Machine-Level Programming II: Control

COMP400727: Introduction to Computer Systems

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Today

- **Review of a few tricky bits from last time**
- Basics of control flow
- Condition codes
- Conditional operations
- Loops
- If we have time: switch statements

Reminder: Machine Instructions

```
*dest = t;
```

```
movq %rax, (%rbx)
```

```
0x40059e:   48 89 03
```

C

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]**

Machine

3 bytes at address **0x40059e**

Compact representation of the assembly instruction

(Relatively) easy for hardware to interpret

Reminder: Machine Instructions

```
*dest = t;
```

```
movq %rax, (%rbx)
```

```
0x40059e:  48 89 03
```

```
0100 1 0 0 0  10001011  00 000 011
REX  W R X B  MOV r->x  Mod R   M
```

C

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]**

Machine

3 bytes at address **0x40059e**

Compact representation of the assembly instruction

(Relatively) easy for hardware to interpret

Reminder: Address 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]]**

Memory operands and LEA

In most instructions, a memory operand accesses memory

Assembly	C equivalent
mov 6(%rbx,%rdi,8), %ax	ax = *(rbx + rdi*8 + 6)
add 6(%rbx,%rdi,8), %ax	ax += *(rbx + rdi*8 + 6)
xor %ax, 6(%rbx,%rdi,8)	*(rbx + rdi*8 + 6) ^= ax

LEA is special: it *doesn’t* access memory

Assembly	C equivalent
lea 6(%rbx,%rdi,8), %rax	rax = rbx + rdi*8 + 6

Why use LEA?

- **CPU designers' intended use: calculate a pointer to an object**
  - An array element, perhaps
  - For instance, to pass just one array element to another function

Assembly	C equivalent
lea (%rbx,%rdi,8), %rax	rax = &rbx[rdi]

- **Compiler authors like to use it for ordinary arithmetic**
  - It can do complex calculations in one instruction
  - It's one of the only three-operand instructions the x86 has
  - It doesn't touch the condition codes (we'll come back to this)

Assembly	C equivalent
lea (%rbx,%rbx,2), %rax	rax = rbx * 3

Which numbers are pointers?

- They aren't labeled
- You have to figure it out from context

```
(gdb) info registers
rax     0x40057d         4195709
rbx     0x0              0
rcx     0x4005e0         4195808
rdx     0x7fffffffdc28   140737488346152
rsi     0x7fffffffdc18   140737488346136
rdi     0x1              1
rbp     0x0              0x0
rsp     0x7fffffffdb38   0x7fffffffdb38
r8      0x7ffff7dd5e80   140737351868032
r9      0x0              0
r10     0x7fffffffd7c0   140737488345024
r11     0x7ffff7a2f460   140737348039776
r12     0x400490         4195472
r13     0x7fffffffdc10   140737488346128
r14     0x0              0
r15     0x0              0
rip     0x40057d         0x40057d
```

Which numbers are pointers?

- They aren't labeled
- You have to figure it out from context

- %rsp and %rip always hold pointers

```
(gdb) info registers
rax        0x40057d          4195709
rbx        0x0               0
rcx        0x4005e0          4195808
rdx        0x7fffffffdc28    140737488346152
rsi        0x7fffffffdc18    140737488346136
rdi        0x1               1
rbp        0x0               0x0
rsp        0x7fffffffdb38    0x7fffffffdb38
r8         0x7ffff7dd5e80    140737351868032
r9         0x0               0
r10        0x7fffffffd7c0    140737488345024
r11        0x7ffff7a2f460    140737348039776
r12        0x400490          4195472
r13        0x7fffffffdc10    140737488346128
r14        0x0               0
r15        0x0               0
rip        0x40057d          0x40057d
```

Today

Review of a few tricky bits from yesterday

Basics of control flow

Condition codes

Conditional operations

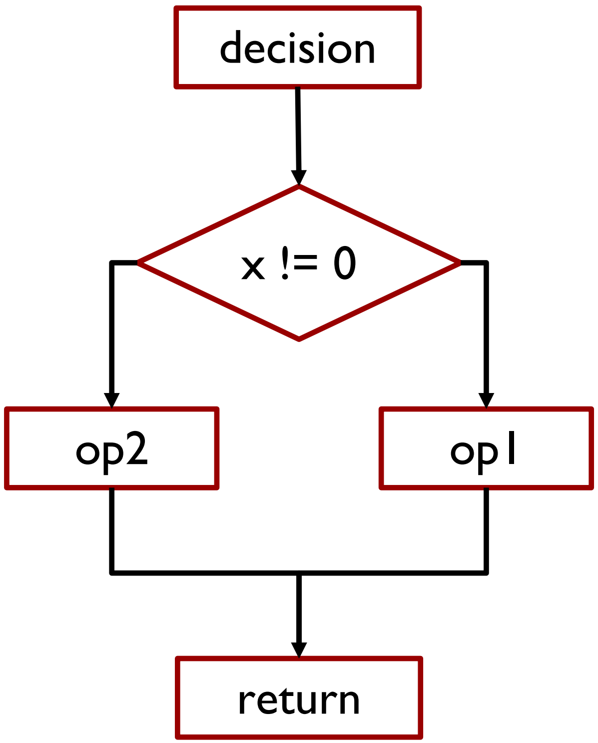
Loops

If we have time: switch statements

Control flow

```
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```



Control flow in assembly language

