Machine-Level Programming II: Control

CSE 238/2038/2138: Systems Programming

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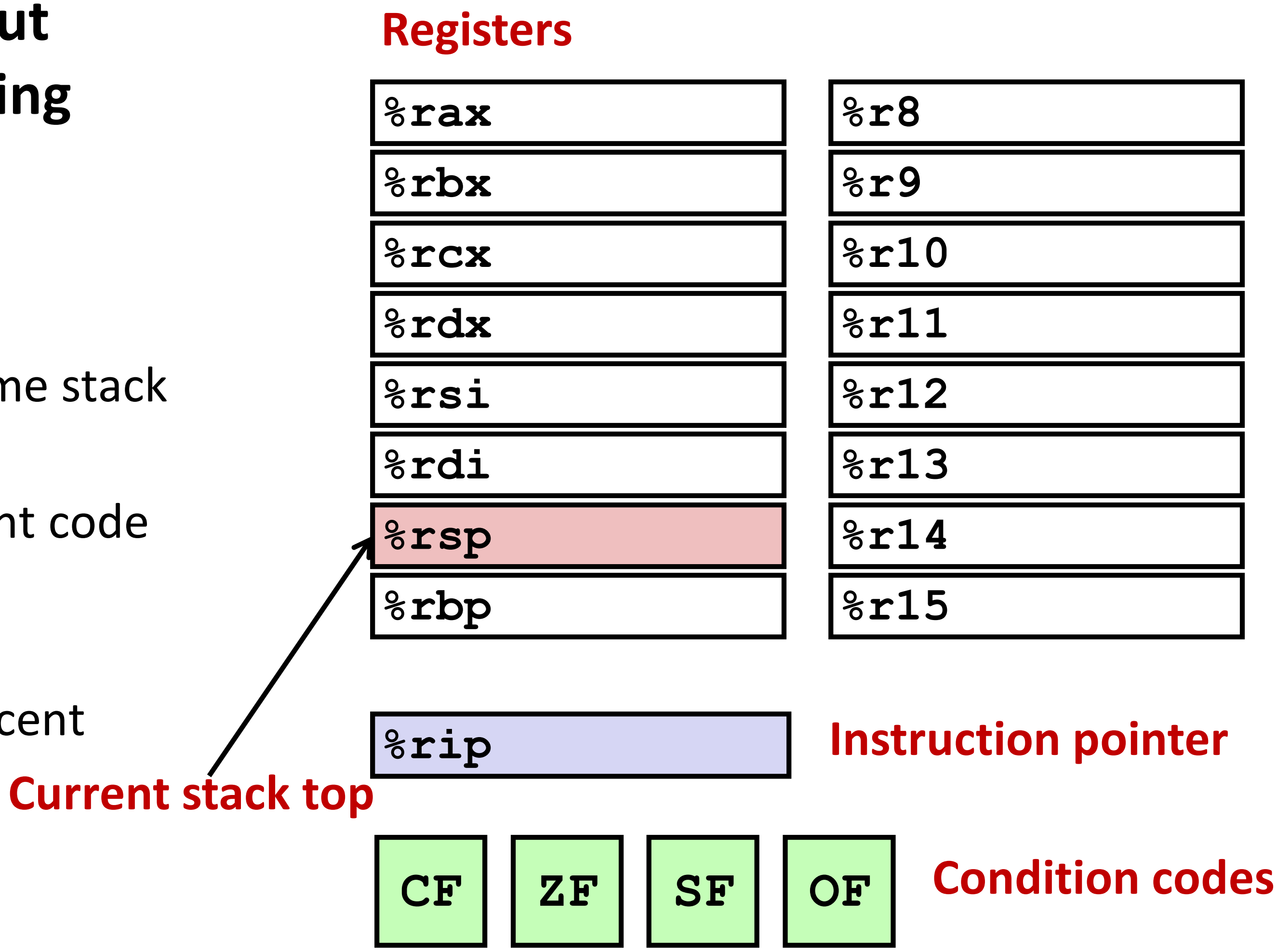
Slides adapted from Bryant & O'Hallaron's slides

Today

- **Control: Condition codes**
- Conditional branches
- Loops
- Switch Statements

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 most recent operations
    (**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)

