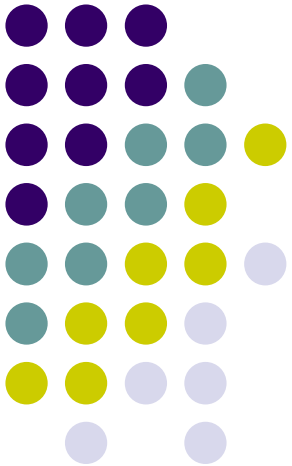
System Programming

07. Machine-Level Programming II: Control (ch 3.6)



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These slides are based on your text book on the slides prepared by Dan Grossman, Ruth Anderson.

Roadmap

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

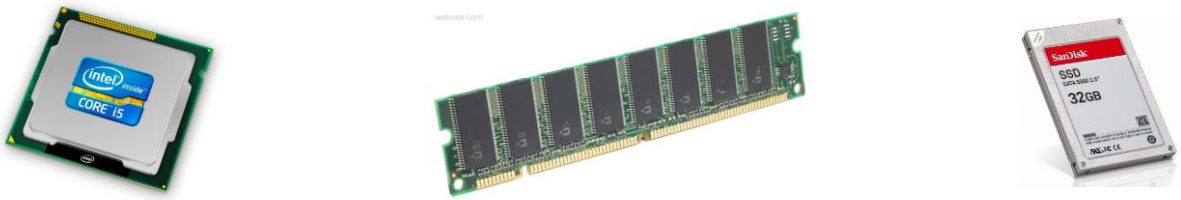
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
10001101000010000000010
1000100111000010
11000001111101000011111
```

OS:

Computer system:



Review

- 3 ways to set condition codes are:
- 2 ways to use condition code are:
- Does leaq set condition codes?

The `leaq` Instruction

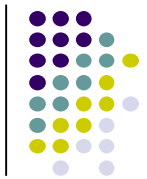
- "lea" stands for *load effective address*
  - Example: **`leaq (%rdx,%rcx,4), %rax`**

Does the `leaq` instruction go to memory?

NO

"`leaq` – it just does math"

Topics: control flow



- Condition codes
- Conditional and unconditional branches
- **Loops**
- Switches

Compiling Loops (1)

C/Java code:

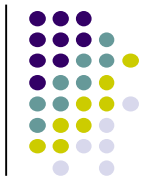
```
while ( sum != 0 ) {
    <loop body>
}
```

Assembly code:

```
loopTop:    testq %rax, %rax
            je    loopDone
            <loop body code>
            jmp   loopTop
loopDone:
```

- Other loops compiled similarly
  - Will show variations and complications in coming slides, but may skip a few examples in the interest of time
- Most important to consider:
  - When should conditionals be evaluated? (*while* vs. *do-while*)
  - How much jumping is involved?

Compiling Loops (2)



C/Java code:

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

Goto version

```
Loop: if ( !Test )  goto Exit;
      Body
      goto Loop;
Exit:
```

- What are the Goto versions of the following?
  - Do…while: Test and Body
  - For loop: Init, Test, Update, and Body

do { Body } while (Test);

for (Init; Test; Update) { Body }

Do…while

```
Loop:
      Body
      if ( Test )  goto Loop;
```

For Loop

```
      Init
Loop: if (~Test) goto Exit;
      Body
      Update
      goto Loop;
Exit:
```

Compiling Loops (3)

While Loop:

C:

```
while ( sum != 0 ) {
    <loop body>
}
```

x86-64:

```
loopTop:    testq %rax, %rax
            je    loopDone
            <loop body code>
            jmp   loopTop
loopDone:
```

Do-while Loop:

C:

```
do {
    <loop body>
} while ( sum != 0 )
```

x86-64:

```
loopTop:
            <loop body code>
            testq  %rax, %rax
            jne    loopTop
loopDone:
```

While Loop (ver. 2):

C:

```
while ( sum != 0 ) {
    <loop body>
}
```

x86-64:

```
            testq %rax, %rax
            je    loopDone
loopTop:
            <loop body code>
            testq %rax, %rax
            jne   loopTop
loopDone:
```

“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 Loop Translation

C Code

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

Goto Version

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

- ***Body:***

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

- ***Test* returns integer**

  = 0 interpreted as false

  ≠ 0 interpreted as true

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 – Translation #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;
}
```

- Used with -Og
- 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 – Translation #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;
}
```

- Used with –O1
- Compare to do-while version of function (one less jump?)
- 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
```

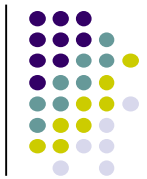
While Version

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

Caveat: C and Java have `break` *and* `continue`

- *Conversion works fine for* `break`
  - *Jump to same label as loop exit condition*
- *But not* `continue`*: would skip doing Update, which it should do with for-loops*
  - *Introduce new label at Update*

