Machine-Level Programming II

Lecture 5

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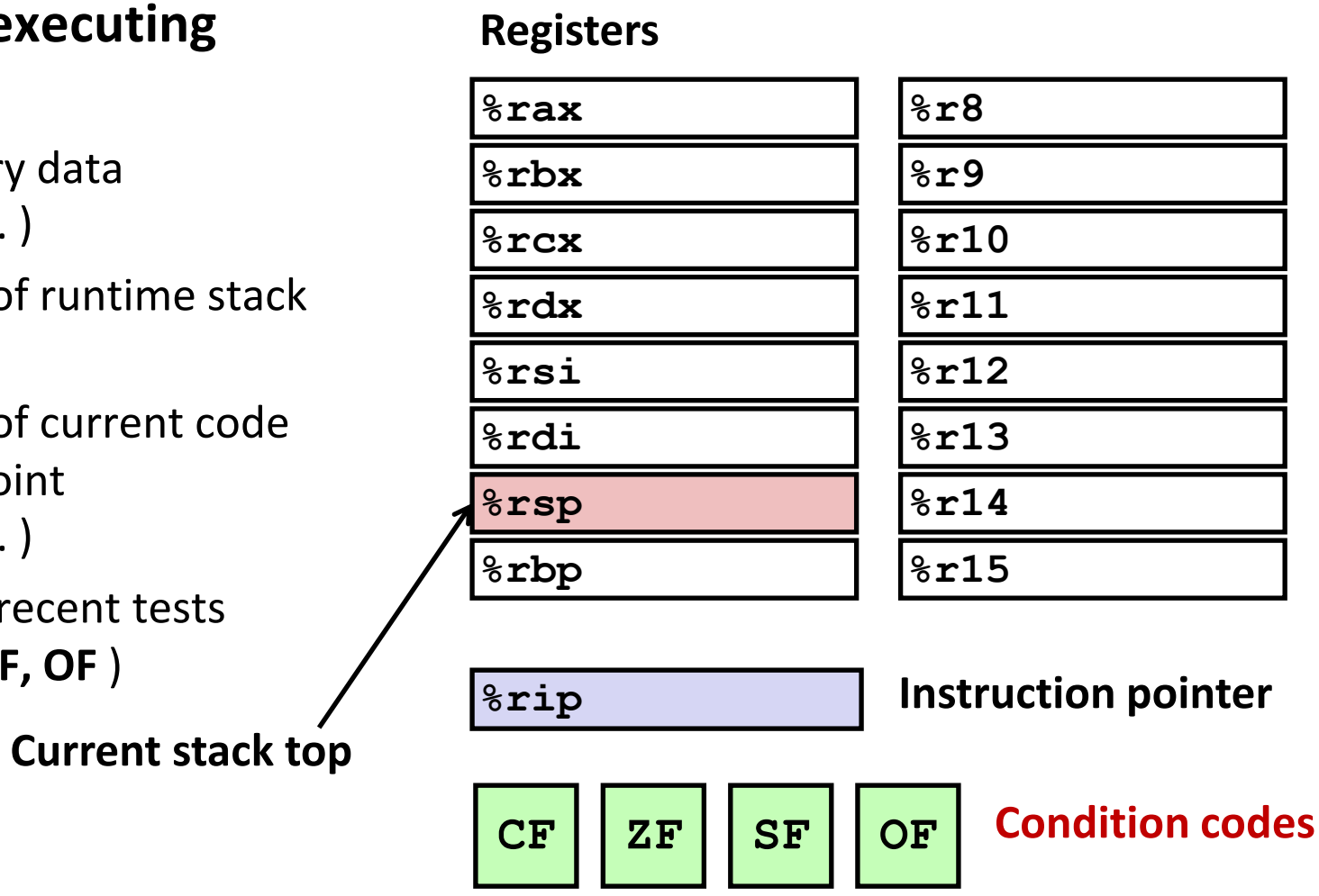
Today