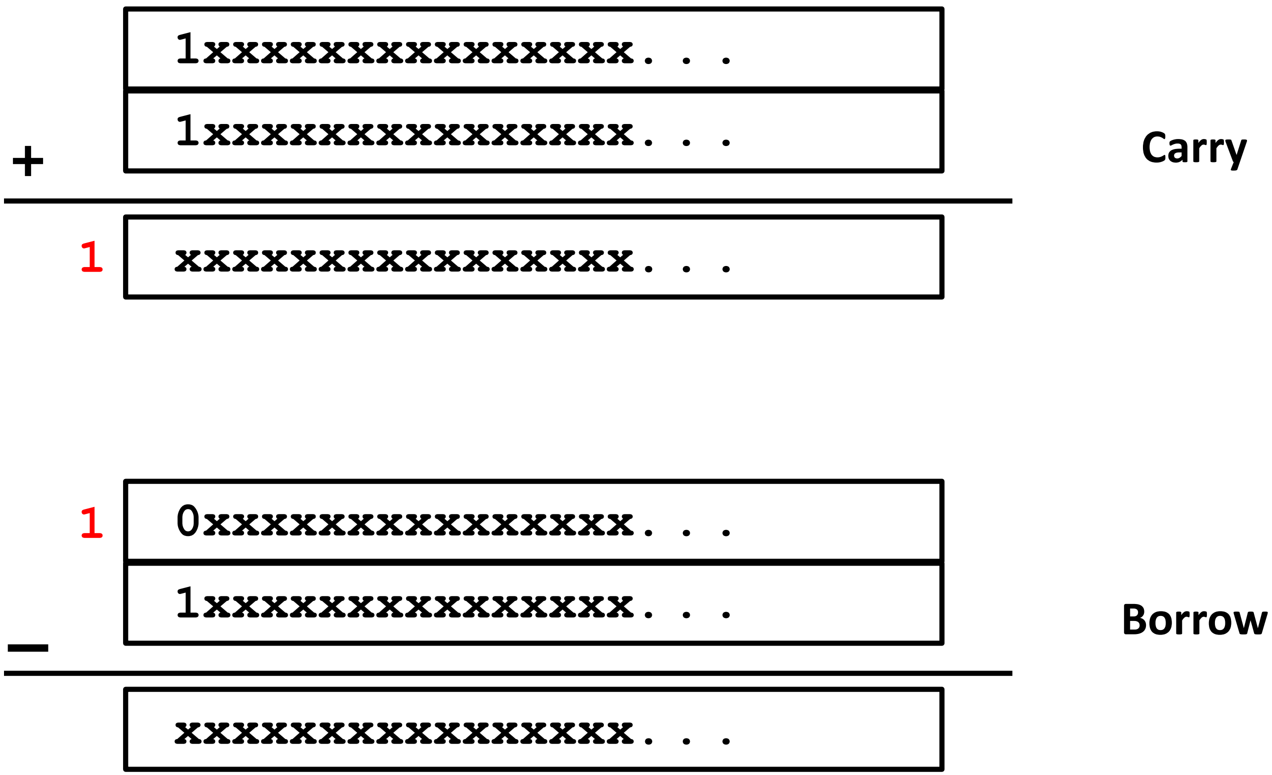
- **Implicitly set (think of it as a side effect) by arithmetic operations**

  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**

CF set when



For unsigned arithmetic, this reports overflow

SF set when

```
  yxxxxxxxxxxxxxxx. . .
+ yxxxxxxxxxxxxxxx. . .
-----------------------
  1xxxxxxxxxxxxxxx. . .
```

For signed arithmetic, this reports when result is a negative number

OF set when

```
  yxxxxxxxxxxxxxxx. . .
+ yxxxxxxxxxxxxxxx. . .
  ---------------------
  zxxxxxxxxxxxxxxx. . .
```

`z = ~y`

For signed arithmetic, this reports overflow

ZF set when

0000000000000000. . .000000

Condition Codes (Explicit Setting: Compare)

- **Explicit Setting by Compare Instruction**
  - **`cmpq`** *Src2*, *Src1*

  - **Example: `cmpq b,a`** like computing **`a-b`** without setting destination
    - **CF set** if carry out from most significant bit
      (used for unsigned comparisons)
    - **ZF set** if **`a == b`**
    - **SF set** if **`(a-b) < 0`** (as signed)
    - **OF set** if two's-complement (signed) overflow
      `(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`

Condition Codes (Explicit Setting: Test)

