
WELCOME
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15-213
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Machine-Level Programming II: Control

15-213/18-213/14-513/15-513/18-613: Introduction to Computer Systems
6th Lecture, February 18, 2021

Announcements

- **Lab 1 (datalab)**
  - Due Thurs, Feb. 18, 11:59pm ET (that’s today!)
- **Written Assignment 1 peer grading**
  - Due Wed, Feb. 24, 11:59pm ET
- **Written Assignment 2 available on Canvas**
  - Due Wed, Feb. 24, 11:59pm ET
- **Lab 2 (bomblab) will be available at midnight via Autolab**
  - Due Tues, March 2, 11:59 pm ET

Recap of Tuesday

- Reviewing LEA (based on after-class questions)
- Reviewing Arithmetic Expressions in ASM
- C -> Assembly -> Machine Code

Memory operands and LEA

- In most instructions, a memory operand accesses memory

Assembly	C equivalent
mov 6(%rbx,%rdi,8), %ax	ax = *(rbx + rdi*8 + 6)
add 6(%rbx,%rdi,8), %ax	ax += *(rbx + rdi*8 + 6)
xor %ax, 6(%rbx,%rdi,8)	*(rbx + rdi*8 + 6) ^= ax

- LEA is special: it *doesn't* access memory

Assembly	C equivalent
lea 6(%rbx,%rdi,8), %rax	rax = rbx + rdi*8 + 6

Why use LEA?

- **CPU designers' intended use: calculate a pointer to an object**
  - An array element, perhaps
  - For instance, to pass just one array element to another function

Assembly	C equivalent
lea (%rbx,%rdi,8), %rax	rax = &rbx[rdi]

- **Compiler authors like to use it for ordinary arithmetic**
  - It can do complex calculations in one instruction
  - It's one of the only three-operand instructions the x86 has
  - It doesn't touch the condition codes (we'll come back to this)

Assembly	C equivalent
lea (%rbx,%rbx,2), %rax	rax = rbx * 3

Arithmetic Expression Example

```
long arith
(long x, long y, long z)
{
  long t1 = x+y;
  long t2 = z+t1;
  long t3 = x+4;
  long t4 = y * 48;
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

```
arith:
  leaq    (%rdi,%rsi), %rax
  addq    %rdx, %rax
  leaq    (%rsi,%rsi,2), %rdx
  salq    $4, %rdx
  leaq    4(%rdi,%rdx), %rcx
  imulq   %rcx, %rax
  ret
```

Interesting Instructions

- **leaq**: addition and/or multiplication by a constant
- **salq**: shift
- **imulq**: multiplication
  - Curious: only used once…

Arithmetic Expression Example

```
long arith
(long x, long y, long z)
{
  long t1 = x+y;
  long t2 = z+t1;
  long t3 = x+4;
  long t4 = y * 48;
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

```
arith:
  leaq    (%rdi,%rsi), %rax    # t1
  addq    %rdx, %rax           # t2
  leaq    (%rsi,%rsi,2), %rdx
  salq    $4, %rdx             # t4
  leaq    4(%rdi,%rdx), %rcx   # t5
  imulq   %rcx, %rax           # rval
  ret
```

Register	Use(s)
`%rdi`	Argument `x`
`%rsi`	Argument `y`
`%rdx`	Argument `z`, `t4`
`%rax`	`t1`, `t2`, `rval`
`%rcx`	`t5`