- **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 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 (think of it as 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**

Condition Codes (Explicit Setting: Compare)

- **Explicit Setting by Compare Instruction**
  - **`cmpq`** *Src2*, *Src1*
  - **`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*
    - **`testq b,a`** like computing **`a&b`** without setting destination
  - Sets condition codes based on value of *Src1* & *Src2*
  - Useful to have one of the operands be a mask
  - **ZF set** when **`a&b == 0`**
  - **SF set** when **`a&b < 0`**

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)

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
```

Today

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

Jumping

- **jX Instructions**
  - Jump to different part of code depending on condition codes
    - update IP

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

C Code

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

Goto Version

```
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;
}
```

Conditional Branch Example

```
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
```

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

Conditional Move Example

C Code

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

Non-Goto Version

```
long absdiff_j
   (long x, long y)
{
      long result = x-y;
      long eval = y-x;
      int ntest = x <= y;
      if (ntest) result = eval;
      return result;
}
```

- **Conditional Move Instructions**
  - Instruction supports: if (Test) Dest ← Src
  - GCC tries to use them only when known to be safe
- **Why?**
  - Branches are very disruptive to instruction flow through pipelines
  - Conditional moves do not require control transfer

Conditional Move Example

```
long absdiff_j
   (long x, long y)
{
     long result = x-y;
     long eval = y-x;
     int ntest = x <= y;
     if (ntest) result = eval;
     return result;
}
```

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

```
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

Risky Computations

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

- Both values get computed
- May have undesirable effects

Computations with side effects

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

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

Today

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

“Do-While” Translation

C Code

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

Goto Version

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

- **Body:**

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

“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
```

“While” Translation #1: Jump-to-Middle

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

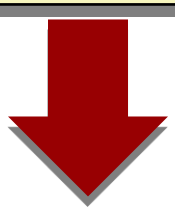
```
long pcount_goto_jtm
   (unsigned long x) {
   long result = 0;
   goto test;
 loop:
   result += x & 0x1;
   x >>= 1;
 test:
   if(x) goto loop;
   return result;
}
```

- Avoid a redundant check unlike the Do-while conversion
- Avoid the execution of a (expensive) conditional jump when the loop condition is unsatisfied initially

General "While" Translation #2: Do-while

While version

```
while (Test)
  Body
```



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:
```

- Insert a guard if for initial test

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;
}
```

- Reduce two jumps when the loop condition is satisfied initially
- The guard if can be optimized away if the compiler assures the loop condition is satisfied initially

“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;
}
```