- **Explicit Setting by Test instruction**
  - **`testq`** *Src2*, *Src1*
  - Sets condition codes based on value of *Src1* & *Src2*
  - Useful to have one of the operands be a mask

  - **Example: `testq b,a`** like computing **`a&b`** without setting destination
    - **ZF set** when **`a&b == 0`**
    - **SF set** when **`a&b < 0`**

Very often:

`testq %rax,%rax`

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	%eax	%al	%r8	%r8d	%r8b
%rbx	%ebx	%bl	%r9	%r9d	%r9b
%rcx	%ecx	%cl	%r10	%r10d	%r10b
%rdx	%edx	%dl	%r11	%r11d	%r11b
%rsi	%esi	%sil	%r12	%r12d	%r12b
%rdi	%edi	%dil	%r13	%r13d	%r13b
%rsp	%esp	%spl	%r14	%r14d	%r14b
%rbp	%ebp	%bpl	%r15	%r15d	%r15b

- Can reference low-order byte

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

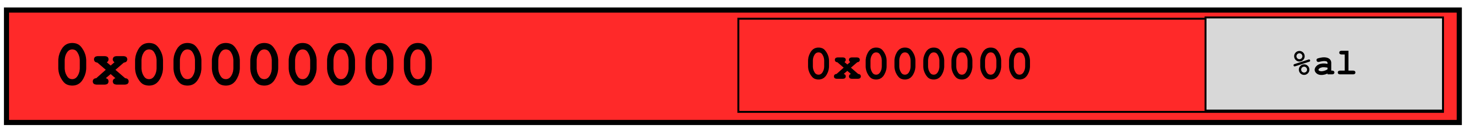
```
int gt (long x, long y)
{
  return x > y;
}
```

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

```
    cmpq   %rsi, %rdi    # Compare x:y
    setg   %al           # Set %al=1 when x>y
    movzbl %al, %eax     # Zero rest of %rax
    ret
```

Reading Condition Codes (Cont.)

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



Exercise

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)

- **`cmpq b,a`** like computing **`a-b`** without setting destination

CF set if carry out from most significant bit (used for unsigned comparisons)
ZF set if **`a == b`**
SF set if **`(a-b) < 0`** (as signed)
OF set if two's-complement (signed) overflow
`(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`

	%rax	SF	CF	OF	ZF
`xor %rax, %rax`					
`sub $1, %rax`					
`cmp $2, %rax`					
`setl %al`					
`movzbl %al, %eax`					

Exercise

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)

- **`cmpq b,a`** like computing **`a-b`** without setting destination

CF set if carry out from most significant bit (used for unsigned comparisons)
ZF set if **`a == b`**
SF set if **`(a-b) < 0`** (as signed)
OF set if two's-complement (signed) overflow
`(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`

		%rax	SF	CF	OF	ZF
`xor`	`%rax, %rax`	0x 0000 0000 0000 0000	0	0	0	1
`sub`	`$1, %rax`	0x FFFF FFFF FFFF FFFF	1	1	0	0
`cmp`	`$2, %rax`	0x FFFF FFFF FFFF FFFF	1	0	0	0
`setl`	`%al`	0x FFFF FFFF FFFF FF01	1	0	0	0
`movzbl`	`%al, %eax`	0x 0000 0000 0000 0001	1	0	0	0

Today

- Control: Condition codes
- **Conditional branches**
- Loops
- Switch Statements

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**

```
unix> gcc –Og -S –fno-if-conversion control.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
   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;
}
```

```
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
```

General Conditional Expression Translation (Using Branches)

C Code

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

```
val = x>y ? x-y : y-x;
```

Goto Version

```
  ntest = !Test;
  if (ntest) goto Else;
  val = Then_Expr;
  goto Done;
Else:
  val = Else_Expr;
Done:
  . . .
```

- Create separate code regions for then & else expressions
- Execute appropriate one

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

Today

- Control: Condition codes
- Conditional branches
- **Loops**
- 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);
```

Goto Version

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

- **Body:**

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

General “While” Translation #1

While version

```
while (Test)
    Body
```

Goto Version #1

```
    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;
}
```

Goto Version #1

```
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 Version

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

Goto Version #2

```
  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;
}
```

Goto Version #2

```
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

```
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

```
long pcount_for_goto_dw
   (unsigned long x)
{
  size_t i;
  long result = 0;
  i = 0;            Init
  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

- Control: Condition codes
- Conditional branches
- Loops
- **Switch Statements**

Switch Statement Example