For Loop-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;
  if (!(i < WSIZE))
    goto done;
 loop:
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
  }
  i++;
  if (i < WSIZE)
    goto loop;
 done:
  return result;
}
```

Init

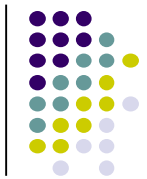
! Test

Body

Update

Test

Topics: control flow



- Condition codes
- Conditional and unconditional branches
- Loops
- **Switches**

```
long switch_ex
    (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

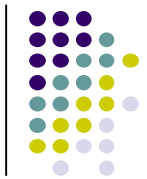
- Multiple case labels
  - Here: 5 & 6
- Fall through cases
  - Here: 2
- Missing cases
  - Here: 4
- How to implement this?

Jump Tables

- Compiles sometimes Implement switch statements with:
  - Jump table
  - Uses the Indirect jump instruction

- Why? When?

Jump Table Structure



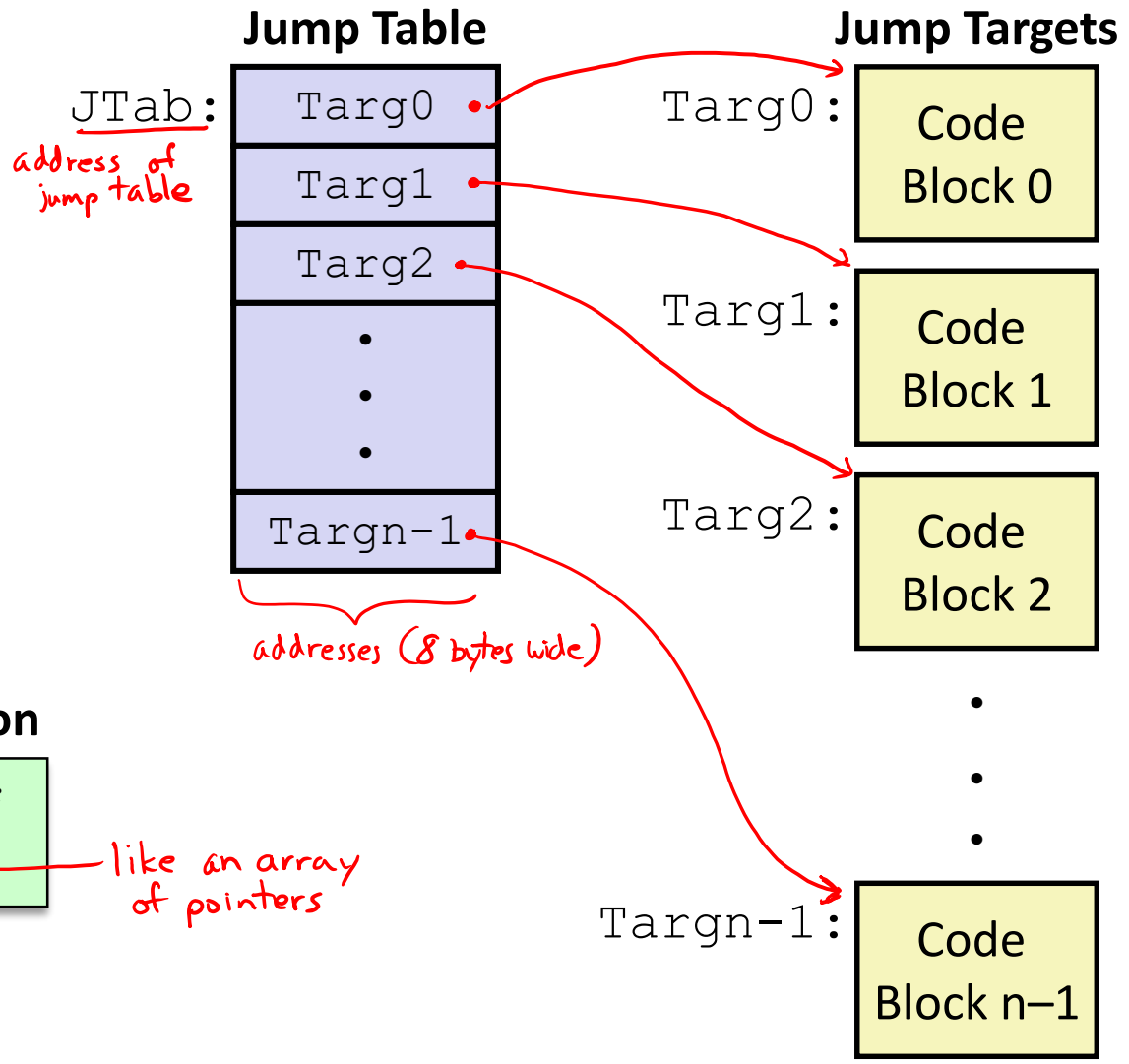
Switch Form

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

