Machine-Level Programming II: Control

15-213: Introduction to Computer Systems
6th Lecture, May 30, 2019

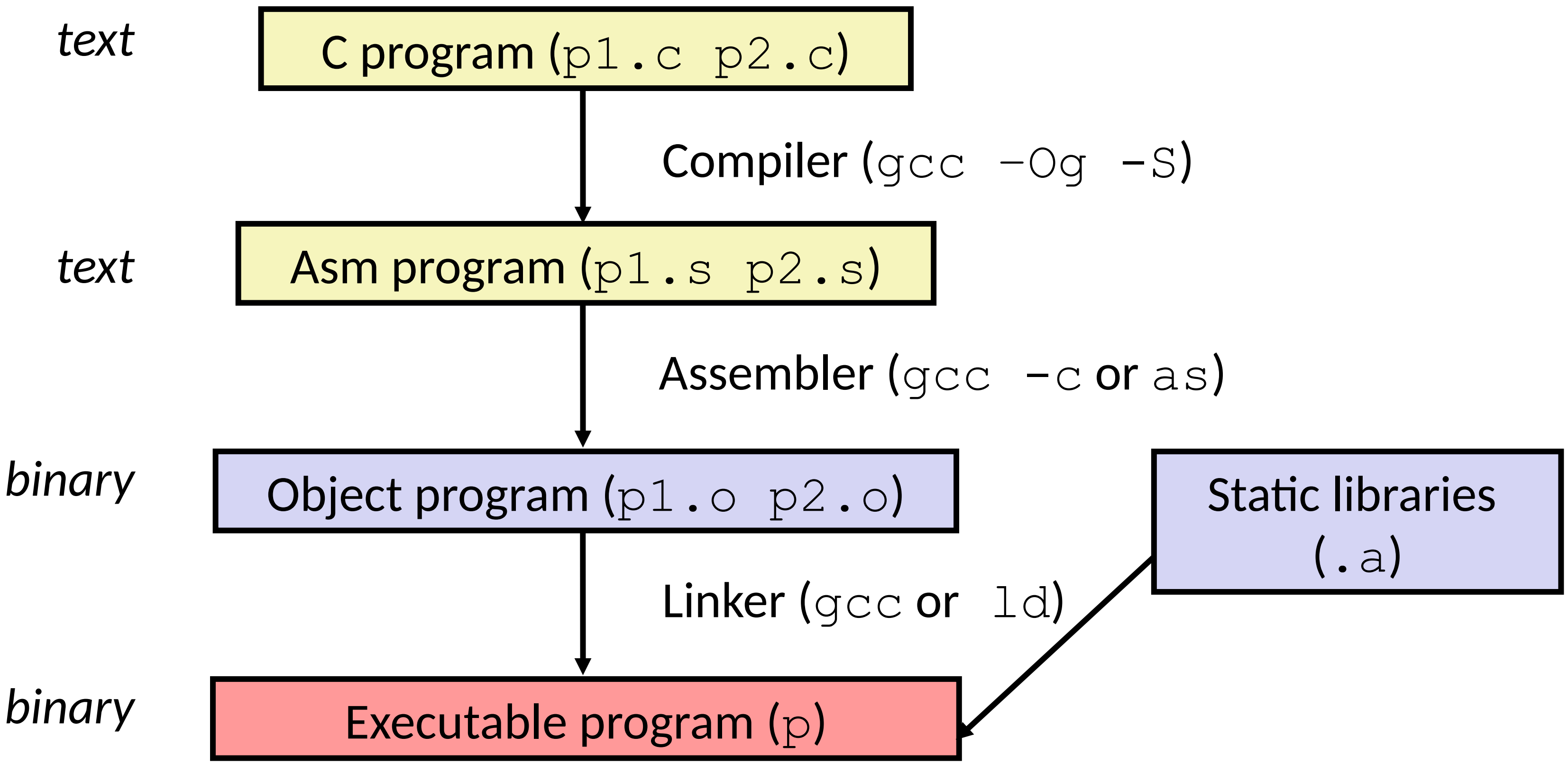
Instructor:
Sol Boucher

Today: Control Flow

- Review
- Unconditional branches
- Condition codes
- Conditional branches
- Structured ifs
- Loops
- Switch Statements