```
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;
}
```

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

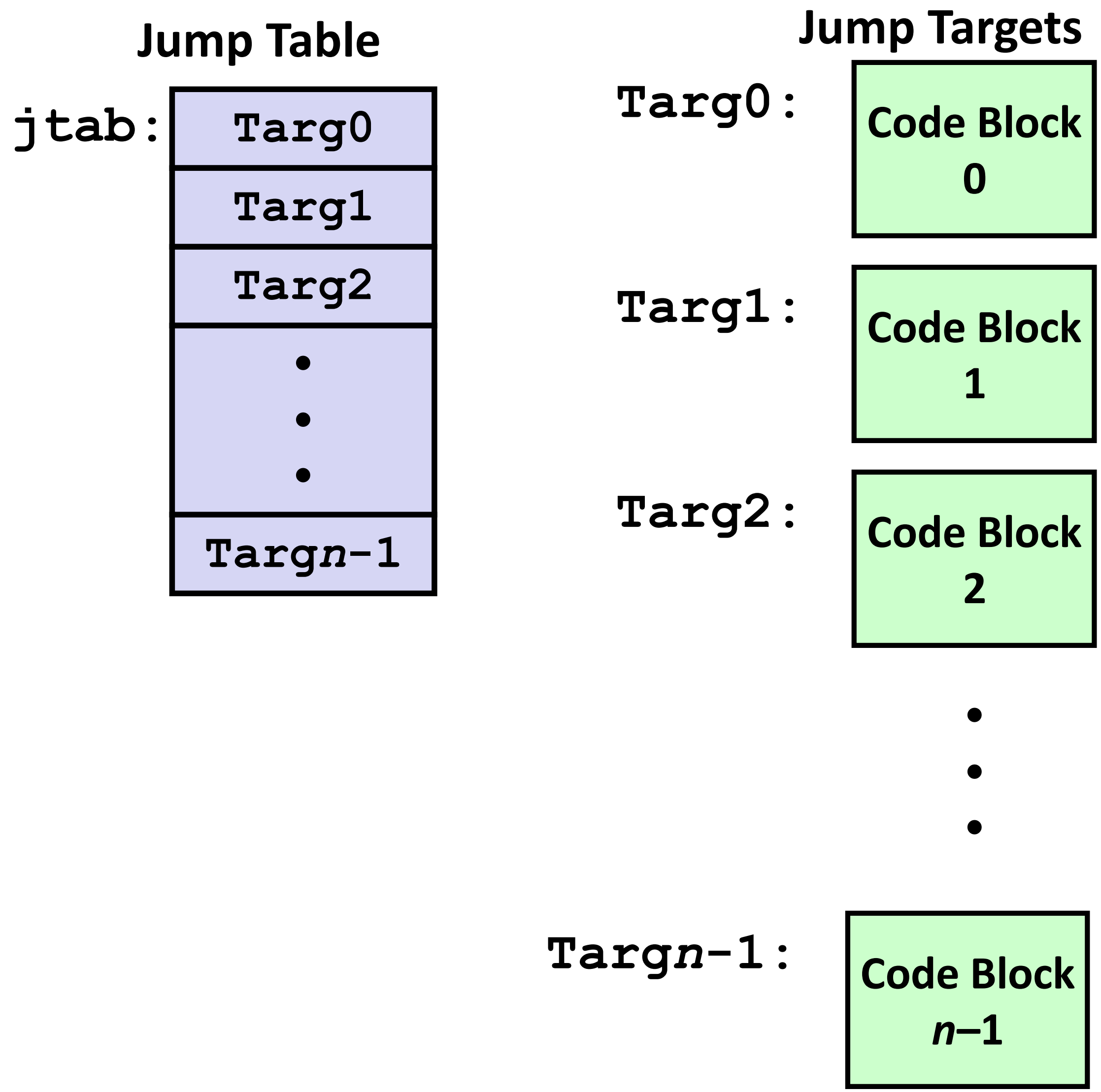
Jump Table Structure

Switch Form

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

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 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 (if-elseif-elseif-else)

Summary

- **Today**
  - Control: Condition codes
  - Conditional branches & conditional moves
  - Loops
  - Switch statements
- **Next Time**
  - Stack
  - Call / return
  - Procedure call discipline