Approximate Translation

```
target = JTab[x];
goto target;
```

like an array of pointers



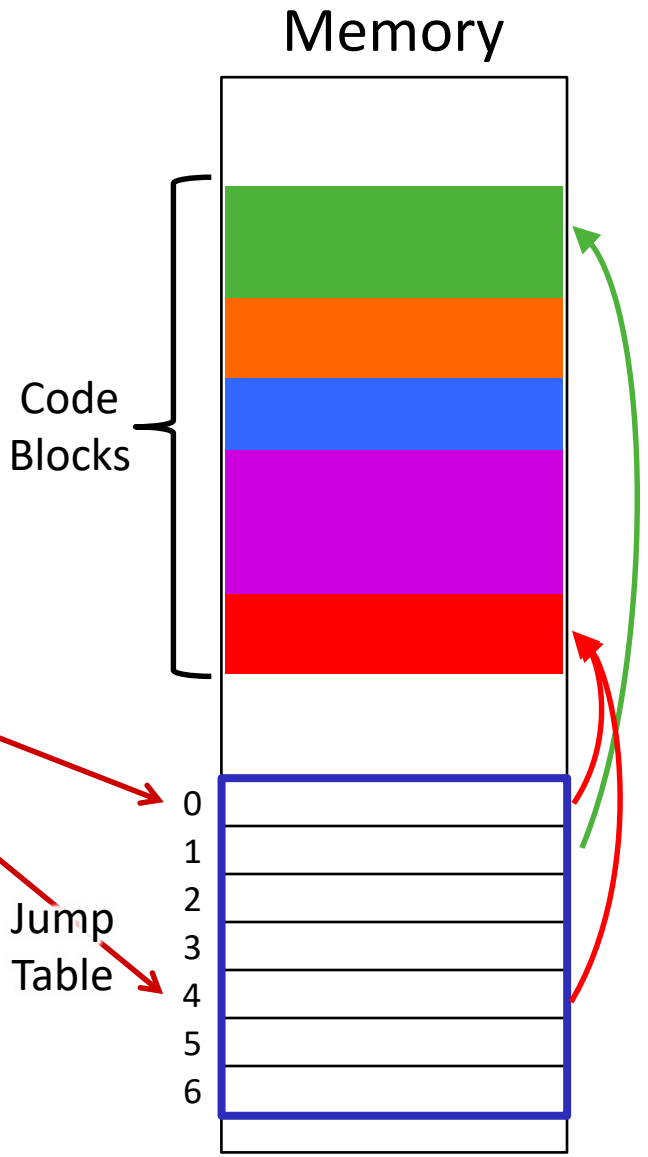
Jump Table Structure

C code:

```
switch (x) {
  case 1: <some code>
          break;
  case 2: <some code>
  case 3: <some code>
          break;
  case 5:
  case 6: <some code>
          break;
  default: <some code>
}
```

Use the jump table when x ≤ 6:

```
if (x <= 6)
  target = JTab[x];
  goto target;
else
  goto default;
```



Switch Statement Example

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

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

Note: compiler chose to not initialize w

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

Take a look!
https://godbolt.org/g/DnOmXb

jump above – unsigned > catches negative default cases

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:

jump above (like jg, but unsigned)

