Controlling Program Execution

- We can now generate programs that execute linear sequences of instructions: access registers and memory, perform computations.
- But what about loops, conditions, etc.?
- Need ISA support for:
  - comparing and testing data values
  - directing program control
    - jump to some instruction that isn’t just the next one in sequence
    - Do so based on some condition that has been tested.

Processor State (x86-64, Partial)

Information about currently executing program.

**Registers**

- Temporary data (%rax, ...)
- Location of runtime stack (%rsp)
- Location of current code control point (%rip)
- Status of recent tests (CF, ZF, SF, OF)

<table>
<thead>
<tr>
<th>%rax</th>
<th>%r8</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rbx</td>
<td>%r9</td>
</tr>
<tr>
<td>%rcx</td>
<td>%r10</td>
</tr>
<tr>
<td>%rdx</td>
<td>%r11</td>
</tr>
<tr>
<td>%rsi</td>
<td>%r12</td>
</tr>
<tr>
<td>%rdi</td>
<td>%r13</td>
</tr>
<tr>
<td>%rsp</td>
<td>%r14</td>
</tr>
<tr>
<td>%rbp</td>
<td>%r15</td>
</tr>
</tbody>
</table>

%rip - Instruction pointer

<table>
<thead>
<tr>
<th>CF</th>
<th>ZF</th>
<th>SF</th>
<th>OF</th>
</tr>
</thead>
</table>

PC-relative Addressing

Don’t use %rip as a general purpose register.

However, the compiler may generate **PC-relative addressing**.

```
jmp 0x10(%rip)
```

The effective address for a PC-relative instruction address is the offset parameter added to the address of the next instruction. This offset is signed to allow reference to code both before and after the instruction.

Can you guess why the compiler might generate such code?
Condition Codes (Implicit Setting)

Single bit registers
- CF: carry flag (for unsigned)
- ZF: zero flag
- SF: sign flag (for signed)
- OF: overflow flag (for signed)

Implicitly set by arithmetic operations
E.g., addq Src, Dest
C analog: 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 overflow:
  \[(a>0 \&\& b>0 \&\& (a-b)<0) \mid (a<0 \&\& b<0 \&\& (a-b)>=0)\]
- Condition codes not set by lea instruction.

Setting Condition Codes: Test Instruction

Explicitly set by Test instruction
testq Src2, Src1
- Sets condition codes based on value of (Src1 & Src2).
- Often useful to have one of the operands be a mask.
- testq b, a is like computing a\&b, without setting a destination.
- ZF set iff (a & b) == 0
- SF set iff (a & b) < 0
- CF and OF are set to 0.

How could you use testq to jump if the value in %rbx is even?

Explicitly set by Compare instruction
cmpq Src2, Src1
- cmpq b, a is like computing (a - b) without setting destination.
- CF set if carry out from most significant bit; used for unsigned computations.
- ZF set if a == b
- SF set if (a-b) < 0
- OF set if two’s complement (signed) overflow:
  \[(a>0 \&\& b>0 \&\& (a-b)<0) \mid (a<0 \&\& b<0 \&\& (a-b)>=0)\]

Explicitly set by Test instruction
testq Src2, Src1
- Sets condition codes based on value of (Src1 & Src2).
- Often useful to have one of the operands be a mask.
- testq b, a is like computing a\&b, without setting a destination.
- ZF set iff (a & b) == 0
- SF set iff (a & b) < 0
- CF and OF are set to 0.

How could you use testq to jump if the value in %rbx is even?

```
testq $1, %rbx
je even
odd:
```
**Reading Condition Codes**

**SetX Instructions**: Set low order bytes of destination to 0 or 1, based on combinations of condition codes.

Does not alter remaining 7 bytes.

<table>
<thead>
<tr>
<th>SetX</th>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sete</td>
<td>ZF</td>
<td>Equal / Zero</td>
</tr>
<tr>
<td>setne</td>
<td>~ZF</td>
<td>Not equal / not zero</td>
</tr>
<tr>
<td>sets</td>
<td>SF</td>
<td>Negative</td>
</tr>
<tr>
<td>setns</td>
<td>~SF</td>
<td>Nonnegative</td>
</tr>
<tr>
<td>setg</td>
<td>~(SF^OF)&amp;~ZF</td>
<td>Greater (signed)</td>
</tr>
<tr>
<td>setge</td>
<td>~(SF^OF)</td>
<td>Greater or equal (signed)</td>
</tr>
<tr>
<td>setl</td>
<td>(SF^OF)</td>
<td>Less (signed)</td>
</tr>
<tr>
<td>setle</td>
<td>(SF^OF)</td>
<td>ZF</td>
</tr>
<tr>
<td>seta</td>
<td>~CF&amp;~ZF</td>
<td>Above (unsigned)</td>
</tr>
<tr>
<td>setb</td>
<td>CF</td>
<td>Below (unsigned)</td>
</tr>
</tbody>
</table>

**x86-64 Registers: Least Significant Byte**

Can reference the low-order byte.

