ILLINOIS TECH

Machine-Level Programming II: Control

CS351: Systems Programming
Day 7: Sep. 13, 2022

Instructor:

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Slides adapted from Bryant and O'Hallaron

Remember to check the course page

Monday	Tuesday	Wednesday	Thursday
Aug 22	Aug 23 **LEC 1:** Introduction **Preparation:** Read CS:APP Chapter 1	Aug 24	Aug 25 **LEC 2:** C and x86_64 toolchains **Preparation:** Read K&R Chapter 1, and work through Ray Toal's NASM tutorial.
Aug 29 **LAB**	Aug 30 **LEC 3:** Bits, Bytes, and Ints: Part 1 **Preparation:** Read CS:APP 2.1 **Assigned:** Lab 1: Preliminaries	Aug 31	Sep 01 **LEC 4:** Bits, Bytes, and Ints: Part 2 **Preparation:** Read CS:APP 2.2-2.3
Sep 05 Labor Day	Sep 06 **LEC 5:** Floating Point **Preparation:** Read CS:APP 2.4	Sep 07	Sep 08 **LEC 6:** Machine Prog: Basics **Preparation:** Read CS:APP 3.1-3.5
Sep 12 **LAB** **DUE:** Lab 1 (Preliminaries)	Sep 13 **LEC 7:** Machine Prog: Control **Preparation:** Read CS:APP 3.6 **Assigned:** Lab 2: Datalab and Data Representations	Sep 14	Sep 15 **LEC 8:** Machine Prog: Procedures **Preparation:** Read CS:APP 3.7

- **See course webpage for:**
  - **New lab assignment.**
  - **Confirm office hours in case there are changes.**
  - **Make sure to carry out the Preparation.**

Questions follow-up

- **What do the different parameters to gcc do?**
  - Use “man gcc”
  - Or “gcc --help” (Note: two dashes)
- **Showcasing assignments on GitHub for job search?**
  - Not much benefit, for the following reasons:
    - Many do this, so it’s hard to stand out with these assignments.
    - Learning-quality code != your best code.
  - Quality > Quantity: One interesting self-motivated or open-source project contribution > 10 lab assignments.
  - Where to start? Some ideas:
    - https://hacktoberfest.com/
    - https://summerofcode.withgoogle.com/ (Note CoI)
    - Look around the Web for more, let me know what you find!

Questions follow-up

- **What if we need more lab sessions to complete a lab?**
  - Work on the lab assignment outside of the "lab"!
  - Reach out to your TA – many students do this on Discord.