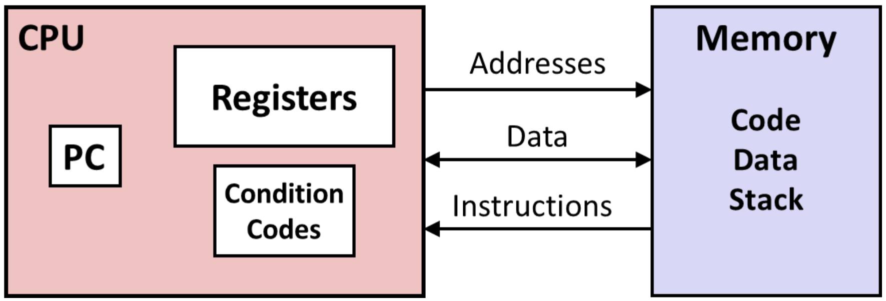
Review: Turning C into Object Code

- Code in files **`p1.c p2.c`**
- Compile with command: **`gcc –Og p1.c p2.c -o p`**
  - Use basic optimizations (**`-Og`**) [New to recent versions of GCC]
  - Put resulting binary in file **`p`**

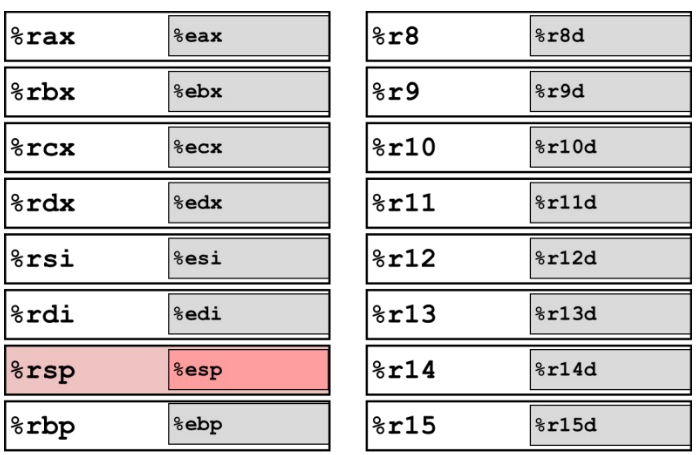


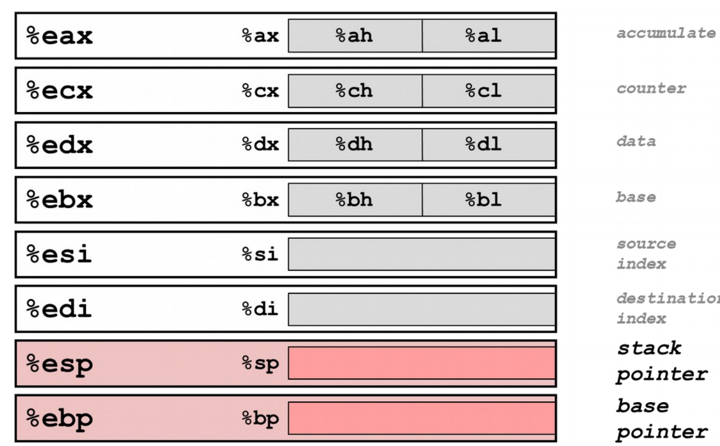
Review: x86-64 Architecture

Abstract view



X86-64 Integer Register File





Review: Address Modes

- **Most General Form**

  D(Rb,Ri,S) Mem[Reg[Rb]+S*Reg[Ri]+ D]

  - D: Constant "displacement" 1, 2, or 4 bytes
    - 0 if omitted
  - Rb: Base register: Any of 16 integer registers
    - to omit, use constant address form: **D Mem[D]**
  - Ri: Index register: Any, except for **`%rsp`**
    - 0 if omitted
  - S: Scale: 1, 2, 4, or 8 (*why these numbers?*)
    - 1 if omitted

Today: Control Flow

- Review
- Unconditional branches
- Condition codes
- Conditional branches
- Structured ifs
- Loops
- Switch Statements

Control Flow

The order in which a set of program instructions are executed.

