CS429: Computer Organization and Architecture
Instruction Set Architecture III

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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.

```
#include <stdio.h>
int main(void)
{
    int count;
    for (count = 1; count <= 500; count++)
        printf("I will not throw paper airplanes in class.");
    return 0;
}
```
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)

### Registers

<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

| CF | ZF | SF | OF | Condition codes |
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?*
**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:
  \[ (a>0 \land \land b>0 \land t<0) \land (a<0 \land \land b<0 \land t \geq 0) \]
- Condition codes not set by lea instruction.
Explicitly set by Compare instruction

\texttt{cmpq Src2, Src1}

- \texttt{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:
  \[
  (a>0 \&\& b>0 \&\& (a-b)<0) \lor (a<0 \&\& b<0 \&\& (a-b)\geq 0)
  \]
Explicitly set by Test instruction

\texttt{testq Src2, Src1}

- Sets condition codes based on value of (Src1 & Src2).
- Often useful to have one of the operands be a mask.
- \texttt{testq b, a} is like computing \texttt{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 \texttt{testq} to jump if the value in \%rbx is even?
Explicitly set by Test instruction

\texttt{testq \texttt{Src2, Src1}}

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

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

\begin{verbatim}
  testq $1, \%rbx
  je even
  odd:
\end{verbatim}
**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>settle</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>
<tr>
<td>%rax</td>
<td>%al</td>
<td>%r8</td>
</tr>
<tr>
<td>%rbx</td>
<td>%bl</td>
<td>%r9</td>
</tr>
<tr>
<td>%rcx</td>
<td>%cl</td>
<td>%r10</td>
</tr>
<tr>
<td>%rdx</td>
<td>%dl</td>
<td>%r11</td>
</tr>
<tr>
<td>%rsi</td>
<td>%sil</td>
<td>%r12</td>
</tr>
<tr>
<td>%rdi</td>
<td>%dil</td>
<td>%r13</td>
</tr>
<tr>
<td>%rsp</td>
<td>%spl</td>
<td>%r14</td>
</tr>
<tr>
<td>%rbp</td>
<td>%bpl</td>
<td>%r15</td>
</tr>
</tbody>
</table>

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

<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>

```assembly
cmpq %rsi, %rdi  # compare x:y
setg %al         # Set if >
movzbl %al, %eax # Zero rest of %rax
retq
```
**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;
}
```

```
absdiff:
    cmpq %rsi, %rdi  # x:y
    jle .L4
    movq %rdi, %rax
    subq %rsi, %rax
    retq

.L4:
    movq %rsi, %rax
    subq %rdi, %rax
    retq
```

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

```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;
}
```
C Code:

\[
\text{val} = \text{Test} \ ? \ \text{Then	extunderscore Expr} : \ \text{Else	extunderscore Expr};
\]

Example:

\[
\text{val} = \text{x>y} \ ? \ \text{x-y} : \ \text{y-x};
\]

Goto Version:

\[
\text{ntest} = !\text{Test}
\text{if (ntest) goto Else;}
\text{val} = \text{Then	extunderscore Expr;}
\text{goto Done;}
\text{Else:}
\text{val} = \text{Else	extunderscore Expr;}
\text{Done:}
\text{...}
\]

- Create separate code regions for then and else expressions.
- Execute the appropriate one.
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.
### Conditional Move Instructions

<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>cmoa</td>
<td>cmovnbe</td>
<td>Above (unsigned)</td>
</tr>
<tr>
<td>cmova</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
val = Test
? Then.Expr :
  Else.Expr
```

Goto Version

```c
result = Then.Expr;
eval = Else.Expr;
nt = !Test;
if (nt) result = eval;
return result;
```
Conditional Move Example

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

### Register Use(s)

<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>

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

Goto Version:

```c
long pcoun_t_goto
 (unsigned long x) {
  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
Goto Version:

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

<table>
<thead>
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<th>Register</th>
<th>Use(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%rdi</td>
<td>Argument x</td>
</tr>
<tr>
<td>%rax</td>
<td>return value</td>
</tr>
</tbody>
</table>