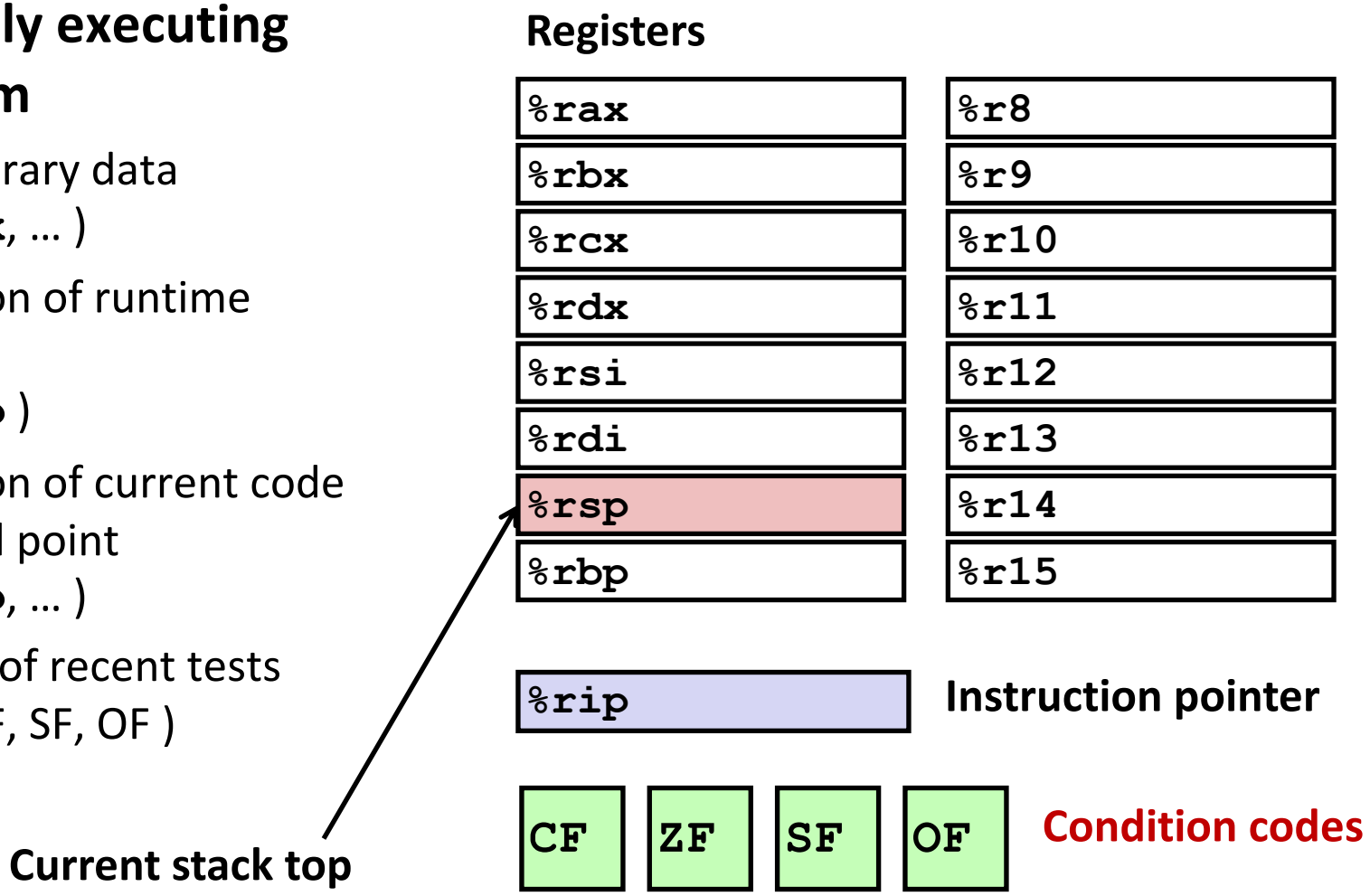
- **What if we've finished the lab early?**
  - (Labs are timed to avoid overlapping assignments; some students need the last "Monday" to finish the lab if they're very stuck.)
  - Do the exercises in the CS:APP3e book and ask your TA if stuck.
  - Practice C – do the exercises in the K&R book!
  - See resources on the course webpage, in particular: https://missing.csail.mit.edu/
  - Continue reading CS:APP3e book, advanced preparation.
  - Work on "above and beyond" problems.

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 (Implicitly set)

- **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)

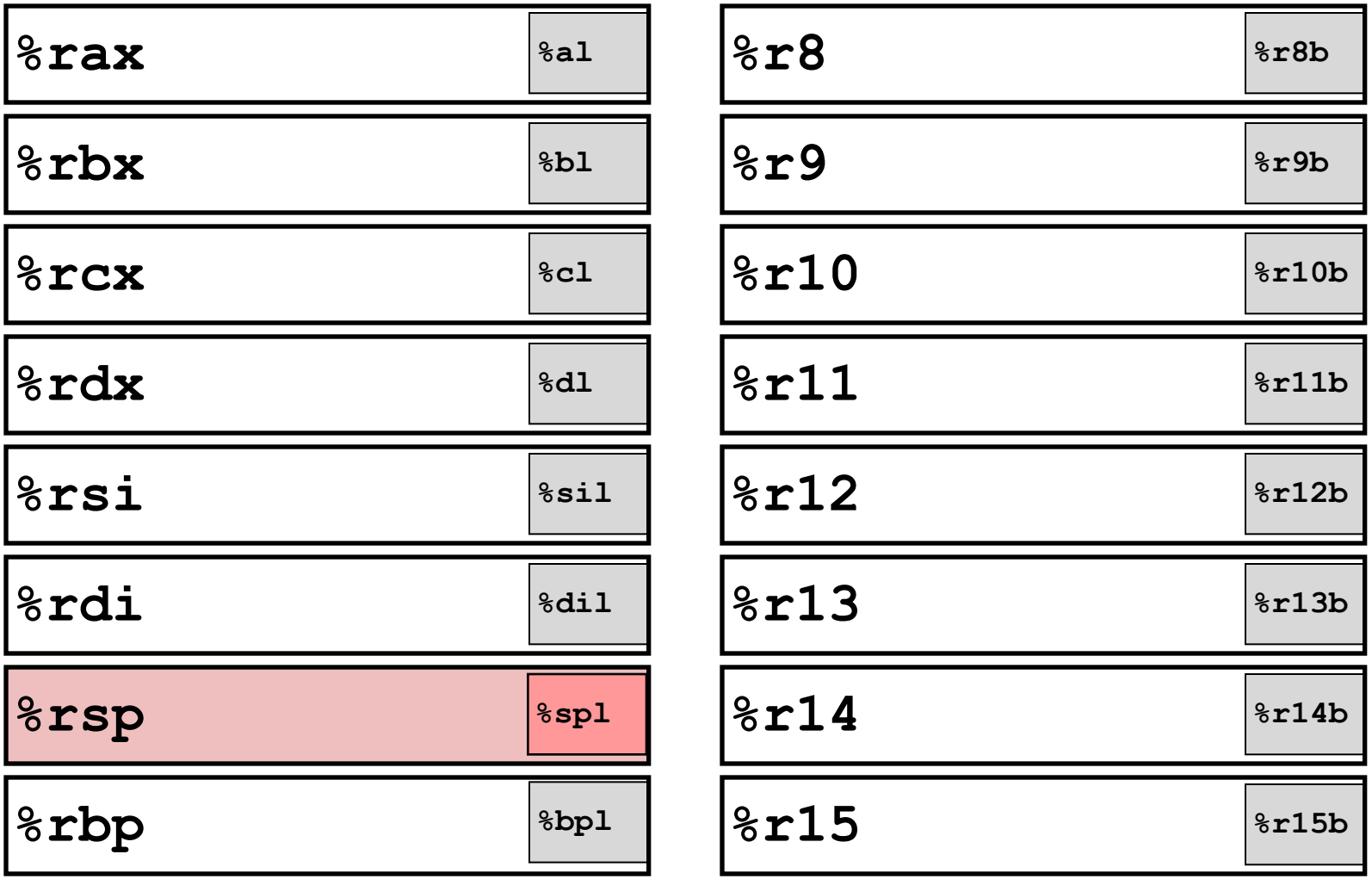
- **Explicit Setting by Test instruction**
  - **`testq`** Src2, Src1
    - **`testq b,a`** like computing **`a&b`** without setting destination
  - Sets condition codes based on value of Src1 & Src2
  - Useful to have one of the operands be a mask
  - ZF set when **`a&b == 0`**
  - SF set when **`a&b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