**Jumping**

**jX Instructions**: Jump to different parts of the code depending on condition codes.

<table>
<thead>
<tr>
<th>jX</th>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>jmp</td>
<td>1</td>
<td>Unconditional</td>
</tr>
<tr>
<td>je</td>
<td>ZF</td>
<td>Equal / Zero</td>
</tr>
<tr>
<td>jne</td>
<td>~ZF</td>
<td>Not equal / not zero</td>
</tr>
<tr>
<td>js</td>
<td>SF</td>
<td>Negative</td>
</tr>
<tr>
<td>jns</td>
<td>~SF</td>
<td>Nonnegative</td>
</tr>
<tr>
<td>jg</td>
<td>~(SF^OF)&amp;~ZF</td>
<td>Greater (signed)</td>
</tr>
<tr>
<td>jge</td>
<td>~(SF^OF)</td>
<td>Greater or equal (signed)</td>
</tr>
<tr>
<td>jl</td>
<td>(SF^OF)</td>
<td>Less (signed)</td>
</tr>
<tr>
<td>jle</td>
<td>(SF^OF)</td>
<td>ZF</td>
</tr>
<tr>
<td>ja</td>
<td>~CF&amp;~ZF</td>
<td>Above (unsigned)</td>
</tr>
<tr>
<td>jb</td>
<td>CF</td>
<td>Below (unsigned)</td>
</tr>
</tbody>
</table>
Conditional Branch Example (Old Style)

Generation: gcc -Og -fno-if-conversion control.c

```c
long absdiff (long x, long y)
{
    long result;
    if (x > y)
        result = x−y;
    else
        result = y−x;
    return result;
}
```

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

A common compilation strategy is to take a C construct and rewrite it into an equivalent C version that is closer to assembly, as an intermediate step toward assembly.

<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>%rax</td>
<td>return value</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Machine Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
</tr>
<tr>
<td>Memory</td>
</tr>
<tr>
<td>Processor</td>
</tr>
<tr>
<td>Assembly</td>
</tr>
<tr>
<td>Memory</td>
</tr>
<tr>
<td>Regs</td>
</tr>
<tr>
<td>Processor</td>
</tr>
<tr>
<td>ALU</td>
</tr>
</tbody>
</table>

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

Data
- 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

Expressing with Goto Code

- C allows “goto” as a means of transferring control.
- Jump to position designated by label.
- Generally considered bad coding style in high level language.

```c
long absdiff_j (long x, long y)
{
    long result;
    int ntest = x <= y;
    if (ntest) goto Else;
    result = x−y;
    goto Done;
Else:
    result = y−x;
    Done:
        return result;
}
```

General Conditional Expression Translation

C Code:

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

Example:

```c
val = x>y ? x−y : y−x;
```

Goto Version:

```c
ntest = !Test
if (ntest) goto Else;
val = Then_Expr;
goto Done;
Else:
    result = y−x;
    Done:
        return result;
```
Conditional Move Instructions

Refer to generically as “cmovXX”
Based on values of condition codes
Conditionally copy value from source to destination.
Can be used to eliminate conditional jump.

<table>
<thead>
<tr>
<th>Inst.</th>
<th>Synonym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cmove</td>
<td>cmovz</td>
<td>Equal / zero</td>
</tr>
<tr>
<td>cmovne</td>
<td>cmovnz</td>
<td>Not equal / not zero</td>
</tr>
<tr>
<td>cmovs</td>
<td></td>
<td>Negative</td>
</tr>
<tr>
<td>cmovns</td>
<td></td>
<td>Not negative</td>
</tr>
<tr>
<td>cmovg</td>
<td>cmovnle</td>
<td>Greater (signed)</td>
</tr>
<tr>
<td>cmovge</td>
<td>cmovnl</td>
<td>Greater or equal (signed)</td>
</tr>
<tr>
<td>cmovl</td>
<td>cmovnge</td>
<td>Less (signed)</td>
</tr>
<tr>
<td>cmovle</td>
<td>cmovng</td>
<td>Less or equal (signed)</td>
</tr>
<tr>
<td>cmova</td>
<td>cmovnbe</td>
<td>Above (unsigned)</td>
</tr>
<tr>
<td>cmovae</td>
<td>cmovnb</td>
<td>Above or equal (unsigned)</td>
</tr>
<tr>
<td>cmovb</td>
<td>cmovnae</td>
<td>Below (unsigned)</td>
</tr>
<tr>
<td>cmovbe</td>
<td>cmovna</td>
<td>Below or equal (unsigned)</td>
</tr>
</tbody>
</table>