Today

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

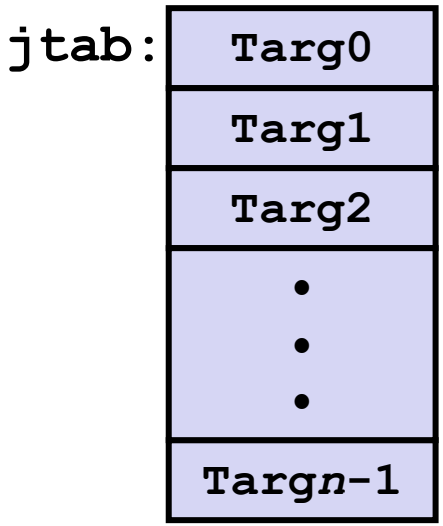
Switch Form

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

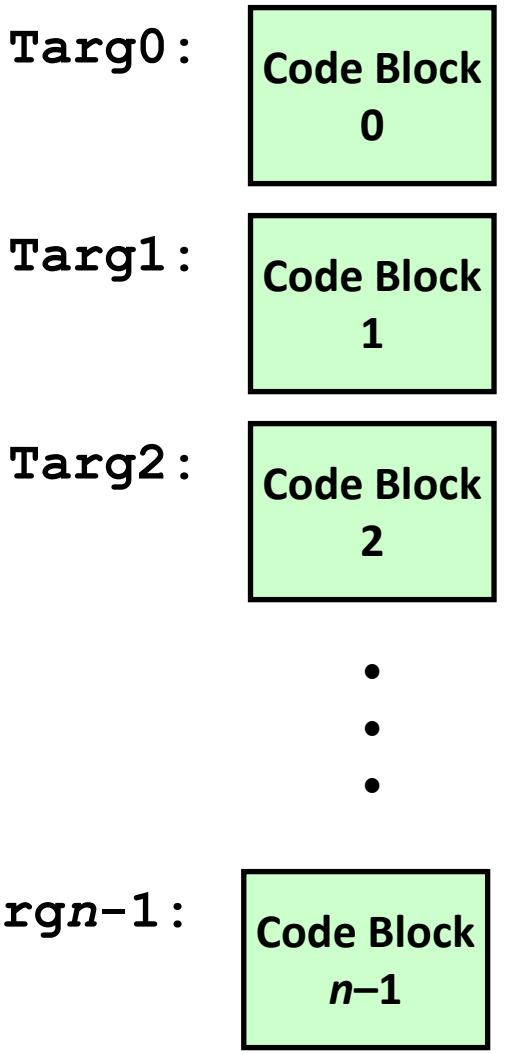
Translation (Extended C)

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

Jump Table



Jump Targets



Switch Statement Example

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

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

Note that **w** not initialized here (some cases may overwrite **w**)

Setup:

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