x86-64 Integer Registers



- 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 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

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

- 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;
}
```

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**

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” 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

From Day 6

```
   movl    $0, %eax    #  result = 0
.L2:                   # loop:
   movq    %rdi, %rdx
   andl    $1, %edx    #  t = x & 0x1
   addq    %rdx, %rax  #  result += t
   shrq    $1, %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

- "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++
```

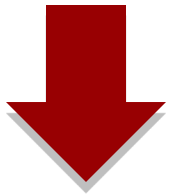
Body

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

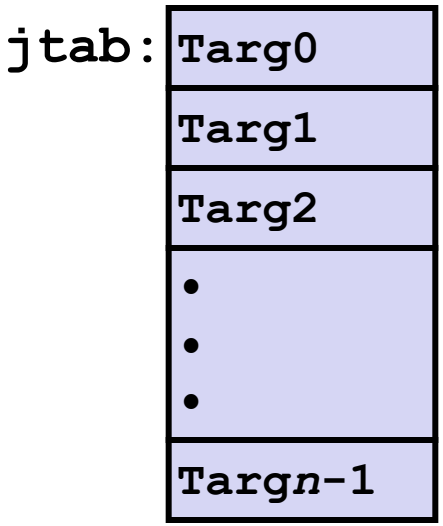
Switch Form

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

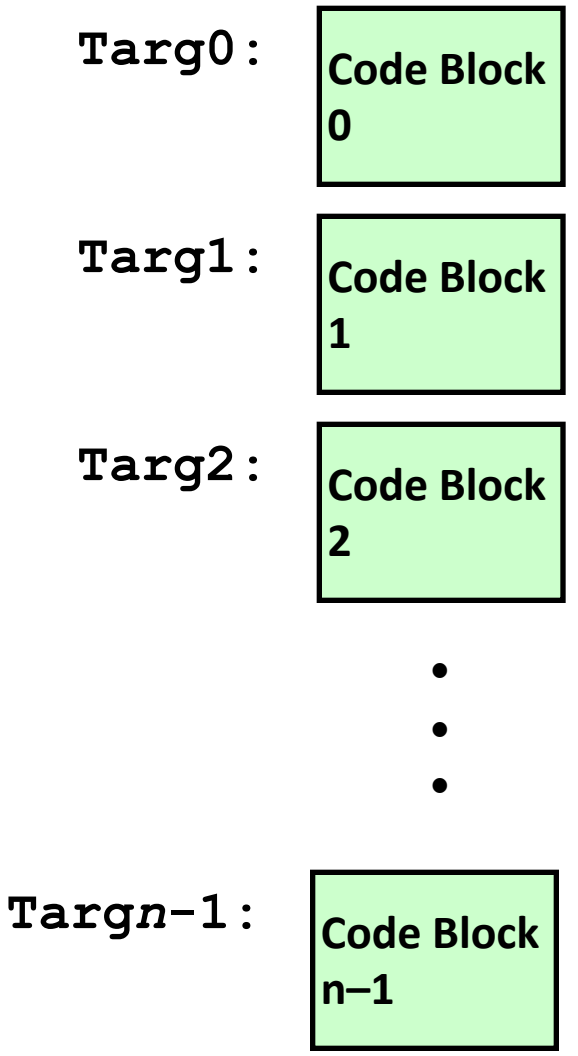
Translation (Extended C)