```
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```

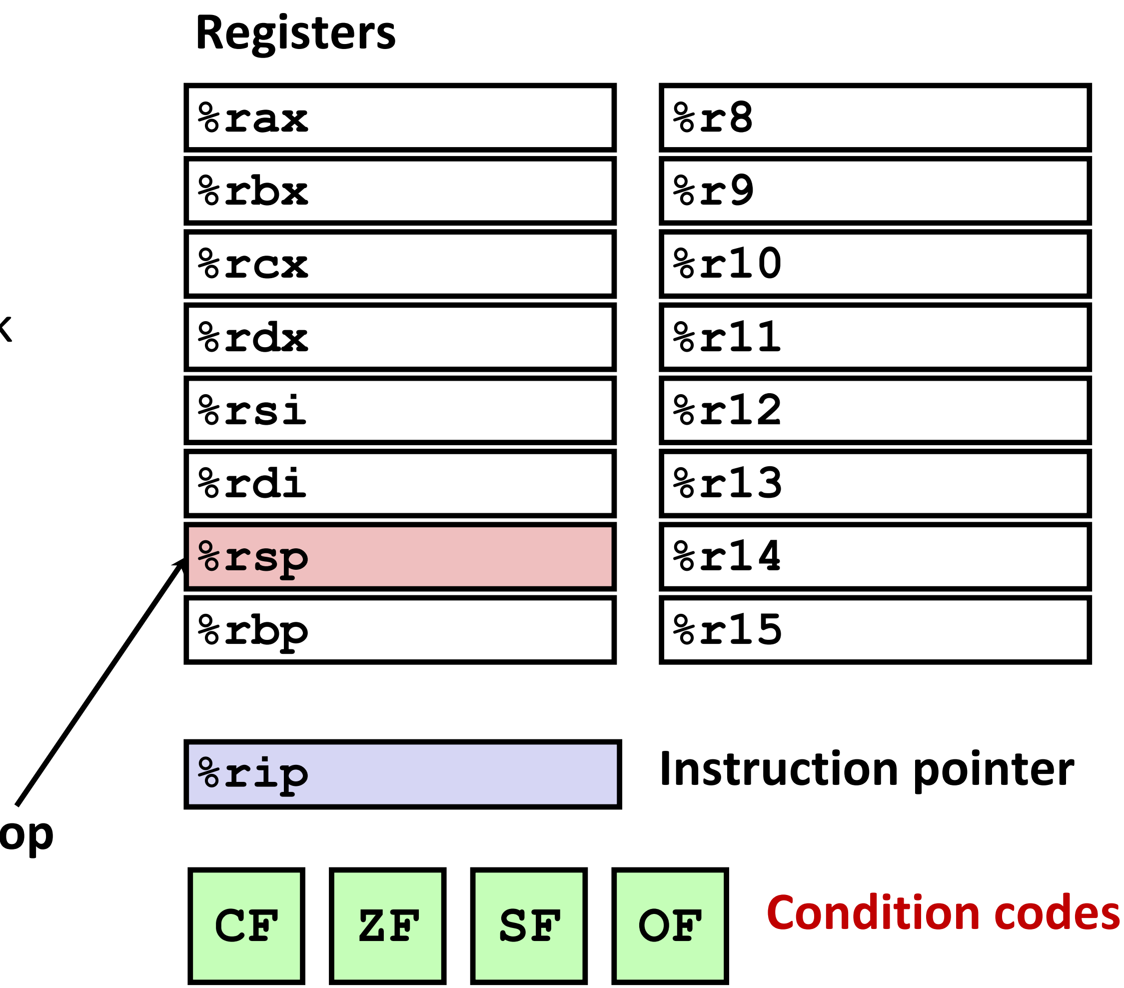
```
decision:
        subq    $8, %rsp
        testl   %edi, %edi
        je      .L2
        call    op1
        jmp     .L1
.L2:
        call    op2
.L1:
        addq    $8, %rsp
        ret
```

It's all done with GOTO!