Linear Control Flow

C Declaration

```
int expr(int d, int s);
```

Assembly Implementation

```
# expr(%edi, %esi) -> %eax
expr:
   xorl  %eax, %eax
   addl  %edi, %eax
   addl  %esi, %eax
   imull %esi, %eax
   ret
```

What algebraic expression does this function compute?

$$(d + s) * s$$

How does the CPU find the next instruction to execute?

`%rip`

Unconditional Branches

C Declaration

```
int expr(int d, int s);
```

Assembly Implementation

```
# expr(%edi, %esi) -> %eax
expr:
  xorl   %eax, %eax
  jmp    .Limul
.Ladd:
  addl   %edi, %eax
  jmp    .Lret
.Limul:
  addl   %esi, %eax
  imull  %esi, %eax
  jmp    .Ladd
.Lret:
  ret
```

What algebraic expression does this function compute?

$\cancel{(d + s) * s}$

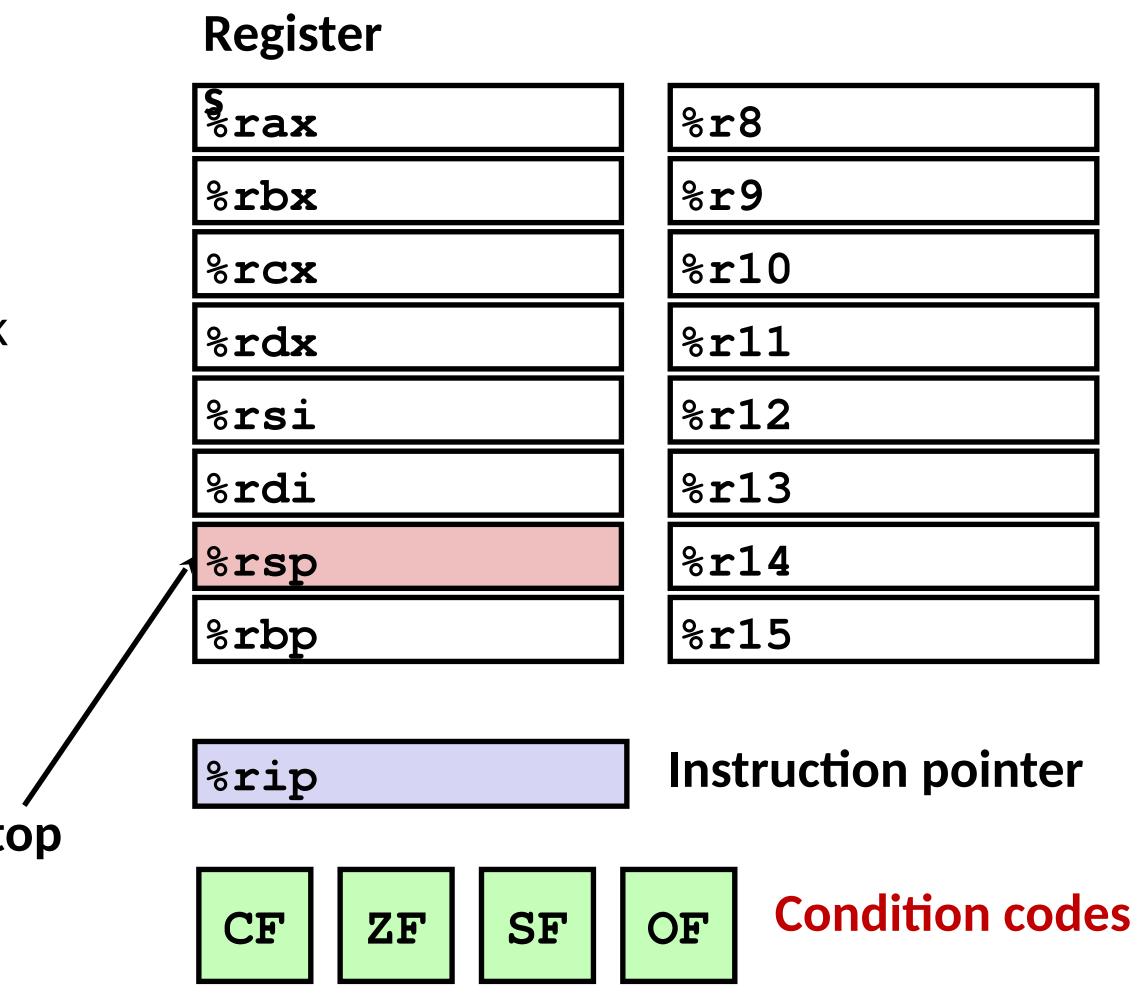
$d + (s * s)$

Today: Control Flow

- Review
- Unconditional branches
- Condition codes
- Conditional branches
- Structured ifs
- 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**
  - **ZF** Zero Flag
  - **CF** Carry Flag (for unsigned)
  - **SF** Sign Flag (for signed)
  - **OF** Overflow Flag (for signed)

- **Implicitly set (as side effect) of arithmetic operations**

  Example: **`addq`** *Src*,*Dest* ↔ **`t = a+b`**

  ZF set if **`t == 0`**

  SF set if **`t < 0`** (as signed)

  CF set if carry out from most significant bit (unsigned overflow)

  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

```
  yxxxxxxxxxxxx...
+ yxxxxxxxxxxxx...
------------------
  1xxxxxxxxxxxx...
```

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

CF set when

```
   1xxxxxxxxxxxxx...
+  1xxxxxxxxxxxxx...
--------------------
1  xxxxxxxxxxxxxx...
```

Carry

```
1  0xxxxxxxxxxxxx...
–  1xxxxxxxxxxxxx...
--------------------
   1xxxxxxxxxxxxx...
```

Borrow

For unsigned arithmetic, this reports overflow

OF set when

```
  yxxxxxxxxxxxx...    a
+ yxxxxxxxxxxxx...    b
---------------------
  zxxxxxxxxxxxx...    t
```

$$z = \sim y$$