Using Conditional Moves

Conditional Move Instructions

- Instruction supports:
  - if (Test) Dest ← Src
- Supported in post-1995 x86 processors
- GCC tries to use them, but only when safe

Why?

- Branches are very disruptive to instruction flow through pipelines.
- Conditional moves do not require control transfer.

C Code

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

Goto Version

```c
val = Test
    ? Then_Expr
    : Else_Expr

result = Then_Expr;
eval = Else_Expr;
nt = !Test;
if (nt) result = eval;
return result;
```

Conditional Move Example

```c
absdiff:
    movq %rdi, %rax # x
    subq %rsi, %rax # result = x - y
    movq %rsi, %rdx
    subq %rdi, %rdx # eval = y - x
    cmpq %rsi, %rdi # x : y
    cmovle %rdx, %rax # if <=, result = eval
    retq
```
Bad Cases for Conditional Move

Expensive Computations:
\[
\text{val} = \text{Test}(x) \ ? \ \text{Hard1}(x) : \ \text{Hard2}(x);
\]
- Both values get computed
- Only makes sense when computations are very simple

Risky Computations:
\[
\text{val} = p \ ? \ ^*p : 0;
\]
- Both values get computed
- May have undesirable side effects.

Computations with Side Effects:
\[
\text{val} = x > 0 \ ? \ x *= 7 : x += 3;
\]
- Both values get computed
- Must be side effect free

Do-While Loop Example

Following our strategy of rewriting a C construct into a semantically equivalent C version that is closer to assembly.

C Code:

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

Goto Version:

```c
long pcount_goto(
    unsigned long x)
{
    long 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:

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

Register Use(s)

<table>
<thead>
<tr>
<th>%rdi</th>
<th>Argument x</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rax</td>
<td>return value</td>
</tr>
</tbody>
</table>

C Code:

```
movl $0, %eax # result = 0
.L2: movq %rdi, %rdx
    andl $1, %edx
    addq %rdx, %rax
    shrq $1, %rdi
    jne .L2 # if (x) goto loop
retq
```

General Do-While Translation

C Code:

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

Goto Version:

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

- Body can be any C statement, typically is a compound statement.
- Test is an expression returning an integer.
  - If it evaluates to 0, that’s interpreted as false.
  - If it evaluates to anything but 0, that’s interpreted as true.
General While Translation #1

- “Jump-to-middle” translation
- Used with -Og

While Loop Example #1

C Code

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

Jump to Middle

```c
long pcount_goto_jtm (unsigned long x) {
    long result = 0;
    goto test;
    loop:
        result += x & 0x1;
        x >>= 1;
    test:
        if (x) goto loop;
    done:
        return result;
}
```

- Compare to do-while version of function
- Initial goto starts loop at test

General While Translation

C Code

```c
while (Test) 
    Body
```

Goto version

```c
goto test;
loop:
    Body
    test:
        if (Test)
            goto loop;
    done:
```

While version

```c
while (Test) 
    Body
```

Do-While version

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

Are all three versions semantically equivalent?

While Loop Example #2

C Code

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

Do-While version

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

- Compare to do-while version of function
- Initial conditional guards entrance to loop
### For Loop Form

**General Form**

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

```c
#define WSIZE 8 + sizeof(long)
long pcount_for (unsigned long x)
{
    size_t i;
    long result = 0;
    for (i = 0; i < WSIZE; i++)
    {
        unsigned bit = (x >> i) & 0x1;
        result += bit;
    }
    return result;
}
```

### For Loop to While Loop

**For version**

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

**Translates to:**

**While version**

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

### For-While Conversion Example

**Init**

```c
i = 0
```

**Test**

```c
i < WSIZE
```

**Update**

```c
i++
```

**Body**

```c
{ unsigned bit = (x >> i) & 0x1;
    result += bit;
    i++;
} return result;
```

### For Loop Do-While Conversion

**C Code:**