```
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;
}
```

Setup:

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

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

Note that w not initialized here

What range of values takes default?

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

From Day 6

Assembly Setup Explanation

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

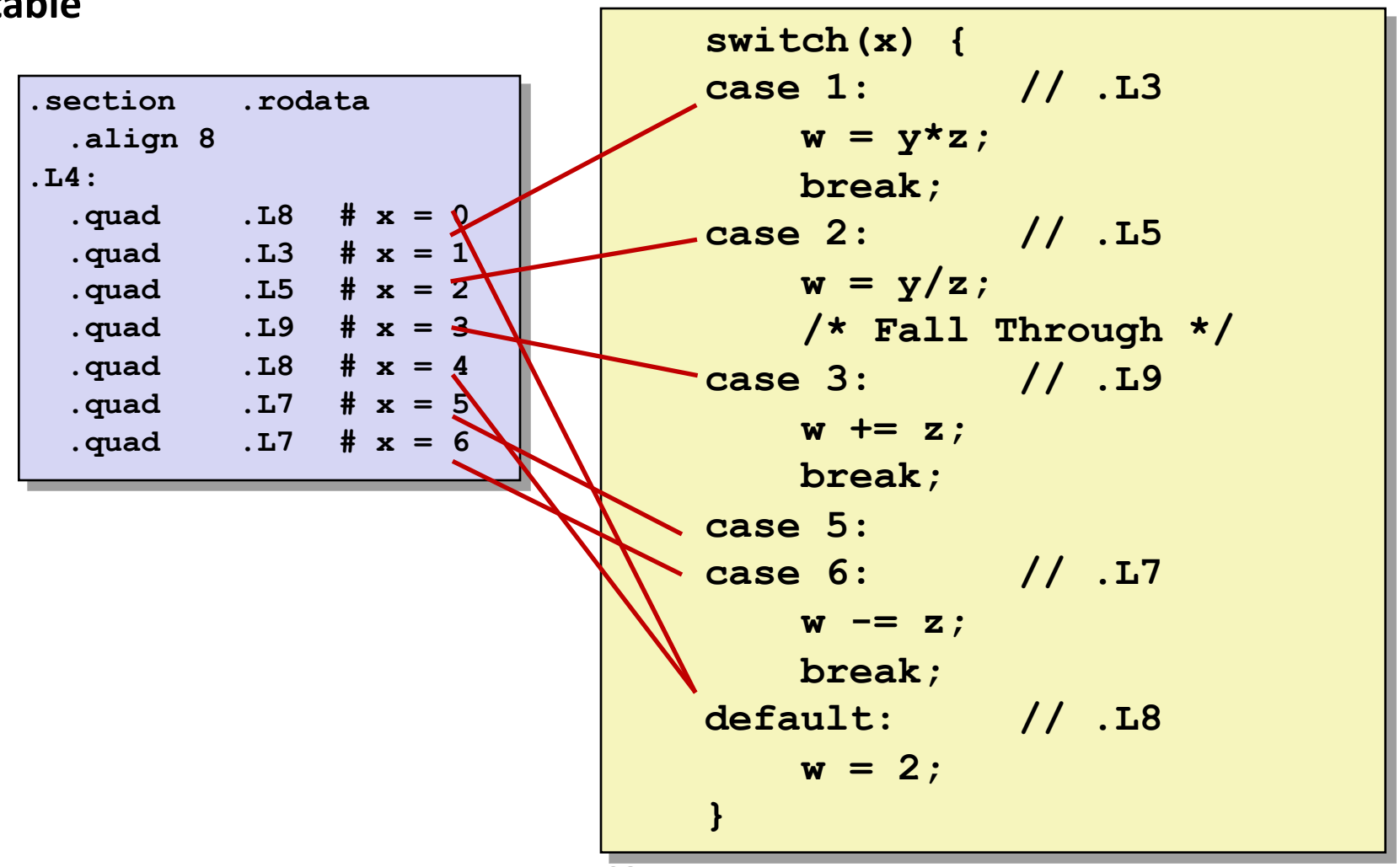
Jump table