Indirect jump

jump to default

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
```

Assembly Setup Explanation

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

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
```

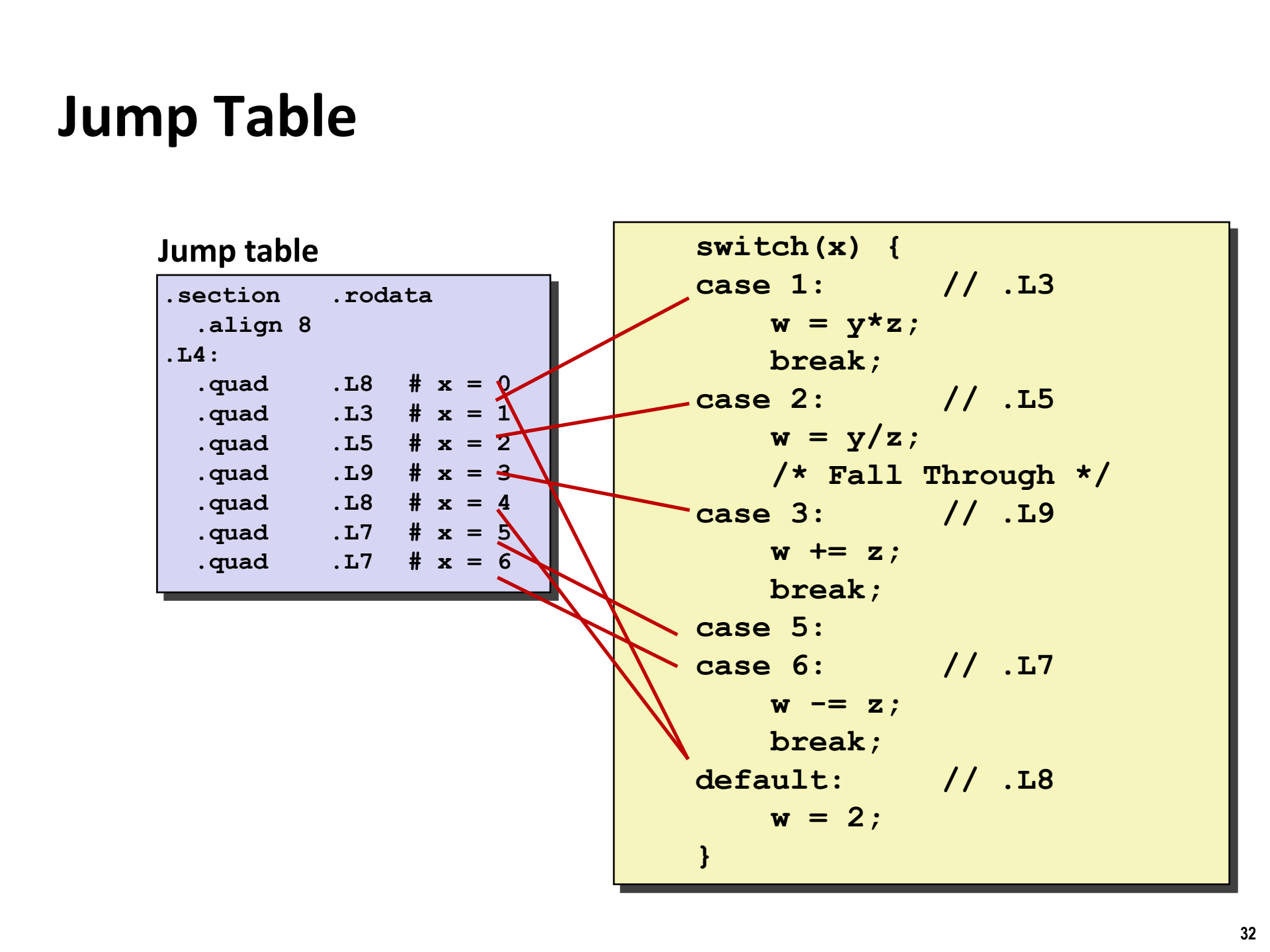
- **Jumping**
  - **Direct:** **`jmp .L8`**
    - Jump target is denoted by label **`.L8`**
  - **Indirect:** **`jmp *.L4(,%rdi,8)`**
    - Start of jump table: **`.L4`**
  - Must scale by factor of 8 (addresses are 8 bytes)
  - Fetch target from effective Address **`.L4 + x*8`**
    - Only for $0 \le \mathbf{x} \le 6$

