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.

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

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?

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

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

* contained in a 64-bit rflags register
**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:
  \[(a>0 \&\& b>0 \&\& t<0) || (a<0 \&\& b<0 \&\& t >0)\]
- Condition codes not set by lea instruction.

**Explicitly set by Compare instruction**
`cmpq Src2, Src1`
- 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:
  \[(a>0 \&\& b>0 \&\& (a-b)<0) || (a<0 \&\& b<0 \&\& (a-b)>=0)\]

**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:
```
**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>

**Reading Condition Codes**

**SetX instructions**
- Set single byte based on combinations of conditions codes.
- Argument is one of addressable byte registers.
  - does not alter remaining bytes;
  - typically use movzbl to finish the job (will also zero 4 high order bytes).

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

**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>
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<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>

Can reference the low-order byte.
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;
}
```

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.

### 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

- Create separate code regions for then and else expressions.
- Execute the appropriate one.

**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
      result = Then_Expr;
      eval = Else_Expr;
    : Else_Expr

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:

```
val = Test(x) ? Hard1(x) : Hard2(x);
```

- Both values get computed
- Only makes sense when computations are very simple

Risky Computations:

```
val = p ? *p : 0;
```

- Both values get computed
- May have undesirable side effects.

Computations with Side Effects:

```
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:

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

Goto Version:

```
long pcount_goto
(unsinged 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:

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

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

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 Do-While Translation

```
do { 
    condition code; 
} while (condition);
```
General While Translation #1

- "Jump-to-middle" translation
- Used with -Og

While version

```c
while (Test) {
    Body
}
```

Goto version

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

C Code

```c
long pcount_while (unsigned long x) {
    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;
}
```

Do-While Version

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

Are all three versions semantically equivalent?

General While Translation #2

```c
while (Test) {
    Body
}
```

which gets compiled as if it were:

Goto Version

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

C Code

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

long pcount_for
    (unsigned long x)
{
    size_t i;
    long result = 0;
    i = 0;
    while (i < WSIZE)
    { 
        unsigned bit =
            (x >> i) & 0x1;
        result += bit;
        i++;
    }
    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)

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

```
Jump Table
JTab:
| Targ0: Code Block 0 |
| Targ1: Code Block 1 |
| Targ2: Code Block 2 |
| … |
| Targn-1: Code Block n-1 |
```

### Translation (Extended C)

```c
goto *JTab[x];
```

Switch Example

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

#### Setup:

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

#### Register Use(s)

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

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

```
.long switch_eq
(long x, long y, long z)
{
    .align 8
    .section .rodata

    L4:
    .align 8
    .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

    w = y * z;
    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;
    ...
}
```

Handling Fall-Through

```
.long w = 1;
...
switch (x) {
    ...
    case 2:
        w = y / z;
        goto merge;
    ...
    case 3:
        w = 1;
        merge:
        w += z;
        break;
    ...
}
```

Register Use(s)

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<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