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

For signed arithmetic, this reports overflow

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`**

Very often:

```
testq   %rax,%rax
```

Condition Codes (Explicit Setting: Compare)

- **Explicit Setting by Compare Instruction**
  - `cmpq` *Src2*, *Src1*
  - `cmpq b,a` like computing `a-b` without setting destination

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

Today: Control Flow

- Review
- Unconditional branches
- Condition codes
- Conditional branches
- Structured ifs
- Loops
- Switch Statements

Jumping

jX Instructions

- Jump to different part of code depending on condition codes

jX	Condition	Description
`jmp`	`1`	Unconditional
`je (jz)`	`ZF`	Equal / Zero
`jne (jnz)`	`~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)

Reading Condition Codes

Activity: `r` 5 ONLY!

SetX Instructions

- Set low-order byte of destination to 0 or 1 from current 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`

- 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;
}
```

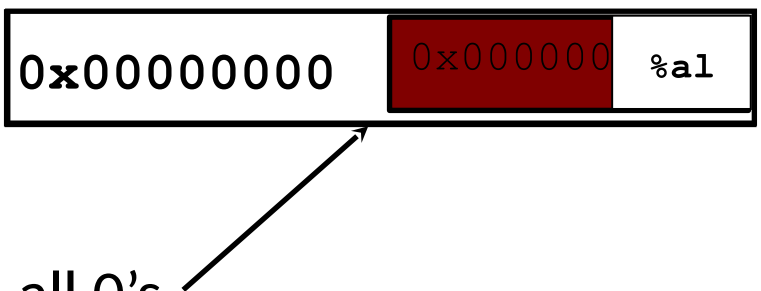
Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rax`	Return value

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

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
```

Today: Control Flow

- Review
- Unconditional branches
- Condition codes
- Conditional branches
- **Structured ifs**
- Loops
- Switch Statements

Conditional Branch Example (Old Style)

No CMOVs
(see appendix)

- Generation

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

```
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

Conditional Branch Example (Old Style)

Generation

```
shark> 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

Activity: do the rest, starting from r 6

Today: Control Flow

- Review
- Unconditional branches
- Condition codes
- Conditional branches
- Structured ifs
- **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