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;
    }
```



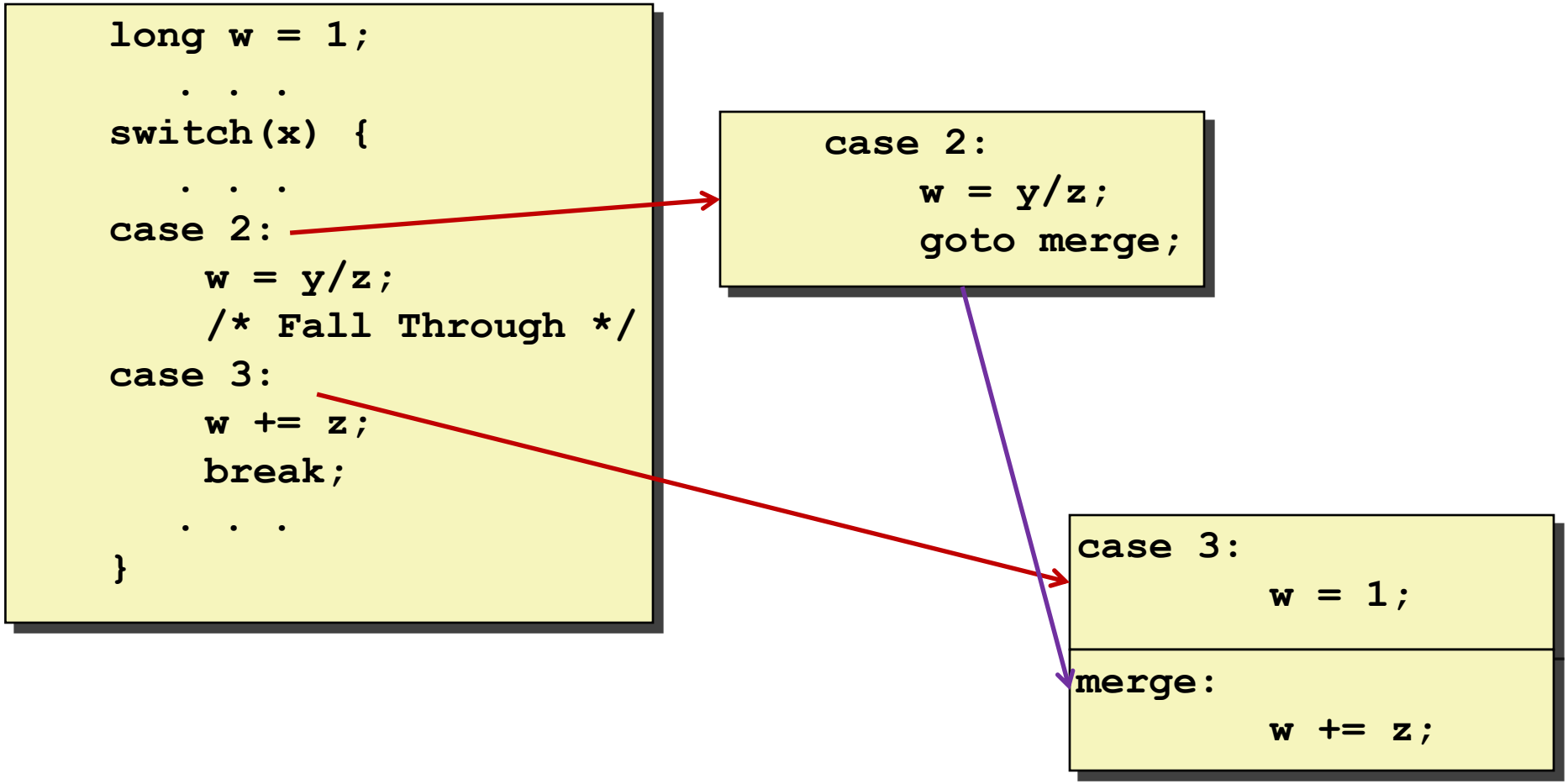
Code Blocks (x == 1)