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

Indirect jump

Assembly Setup Explanation

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

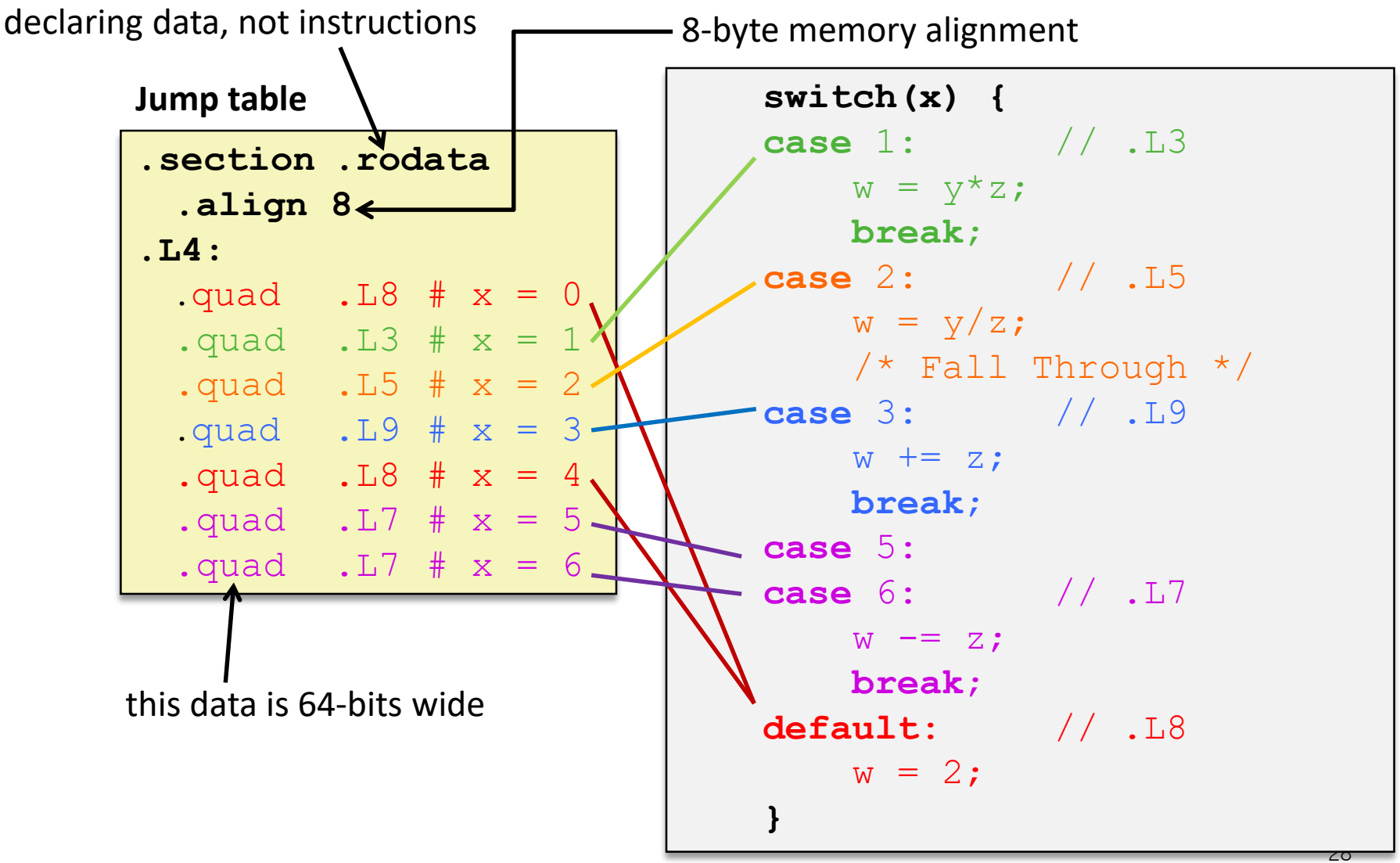
- **Direct jump:** `jmp .L8`
  - Jump target is denoted by label `.L8`

- **Indirect jump:** `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


declaring data, not instructions
8-byte memory alignment
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
this data is 64-bits wide
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;
}

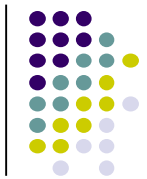
Code Blocks (x == 1)

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

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

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

Handling Fall-Through



```
long w = 1;
    . . .
switch (x) {
    . . .
  case 2:   // .L5
    w = y/z;
  /* Fall Through */
  case 3:   // .L9
    w += z;
    break;
    . . .
}
```

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

```
case 3:
        w = 1;
merge:
        w += z;
```

More complicated choice than "just fall-through" forced by "migration" of `w = 1;`

- *Example compilation trade-off*

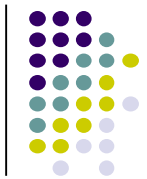
Code Blocks (x == 2, x == 3)

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

```
long w = 1;
    . . .
switch (x) {
    . . .
  case 2:   // .L5
    w = y/z;
  /* Fall Through */
  case 3:   // .L9
    w += z;
    break;
    . . .
}
```

```
.L5:                          # Case 2:
   movq     %rsi, %rax        #  y in rax
   cqto                       #  Div prep
   idivq    %rcx              #  y/z
   jmp      .L6               #  goto merge
.L9:                          # Case 3:
   movl     $1, %eax          #  w = 1
.L6:                          # merge:
   addq     %rcx, %rax        #  w += z
   ret
```

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



Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	Return value

```
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
```

Question

- **Would you implement this with a jump table?**

```
  switch(x) {
    case 0: <some code>
       break;
    case 10: <some code>
       break;
    case 52000: <some code>
       break;
    default: <some code>
       break;
}
```

- **Probably not:**
  - Don't want a jump table with 52001 entries for only 4 cases (too big)
  - about 200KB = 200,000 bytes
  - text of this switch statement = about 200 bytes

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)

Q&A