- "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;
}
```

Goto Version

```
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;
}
```

- Initial test can be optimized away

Today: Control Flow

- Review
- Unconditional branches
- Condition codes
- Conditional branches
- Structured ifs
- 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

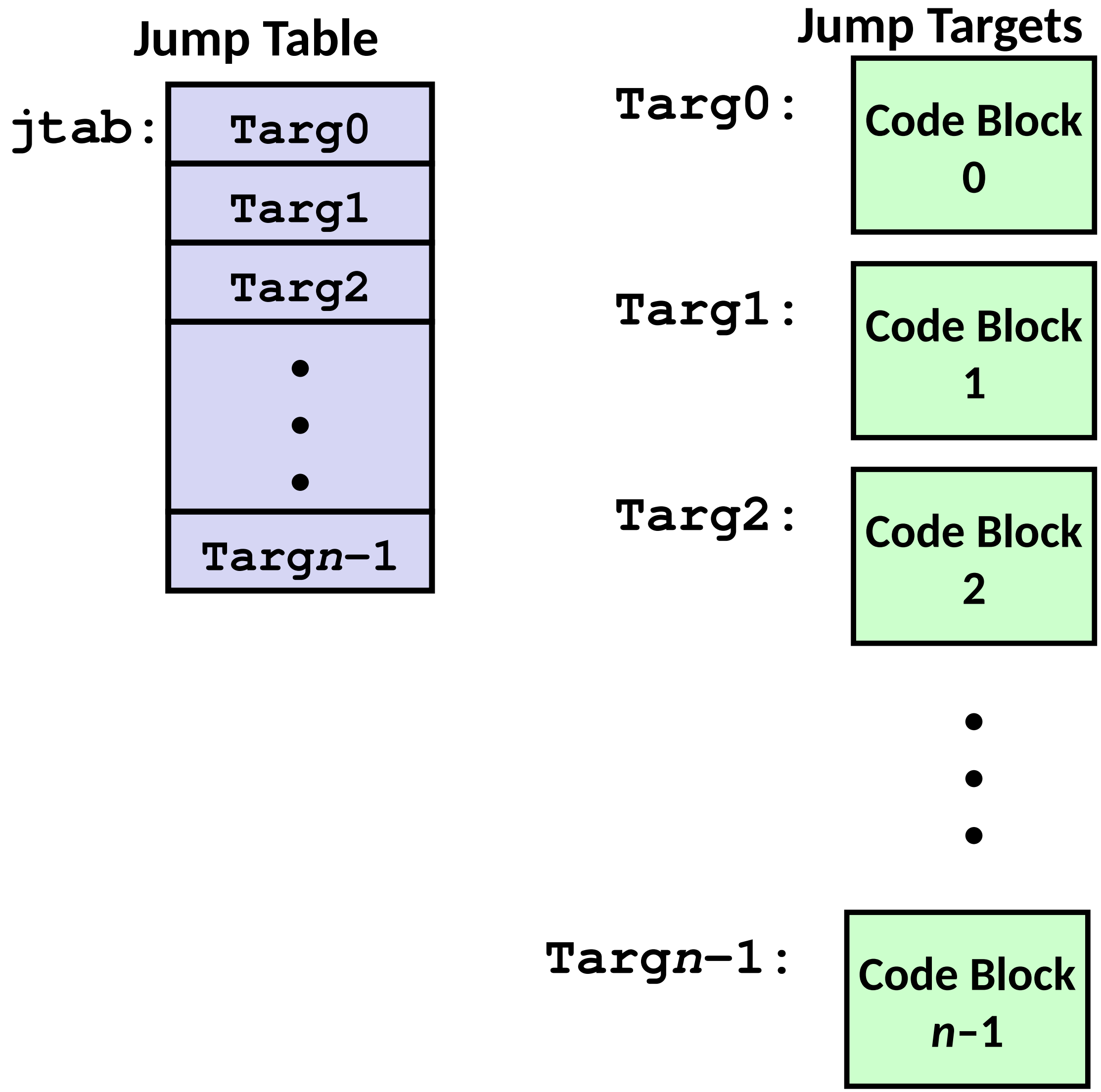
Jump Table Structure

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];
```