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**)



Condition Codes (Implicit Setting)

Single bit registers

CF	Carry Flag (for unsigned)	**SF**	Sign Flag (for signed)
ZF	Zero Flag	**OF**	Overflow Flag (for signed)

Implicitly set (as side effect) of arithmetic operations

Example: `addq` *Src,Dest* ↔ `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 (signed) overflow

`(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`

Not set by `leaq` instruction

ZF set when

000000000000…00000000000

SF set when

```
1xxxxxxxxxxx…xxxxxxxxxxxx
```

CF set when

```
   yxxxxxxxxxxxx. . .
+  yxxxxxxxxxxxx. . .
---------------------
1  zxxxxxxxxxxxx. . .
```

OF set when

```
  wxxxxxxxxxxxx...
+ yxxxxxxxxxxxx...
------------------
  zxxxxxxxxxxxx...
```

w == y && w != z

Compare Instruction

`cmp a, b`

Computes $b - a$ (just like **`sub`**)

Sets condition codes based on result, but…

Does not change *b*

CF set if carry out from most significant bit (used for unsigned comparisons) (when b<a)

ZF set if b==a

SF set if (b-a) < 0 (as signed)

OF set if two's-complement (signed overflow)

(b > 0 && a < 0 && (b-a) < 0) || (b < 0 && a > 0 && (b-a) > 0)

Used for **`if (a < b) { … }`**
whenever $a - b$ isn't needed for anything else

Test Instruction

`test a, b`

Computes $b\&a$ (just like **`and`**)

Sets condition codes (only SF and ZF) based on result, but…

Does not change *b*

ZF Set when a&b == 0

SF Set when a&b < 0

Most common use: `test %rX, %rX`
to compare `%rX` to zero

Today

- Review of a few tricky bits from yesterday
- Basics of control flow
- Condition codes
- **Conditional operations**
- Loops
- If we have time: switch statements

Reading Condition Codes

SetX Instructions

Set low-order byte of destination to 0 or 1 based on *combinations* of condition codes

Does not alter remaining 7 bytes

SetX	Condition	Description
`sete`	`ZF`	Equal / Zero
`setne`	`~ZF`	Not Equal / Not Zero
`sets`	`SF`	Negative
`setns`	`~SF`	Nonnegative
`setg`	`~(SF^OF)&~ZF`	Greater (Signed)
`setge`	`~(SF^OF)`	Greater or Equal (Signed)
`setl`	`(SF^OF)`	Less (Signed)
`setle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`seta`	`~CF&~ZF`	Above (unsigned)
`setb`	`CF`	Below (unsigned)

x86-64 Integer Registers

%rax	%al	%r8	%r8b
%rbx	%bl	%r9	%r9b
%rcx	%cl	%r10	%r10b
%rdx	%dl	%r11	%r11b
%rsi	%sil	%r12	%r12b
%rdi	%dil	%r13	%r13b
%rsp	%spl	%r14	%r14b
%rbp	%bpl	%r15	%r15b

SetX argument is always a low byte (%al, %r8b, etc.)

Reading Condition Codes (Cont.)

SetX Instructions:

Set single byte based on combination of condition codes

One of addressable byte registers

Does not alter remaining bytes

Typically use **`movzbl`** to finish job

32-bit instructions also set upper 32 bits to 0

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

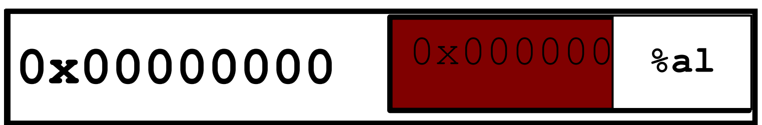
Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rax`	Return value

```
    cmpq    %rsi, %rdi     # Compare x:y
    setg    %al            # Set when >
    movzbl  %al, %eax      # Zero rest of %rax
    ret
```

Reading Condition Codes (Cont.)

Beware weirdness **`movzbl`** (and others)

`movzbl %al, %eax`



Zapped to all 0's

Use(s)
Argument **`x`**
Argument **`y`**
Return value

```
cmpq   %rsi, %rdi    # Compare x:y
setg   %al           # Set when >
movzbl %al, %eax     # Zero rest of %rax
ret
```

Jumping

jX Instructions

Jump to different part of code depending on condition codes

jX	Condition	Description
`jmp`	`1`	Unconditional
`je`	`ZF`	Equal / Zero
`jne`	`~ZF`	Not Equal / Not Zero
`js`	`SF`	Negative
`jns`	`~SF`	Nonnegative
`jg`	`~(SF^OF)&~ZF`	Greater (Signed)
`jge`	`~(SF^OF)`	Greater or Equal (Signed)
`jl`	`(SF^OF)`	Less (Signed)
`jle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`ja`	`~CF&~ZF`	Above (unsigned)
`jb`	`CF`	Below (unsigned)

Conditional Branch Example (Old Style)