```c
long pcount_for_goto_dw (unsigned long x) {
    size_t i;
    long result = 0;
    i = 0;
    if (! (i < WSIZE)) # drop
goto done; # drop
loop:
{
    unsigned bit =
        (x >> i) & 0x1;
    result += bit;
    i++;
    if (i < WSIZE)
goto loop;
done:
    return result;
}
```

Note that the initial test is not needed. Why?
Switch Statement Example

```c
long switch_eq(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;
}
```

- Multiple case labels (e.g., 5, 6)
- Fall through cases (e.g., 2)
- Missing cases (e.g., 4)

Switch Example

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

Setup:

<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>return value</td>
</tr>
</tbody>
</table>

Note that w is not initialized here.

Jump Table Structure

**Switch Form**

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

**Jump Table**

<table>
<thead>
<tr>
<th>Jump Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targ0:</td>
</tr>
<tr>
<td>Code</td>
</tr>
<tr>
<td>Block 0</td>
</tr>
<tr>
<td>Targ1:</td>
</tr>
<tr>
<td>Code</td>
</tr>
<tr>
<td>Block 1</td>
</tr>
<tr>
<td>Targ2:</td>
</tr>
<tr>
<td>Code</td>
</tr>
<tr>
<td>Block 2</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>Targn-1:</td>
</tr>
<tr>
<td>Code</td>
</tr>
<tr>
<td>Block n-1</td>
</tr>
</tbody>
</table>

**Jump Table**

<table>
<thead>
<tr>
<th>Jump Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>JTab:</td>
</tr>
<tr>
<td>Targ0</td>
</tr>
<tr>
<td>Targ1</td>
</tr>
<tr>
<td>Targ2</td>
</tr>
<tr>
<td>Targn-1</td>
</tr>
</tbody>
</table>

Setup:

```c
switch_eq:
    movq %rdx, %rcx
    cmpq $6, %rdi        # x:6
    ja .L8
    jmp *.L4(, %rdi, 8)
```

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

```
.section .rodata
.align 8
.L4:
    .quad .L8        # x = 0
    .quad .L3        # x = 1
    .quad .L5        # x = 2
    .quad .L9        # x = 3
    .quad .L8        # x = 4
    .quad .L7        # x = 5
    .quad .L7        # x = 6
```

```
switch_eq:
    movq %rdx, %rcx
    cmpq $6, %rdi        # x:6
    ja .L8
    jmp *.L4(, %rdi, 8)
```

```
.switch_eq:
    movq %rdx, %rcx
    cmpq $6, %rdi        # x:6
    ja .L8
    jmp *.L4(, %rdi, 8)
```

Note that w is not initialized here.
Assembly Setup Explanation

Table Structure
- Each target requires 8 bytes
- Base address at .L4

Jumping
- Direct: jmp .L8
- Jump target is denoted by label .L8
- Indirect:
  jmp *.L4(, %rdi, 8)
- Start of jump table: .L4
- Must scale by factor of 8 (addresses are 8 bytes)
- Fetch target from effective address (.L4 + x*8), but only for 0 ≤ x ≤ 6

Jump Table

| .section .rodata | .align 8 |
| .L4:             |        |
| .quad .L8 # x = 0 |        |
| .quad .L3 # x = 1 |        |
| .quad .L5 # x = 2 |        |
| .quad .L9 # x = 3 |        |
| .quad .L8 # x = 4 |        |
| .quad .L7 # x = 5 |        |
| .quad .L7 # x = 6 |        |

Handling Fall-Through

```
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;
```

Code Blocks (x == 1)

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

.L3:        
  movq %rsi, %rax # y
  imulq %rdx, %rax # y*z
  retq
```

Register Use(s)

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<td>Argument y</td>
</tr>
<tr>
<td>%rdx</td>
<td>Argument z</td>
</tr>
<tr>
<td>%rax</td>
<td>return value</td>
</tr>
</tbody>
</table>
Jump Table Structure

Suppose you have a set of switch labels that are “sparse” (widely separated).

In this case, it doesn’t make sense to use a jump table.

- If there are only a few labels, simply use a nested if structure.
- If there are many, build a balanced binary search tree.

The compiler decides the appropriate thresholds for what’s “sparse,” what are “a few,” etc.

C Control

- if-then-else
- do-while
- while, for
- switch

Assembler Control

- Conditional jump
- Conditional move
- Indirect jump (via jump tables)
- Compiler generates code sequence to implement more complex control

Standard Techniques

- Loops converted to do-while or jump-to-middle form
- Large switch statements use jump tables
- Sparse switch statements may use decision trees