```
  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



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

Sparse switch statement

- **Jump table-based implementation may be more efficient than if-elseif based one by reducing comparisons**
- **However, it is only true when targets are contiguous.**
  - In the following example, compiler can generate a jump table in a way of subtracting 100 from the variable x.

```
int div111(int x)
{
 switch(x) {
 case 101: return 1;
 case 102: return 2;
 case 103: return 3;
 case 104: return 4;
 case 105: return 5;
 case 106: return 6;
 case 107: return 7;
 case 108: return 8;
 default: return -1;
 }
}
```

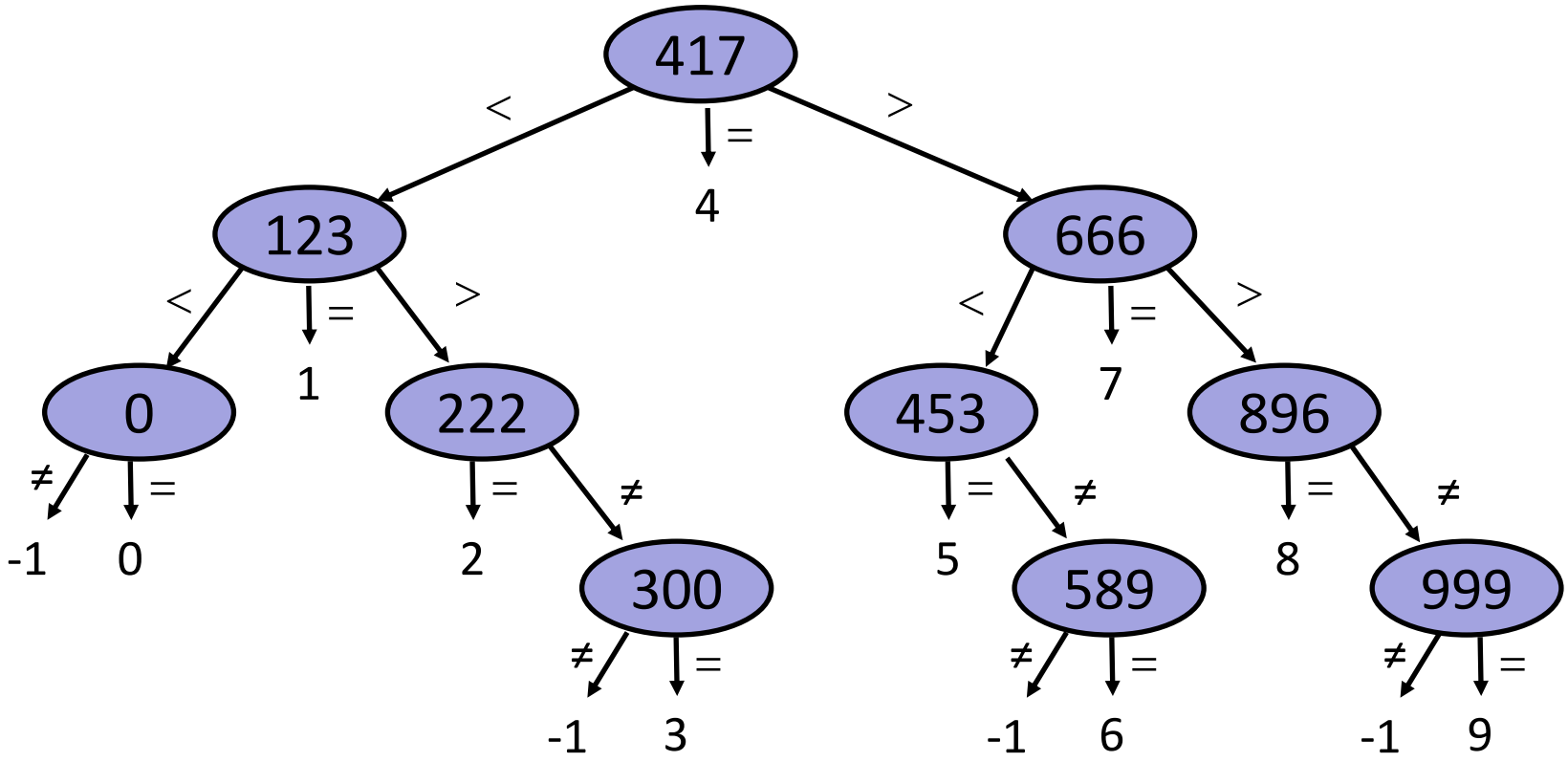
Sparse switch statement

- However, jump-table based implementation will be inefficient when targets are sparse
- In the example, more than 990 entries will be associated with the default case
  - bloated jump table
- If-elseif based implementation needs 9 tests

```
int div111(int x)
{
 switch(x) {
 case 0: return 0;
 case 123: return 1;
 case 222: return 2;
 case 300: return 3;
 case 417: return 4;
 case 453: return 5;
 case 589: return 6;
 case 666: return 7;
 case 896: return 8;
 case 999: return 9;
 default: return -1;
 }
}
```

Better approach: decision tree

- **Fine the case that matches x using binary search**
  - cut down comparisons in a logarithmic scale



Better approach: decision tree

```
cmpq $417,%rdi # Compare to 444
je .L8
jg .L16
cmpq $123,% rdi # Compare to 111
je .L5
jg .L17
testq %rdi,%rdi # Compare to 0
je .L4
jmp .L14
...
```

```
 ...
.L5:
  movl $1,%eax
  jmp .L19
.L6:
  movl $2,%eax
  jmp .L19
.L7:
  movl $3,%eax
  jmp .L19
.L8:
  movl $4,%eax
  jmp
```

Summarizing

- **C Control**
  - if-then-else
  - do-while
  - while, for
  - switch
- **Assembler Control**
  - Conditional jump
  - Conditional move
  - Indirect jump (via jump tables)
- **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)