Generation

```
shark> gcc –Og -S –fno-if-conversion cont
```

I'll get to this shortly.

```
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
   ret
.L4:               # x <= y
   movq    %rsi, %rax
   subq    %rdi, %rax
   ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	Return value

Expressing with Goto Code

- C allows `goto` statement
- Jump to position designated by label

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

```
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;
}
```

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 known to be safe

Why?

Branches are very disruptive to instruction flow through pipelines

Conditional moves do not require control transfer

C Code

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

Goto Version

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

Conditional Move Example

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

Register	Use(s)
`%rdi`	Argument `x`
`%rsi`	Argument `y`
`%rax`	Return value

```
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
   ret
```

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

Bad Performance

Risky Computations

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

- Both values get computed
- May have undesirable effects

Unsafe

Computations with side effects

```
val = x > 0 ? x*=7 : x+=3;
```

- Both values get computed
- Must be side-effect free

Illegal

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- **Loops**
- If we have time: switch statements

"Do-While" Loop Example

C Code

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

Goto Version

```
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

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

Register	Use(s)
%rdi	Argument x
%rax	result

```
movl    $0, %eax              #  result = 0
.L2:                          # loop:
   movq    %rdi, %rdx
   andl    $1, %edx           #  t = x & 0x1
   addq    %rdx, %rax         #  result += t
   shrq    %rdi               #  x >>= 1
   jne     .L2                #  if (x) goto
loop
   rep; ret
```

General "Do-While" Translation

C Code

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

Body:

```
{
   Statement1;
   Statement2;
     …
   Statementn;
}
```

Goto Version

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

General "While" Translation #1

"Jump-to-middle" translation

Used with `-Og`

While version

```
while (Test)
  Body
```

Goto Version

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

While Loop Example #1

C Code

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

Jump to Middle

```
long pcount_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

General "While" Translation #2

While version

```
while (Test)
    Body
```

"Do-while" conversion

Used with –O1

Do-While Version

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

Goto Version

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

While Loop Example #2

C Code

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

Do-While Version

```
long pcount_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

```
for (Init; Test; Update )

    Body
```

```
#define WSIZE (8*sizeof(int))
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;
}
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

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

"For" Loop → While Loop

For Version

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

While Version

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

For-While Conversion

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

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

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

“For” Loop Do-While Conversion

C Code

```
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;
}
```

Initial test can be optimized away

Goto Version

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

Today

- Review of a few tricky bits from yesterday
- Basics of control flow
- Condition codes
- Conditional operations
- Loops
- **If we have time: switch statements**

```
long switch_eg
   (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;
}
```

Switch Statement Example

- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

Jump Table Structure

Switch Form

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

Jump Table

jtab:

Targ0
Targ1
Targ2
• • •
Targn-1

Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

• • •

Targn-1: Code Block *n*–1

Translation (Extended C)

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

Switch Statement Example

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

Setup:

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

What range of values takes default?

Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rdx`	Argument **`z`**
`%rax`	Return value

Note that **`w`** not initialized here

Switch Statement Example

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

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
```

Setup:

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi        # x:6
    ja      .L8             # Use default
    jmp     *.L4(,%rdi,8)   # goto *JTab[x]
```

Indirect jump

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**

Only for $0 \le x \le 6$

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
```

Jump Table

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
```

```
switch(x) {
case 1:       // .L3
    w = y*z;
    break;
case 2:       // .L5
    w = y/z;
    /* Fall Through */
case 3:       // .L9
    w += z;
    break;
case 5:
case 6:       // .L7
    w -= z;
    break;
default:      // .L8
    w = 2;
}
```

Code Blocks (x == 1)

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

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

Register	Use(s)
`%rdi`	Argument **x**
`%rsi`	Argument **y**
`%rdx`	Argument **z**
`%rax`	Return value

Handling Fall-Through

```
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)

```
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             #  y/z
   jmp     .L6              #  goto merge
.L9:                        # Case 3
   movl    $1, %eax         #  w = 1
.L6:                        # merge:
   addq    %rcx, %rax       #  w += z
   ret
```

Register	Use(s)
`%rdi`	Argument **x**
`%rsi`	Argument **y**
`%rdx`	Argument **z**
`%rax`	Return value

Code Blocks (x == 5, x == 6, default)

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

```
.L7:                      # Case 5,6
  movl   $1, %eax         #  w = 1
  subq   %rdx, %rax       #  w -= z
  ret
.L8:                      # Default:
  movl   $2, %eax         #  2
  ret
```

Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rdx`	Argument **`z`**
`%rax`	Return value

Summarizing

C Control

- If-then-else
- Do-while
- While, for
- Switch

Assembler Control

- Conditional jump
- Conditional move
- Indirect jump (via dump 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 (if-elseif-elseif-else)