td>0x108</td>
</tr>
<tr>
<td></td>
<td>123</td>
<td>0x100</td>
</tr>
</tbody>
</table>
Simple Addressing Modes

- **Immediate**: value
  \[
  \text{movq } \$0\text{ab}, \%rbx
  \]

- **Register**: Reg[R]
  \[
  \text{movq } \%rcx, \%rbx
  \]

- **Normal (R)**: Mem[Reg[R]]
  - Register R specifies memory address.
  - This is often called *indirect* addressing.
  - Aha! Pointer dereferencing in C
  \[
  \text{movq } (%rcx), \%rax
  \]

- **Displacement D(R)**: Mem[Reg[R] + D]
  - Register R specifies start of memory region.
  - Constant displacement D specifies offset
  \[
  \text{movq } 8(\%rcb), \%rdx
  \]
Indexed Addressing Modes

**Most General Form:**

$$D(R_b, R_i, S) \quad Mem[Reg[R_b] + S*Reg[R_i] + D]$$

- **D:** Constant “displacement” of 1, 2 or 4 bytes
- **R_b:** Base register, any of the 16 integer registers
- **R_i:** Index register, any except `%rsp` (and probably not `%rbp`)
- **S:** Scale, must be 1, 2, 4 or 8.

**Special Cases:**

- $$(R_b, R_i) \quad Mem[Reg[R_b] + Reg[R_i]]$$
- $$D(R_b, R_i) \quad Mem[Reg[R_b] + Reg[R_i] + D]$$
- $$(R_b, R_i, S) \quad Mem[Reg[R_b] + S * Reg[R_i]]$$
## Addressing Modes

<table>
<thead>
<tr>
<th>Type</th>
<th>Form</th>
<th>Operand value</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate</td>
<td>$D$</td>
<td>D</td>
<td>Immediate</td>
</tr>
<tr>
<td>Register</td>
<td>$E_a$</td>
<td>$R[E_a]$</td>
<td>Register</td>
</tr>
<tr>
<td>Memory</td>
<td>D</td>
<td>$M[D]$</td>
<td>Absolute</td>
</tr>
<tr>
<td>Memory</td>
<td>$(E_a)$</td>
<td>$M[R[E_a]]$</td>
<td>Indirect</td>
</tr>
<tr>
<td>Memory</td>
<td>$D(E_b)$</td>
<td>$M[D + R[E_b]]$</td>
<td>Base + displacement</td>
</tr>
<tr>
<td>Memory</td>
<td>$(E_b, E_i)$,</td>
<td>$M[R[E_b] + R[E_i]]$</td>
<td>Indexed</td>
</tr>
<tr>
<td>Memory</td>
<td>$D(E_b, E_i)$,</td>
<td>$M[D + R[E_b] + R[E_i]]$</td>
<td>Indexed</td>
</tr>
<tr>
<td>Memory</td>
<td>$(E_b, E_i, s)$</td>
<td>$M[R[E_i] \cdot s]$</td>
<td>Scaled indexed</td>
</tr>
<tr>
<td>Memory</td>
<td>$D(, E_i, s)$</td>
<td>$M[D + R[E_i] \cdot s]$</td>
<td>Scaled indexed</td>
</tr>
<tr>
<td>Memory</td>
<td>$(E_b, E_i, s)$</td>
<td>$M[R[E_b] + R[E_i] \cdot s]$</td>
<td>Scaled indexed</td>
</tr>
<tr>
<td>Memory</td>
<td>$D(E_b, E_i, s)$</td>
<td>$M[D + R[E_b] + R[E_i] \cdot s]$</td>
<td>Scaled indexed</td>
</tr>
</tbody>
</table>

The scaling factor $s$ can only be 1, 2, 4, or 8.
### Address Computation Example

<table>
<thead>
<tr>
<th>Expression</th>
<th>Computation</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0x8(%rdx))</td>
<td>(0xf000 + 0x8)</td>
<td>(0xf008)</td>
</tr>
<tr>
<td>((%rdx, %rcx))</td>
<td>(0xf000 + 0x100)</td>
<td>(0xf100)</td>
</tr>
<tr>
<td>((%rdx, %rcx, 4))</td>
<td>(0xf000 + 4\times0x100)</td>
<td>(0xf400)</td>
</tr>
<tr>
<td>(0x80(%rdx, 2))</td>
<td>(2\times0xf000 + 0x80)</td>
<td>(0x1e080)</td>
</tr>
<tr>
<td>(0x80(%rdx, 2))</td>
<td>Illegal. Why?</td>
<td></td>
</tr>
<tr>
<td>(0x80(%rdx, 3))</td>
<td>Illegal. Why?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>%rdx</th>
<th>0xf000</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rcx</td>
<td>0x100</td>
</tr>
</tbody>
</table>
Indexed addressing modes are extremely useful when iterating over an array.

```c
long sumArray ( long A[], int len ) {
    long i;
    long sum = 0;

    for ( i = 0; i < len; i++ )
        sum += A[i];
    return sum;
}
```
> gcc -S -Og test.c
causes sumArray on the previous slide to compile to:

```
sumArray:
    movl  $0, %eax
    movl  $0, %edx
    jmp   .L2
.L3:
    addq  (%rdi,%rdx,8), %rax
    addq  $1, %rdx
.L2:
    movslq %esi, %rcx
    cmpq  %rcx, %rdx
    jl    .L3
    rep   ret
```
## Two operand instructions:

<table>
<thead>
<tr>
<th>Format</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>addq Src, Dest</code></td>
<td>Dest = Dest + Src</td>
</tr>
<tr>
<td><code>subq Src, Dest</code></td>
<td>Dest = Dest - Src</td>
</tr>
<tr>
<td><code>imulq Src, Dest</code></td>
<td>Dest = Dest * Src</td>
</tr>
<tr>
<td><code>salq Src, Dest</code></td>
<td>Dest = Dest &lt;&lt; Src</td>
</tr>
<tr>
<td><code>sarq Src, Dest</code></td>
<td>Dest = Dest &gt;&gt; Src</td>
</tr>
<tr>
<td><code>shrq Src, Dest</code></td>
<td>Dest = Dest &gt;&gt;&gt; Src</td>
</tr>
<tr>
<td><code>xorq Src, Dest</code></td>
<td>Dest = Dest ^ Src</td>
</tr>
<tr>
<td><code>andq Src, Dest</code></td>
<td>Dest = Dest &amp; Src</td>
</tr>
<tr>
<td><code>orq Src, Dest</code></td>
<td>Dest = Dest</td>
</tr>
</tbody>
</table>

- Watch out for argument order!
- There's no distinction between signed and unsigned. Why?
### One operand instructions:

<table>
<thead>
<tr>
<th>Format</th>
<th>Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>incq Dest</td>
<td>Dest = Dest + 1</td>
</tr>
<tr>
<td>decq Dest</td>
<td>Dest = Dest - 1</td>
</tr>
<tr>
<td>negq Dest</td>
<td>Dest = -Dest</td>
</tr>
<tr>
<td>notq Dest</td>
<td>Dest = ~Dest</td>
</tr>
</tbody>
</table>

More instructions in the book.
**Form:** `leaq Src, Dest`  
- `Src` is address mode expression.  
- Sets `Dest` to *address* denoted by the expression

LEA stands for “load effective address.”

After the effective address computation, place the *address*, not the contents of the address, into the destination.
Consider the following computation:

<table>
<thead>
<tr>
<th>Reg.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rax</td>
<td>0x100</td>
</tr>
<tr>
<td>%rbx</td>
<td>0x200</td>
</tr>
</tbody>
</table>

\[
\text{movq} \ 0\times10(\%rbx, \%rax, 4), \%rcx
\]
\[
\text{leaq} \ 0\times10(\%rbx, \%rax, 4), \%rdx
\]

After this sequence,

- %rcx will contain the contents of location 0x610;
- %rdx will contain the number (address) 0x610.

**What should the following do?**

\[
\text{leaq} \ %rbx, \%rdx
\]
Consider the following computation:

<table>
<thead>
<tr>
<th>Reg.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rax</td>
<td>0x100</td>
</tr>
<tr>
<td>%rbx</td>
<td>0x200</td>
</tr>
</tbody>
</table>

```plaintext

movq 0x10(%rbx, %rax, 4), %rcx
leaq 0x10(%rbx, %rax, 4), %rdx
```

After this sequence,
- %rcx will contain the *contents* of location 0x610;
- %rdx will contain the number (address) 0x610.

**What should the following do?**

```plaintext

leaq %rbx, %rdx
```

It really shouldn’t be legal since %rbx doesn’t have an address. However, the semantics makes it equal to `movq %rbx, %rdx`. 
The `leaq` instruction is widely used for address computations and for some general arithmetic computations.

**Uses:**
- Computing address without doing a memory reference:
  - E.g., translation of `p = &x[i];`
- Computing arithmetic expressions of the form `x + k \times y`, where `k \in \{1, 2, 4, 8\}`

**Example:**

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

**Converted to ASM by compiler:**

```
leaq (%rdi,%rdi,2),%rax  # t <- x+x*2
salq $2,%rax             # ret. t<<2
```
Arithmetic Expression Example

```c
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;
}
```

**Interesting instructions:**

- **leaq**: address computation
- **salq**: shift
- **imulq**: multiplication, but only used once
Understanding our Arithmetic Expression Example

```c
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
```

<table>
<thead>
<tr>
<th>Register</th>
<th>Use(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rdi</td>
<td>Argument x</td>
</tr>
<tr>
<td>%rsi</td>
<td>Argument y</td>
</tr>
<tr>
<td>%rdx</td>
<td>Argument z</td>
</tr>
<tr>
<td>%rax</td>
<td>t1, t2, rval</td>
</tr>
<tr>
<td>%rdx</td>
<td>t4</td>
</tr>
<tr>
<td>%rcx</td>
<td>t5</td>
</tr>
</tbody>
</table>
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, etc.
- Compiler must transform statements, expressions, procedures into low-level instruction sequences

Assembly Basics: Registers, operands, move
- The x86-64 move instructions cover a wide range of data movement forms

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