```
movl $0, %eax      # result = 0
.L2:                # loop:
    movq %rdi, %rdx  # t = x & 0x1
    andl $1, %edx    # result += t
    addq %rdx, %rax  # x >>= 1
    shrq $1, %rdi    # if (x) goto loop
    jne .L2          #
    retq
```
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.
“Jump-to-middle” translation
Used with -Og

While version

```
while (Test)
    Body
```

Goto version

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

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

Jump to Middle

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

- Compare to do-while version of function
- Initial goto starts loop at test
which is equivalent to:

Do-While Version

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

which gets compiled as if it were:

Goto Version

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

Are all three versions semantically equivalent?
C Code

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

Do-While version

```c
long pcound_goto_dw (unsigned long x) {
    long result = 0;
    if (!x) goto done;
    loop:
        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 version

```plaintext
for (Init; Test; Update)
    Body
```
	ranslates to:

While version

```plaintext
Init;
while (Test) {
    Body;
    Update;
}
```
**For-While Conversion Example**

**Init**

\[ i = 0 \]

**Test**

\[ i < \text{WSIZE} \]

**Update**

\[ i++ \]

**Body**

\[
\begin{align*}
\text{long pcount_for_while} \\
(\text{unsigned long } x) \\
\begin{cases}
\begin{align*}
\text{size_t } i; \\
\text{long result} = 0; \\
i = 0; \\
\text{while } (i < \text{WSIZE}) \\
\{ \\
\quad \text{unsigned bit} = \\
\quad \quad (x >> i) \& \text{0x1}; \\
\quad \text{result} += \text{bit}; \\
\quad i++; \\
\} \\
\text{return result;}
\end{align*}
\end{cases}
\end{align*}
\]

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C Code:

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

Note that the initial test is not needed. Why?
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;
}
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
}
```

Translation (Extended C)

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

Jump Table

<table>
<thead>
<tr>
<th>Targ0</th>
<th>Targ1</th>
<th>Targ2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Targn-1</td>
</tr>
</tbody>
</table>

Jump Targets

- Targ0: Code Block 0
- Targ1: Code Block 1
- Targ2: Code Block 2
- Targn-1: Code Block n-1
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.
Switch Statement Example

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

Jump table

```assembly
.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
```

Setup:

```assembly
switch_eq:
    movq   %rdx, %rcx
    cmpq   $6, %rdi
    ja     .L8
    jmp    *.L4(, %rdi, 8)
```
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 $0 \leq x \leq 6$

```
.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
```
Jump Table:

```
.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;
}
```

Jump Table:

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

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

<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>
long w = 1;
...
switch (x) {
    ...
    case 2:
        w = y/z;
        // Fall Through */
    case 3:
        w += z;
        break;
    ...
}

case 2:
    w = y/z;
    goto merge;
...

case 3:
    w = 1;
merge:
    w += z;
Code Blocks ($x == 2, x == 3$)

```c
long w = 1;
...
switch (x) {
  ...
  case 2:
    w = y / z;
    /* Fall Through */
  case 3:
    w += z;
    break;
  ...
}
```

```
.L5:
    #Case 2
    movq %rsi, %rax
    cqto
    idivq %rcx
    jmp .L6
    # y/z
    jmp .L6
    # goto merge
    .L9:
    movl $1, %eax
    # w = 1
    # merge:
    .L6:
    addq %rcx, %rax
    retq
    # w += z
```

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

CS429 Slideset 8: 41 Instruction Set Architecture III
Code Blocks ($x == 5, x == 6, default$)

```plaintext
switch (x) {
    ...
    case 5:    // .L7
        w = z;
        break;
    case 6:    // .L7
        w = z;
    default:    // .L8
        w = 2;
}
```

```
.L7:
    movl $1, %eax    # w = 1
    subq %rdx, %rax  # w -= z
    retq

.L8:
    movl $2, %eax    # default

Register | Use(s)
--- | ---
%rdi | Argument x
%rsi | Argument y
%rdx | Argument z
%rax | return value
```
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