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`** ≤ 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

Finding Jump Table in Binary

```
 00000000004005e0 <switch_eg>:
4005e0:       48 89 d1                 mov     %rdx,%rcx
4005e3:       48 83 ff 06              cmp     $0x6,%rdi
4005e7:       77 2b                    ja      400614 <switch_eg+0x34>
4005e9:       ff 24 fd f0 07 40 00     jmpq    *0x4007f0(,%rdi,8)
4005f0:       48 89 f0                 mov     %rsi,%rax
4005f3:       48 0f af c2              imul    %rdx,%rax
4005f7:       c3                       retq
4005f8:       48 89 f0                 mov     %rsi,%rax
4005fb:       48 99                    cqto
4005fd:       48 f7 f9                 idiv    %rcx
400600:       eb 05                    jmp     400607 <switch_eg+0x27>
400602:       b8 01 00 00 00           mov     $0x1,%eax
400607:       48 01 c8                 add     %rcx,%rax
40060a:       c3                       retq
40060b:       b8 01 00 00 00           mov     $0x1,%eax
400610:       48 29 d0                 sub     %rdx,%rax
400613:       c3                       retq
400614:       b8 02 00 00 00           mov     $0x2,%eax
400619:       c3                       retq
```

Finding Jump Table in Binary (cont.)

```
 00000000004005e0 <switch_eg>:
. . .
4005e9:       ff 24 fd f0 07 40 00    jmpq   *0x4007f0(,%rdi,8)
. . .
```

```
 % gdb switch
(gdb) x /8xg 0x4007f0
0x4007f0:       0x0000000000400614      0x00000000004005f0
0x400800:       0x00000000004005f8      0x0000000000400602
0x400810:       0x0000000000400614      0x000000000040060b
0x400820:       0x000000000040060b      0x2c646c25203d2078
(gdb)
```

Finding Jump Table in Binary (cont.)

```
 % gdb switch
(gdb) x /8xg 0x4007f0
0x4007f0:       0x0000000000400614      0x00000000004005f0
0x400800:       0x00000000004005f8      0x0000000000400602
0x400810:       0x0000000000400614      0x000000000040060b
0x400820:       0x000000000040060b      0x2c646c25203d2078
```

```
  . . .
  4005f0:       48 89 f0                mov    %rsi,%rax
  4005f3:       48 0f af c2             imul   %rdx,%rax
  4005f7:       c3                      retq
  4005f8:       48 89 f0                mov    %rsi,%rax
  4005fb:       48 99                   cqto
  4005fd:       48 f7 f9                idiv   %rcx
  400600:       eb 05                   jmp    400607 <switch_eg+0x27>
  400602:       b8 01 00 00 00          mov    $0x1,%eax
  400607:       48 01 c8                add    %rcx,%rax
  40060a:       c3                      retq
  40060b:       b8 01 00 00 00          mov    $0x1,%eax
  400610:       48 29 d0                sub    %rdx,%rax
  400613:       c3                      retq
  400614:       b8 02 00 00 00          mov    $0x2,%eax
  400619:       c3                      retq
```

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 Flow**
  - Branches & condition codes
  - If statements
  - Loops
  - Switch statements
- **Next Time: Functions!**
  - Stack
  - Call / return
  - Procedure call discipline

Appendix

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

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)`

```
xor    %rax, %rax
sub    $1, %rax
cmp    $2, %rax
setl   %al
movzbl %al, %eax
```

`%rax`	SF	CF	OF	ZF

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)`

```
xor    %rax, %rax
sub    $1, %rax
cmp    $2, %rax
setl   %al
movzbl %al, %eax
```

`%rax`	SF	CF	OF	ZF
0x0000 0000 0000 0000	0	0	0	1
0xFFFF FFFF FFFF FFFF	1	1	0	0
0xFFFF FFFF FFFF FFFF	1	0	0	0
0xFFFF FFFF FFFF FF01	1	0	0	0
0x0000 0000 0000 0001	1	0	0	0