```
.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



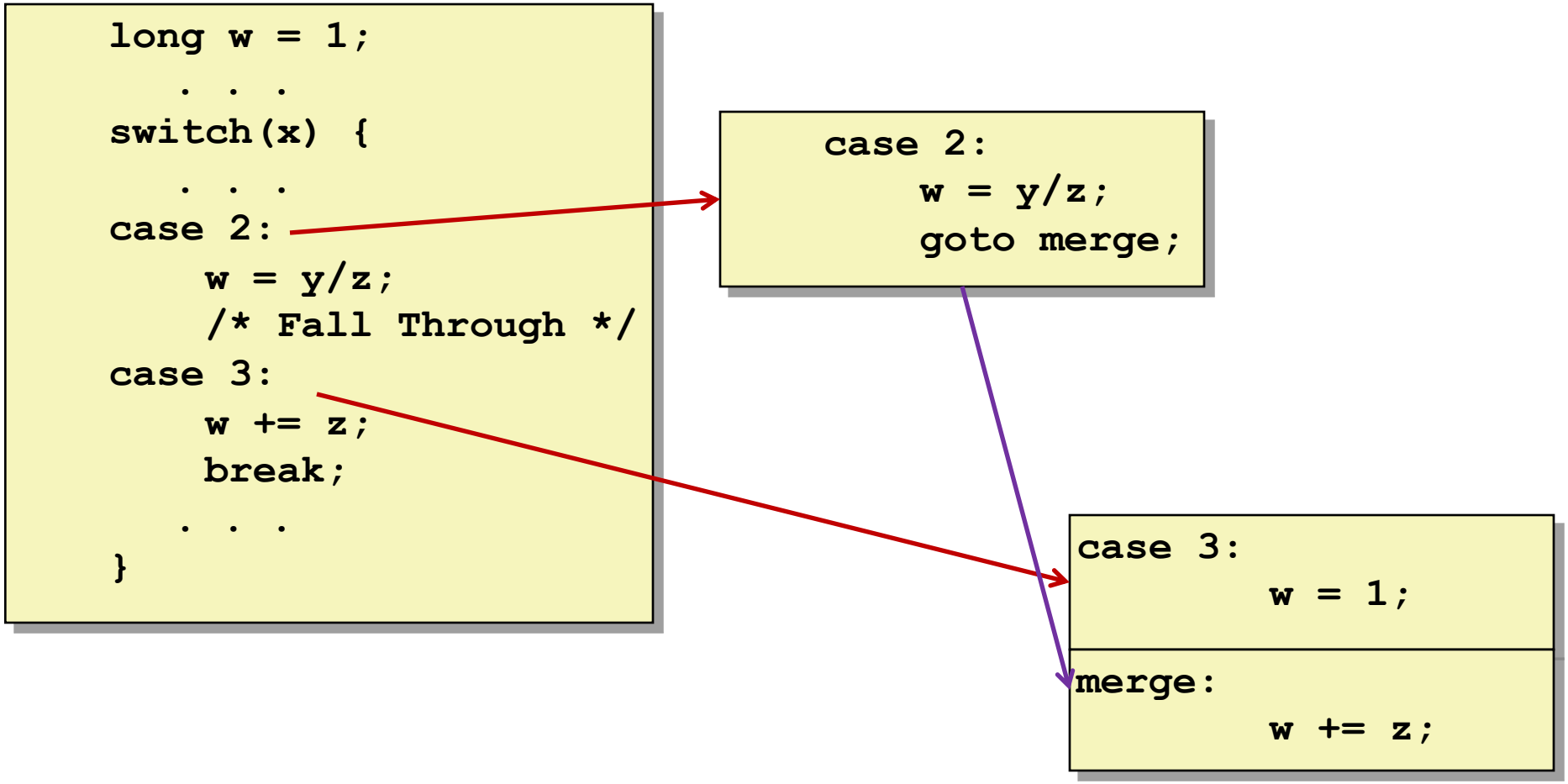
Code Blocks (x == 1)

```
  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;
       . . .
    }
```

Recognize?

```
.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

Per-lecture feedback

- Better sooner rather than later!
- I can help with issues sooner.
- There is a per-lecture feedback form.
- **The form is anonymous.**
  (It checks that you're at Illinois Tech to filter abuse, but I don't see who submitted any of the forms.)
- https://forms.gle/qoeEbBuTYXo5FiU1A
- I'll remind about this at each lecture.