Sidebar: instruction suffixes

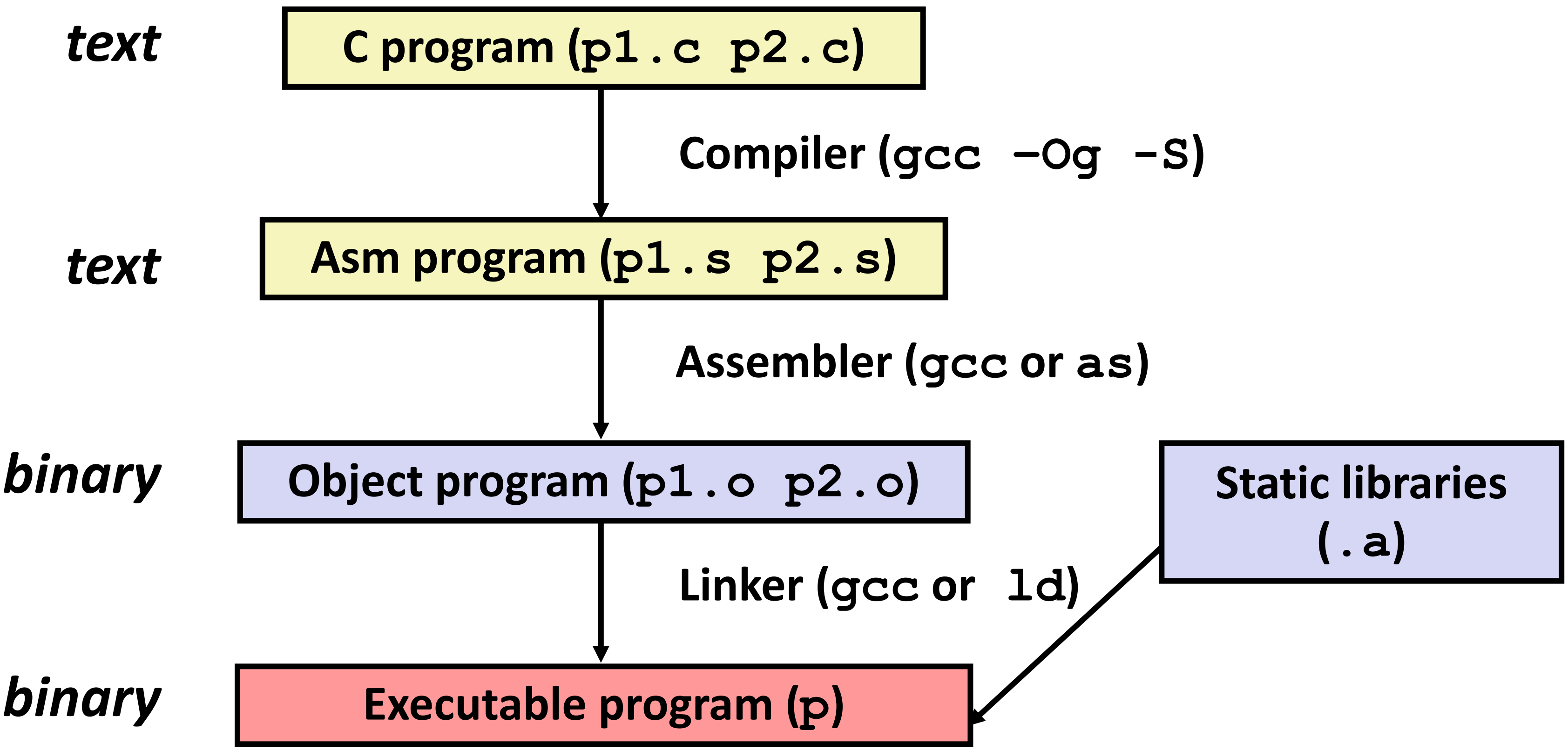
- **Most x86 instructions can be written with or without a suffix**
  - `imul    %rcx, %rax`
  - `imulq   %rcx, %rax`

There's no difference!

- **The suffix indicates the operation size**
  - b=byte, w=short, l=int, q=long
  - If present, must match register names
- **Assembly output from the compiler (gcc –S) usually has suffixes**
- **Disassembly dumps (objdump –d, gdb 'disas') usually omit suffixes**
- **Intel's manuals always omit the suffixes**

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`**



Compiling Into Assembly

C Code (sum.c)

```
long plus(long x, long y);

void sumstore(long x, long y,
              long *dest)
{
    long t = plus(x, y);
    *dest = t;
}
```

Generated x86-64 Assembly

```
sumstore:
   pushq   %rbx
   movq    %rdx, %rbx
   call    plus
   movq    %rax, (%rbx)
   popq    %rbx
   ret
```

Obtain (on shark machine) with command

```
gcc –Og –S sum.c
```

Produces file `sum.s`

***Warning*: Will get very different results on non-Shark machines (Andrew Linux, Mac OS-X, …) due to different versions of gcc and different compiler settings.**

gcc –S output has lots of directives

```
        .globl  sumstore
        .type   sumstore, @function
sumstore:
.LFB35:
        .cfi_startproc
        pushq   %rbx
        .cfi_def_cfa_offset 16
        .cfi_offset 3, -16
        movq    %rdx, %rbx
        call    plus
        movq    %rax, (%rbx)
        popq    %rbx
        .cfi_def_cfa_offset 8
        ret
        .cfi_endproc
.LFE35:
        .size   sumstore, .-sumstore
```

gcc –S output has lots of directives

```
        .globl  sumstore
        .type   sumstore, @function
sumstore:
.LFB35:
        .cfi_startproc
        pushq   %rbx
        .cfi_def_cfa_offset 16
        .cfi_offset 3, -16
        movq    %rdx, %rbx
        call    plus
        movq    %rax, (%rbx)
        popq    %rbx
        .cfi_def_cfa_offset 8
        ret
        .cfi_endproc
.LFE35:
        .size   sumstore, .-sumstore
```

You can ignore most lines that start with a '.'

```
sumstore:
    pushq   %rbx
    movq    %rdx, %rbx
    call    plus
    movq    %rax, (%rbx)
    popq    %rbx
    ret
```

Object Code

- **Assembly instructions become machine instructions**
- **Placeholders for unknown addresses**

```
0000000000400595 <sumstore>:
  400595:   53                  push   %rbx
  400596:   48 89 d3            mov    %rdx,%rbx
  400599:   e8 f2 ff ff ff      callq  <plus>
  40059e:   48 89 03            mov    %rax,(%rbx)
  4005a1:   5b                  pop    %rbx
  4005a2:   c3                  retq
```

- **Disassembler**

  `objdump -d sum`

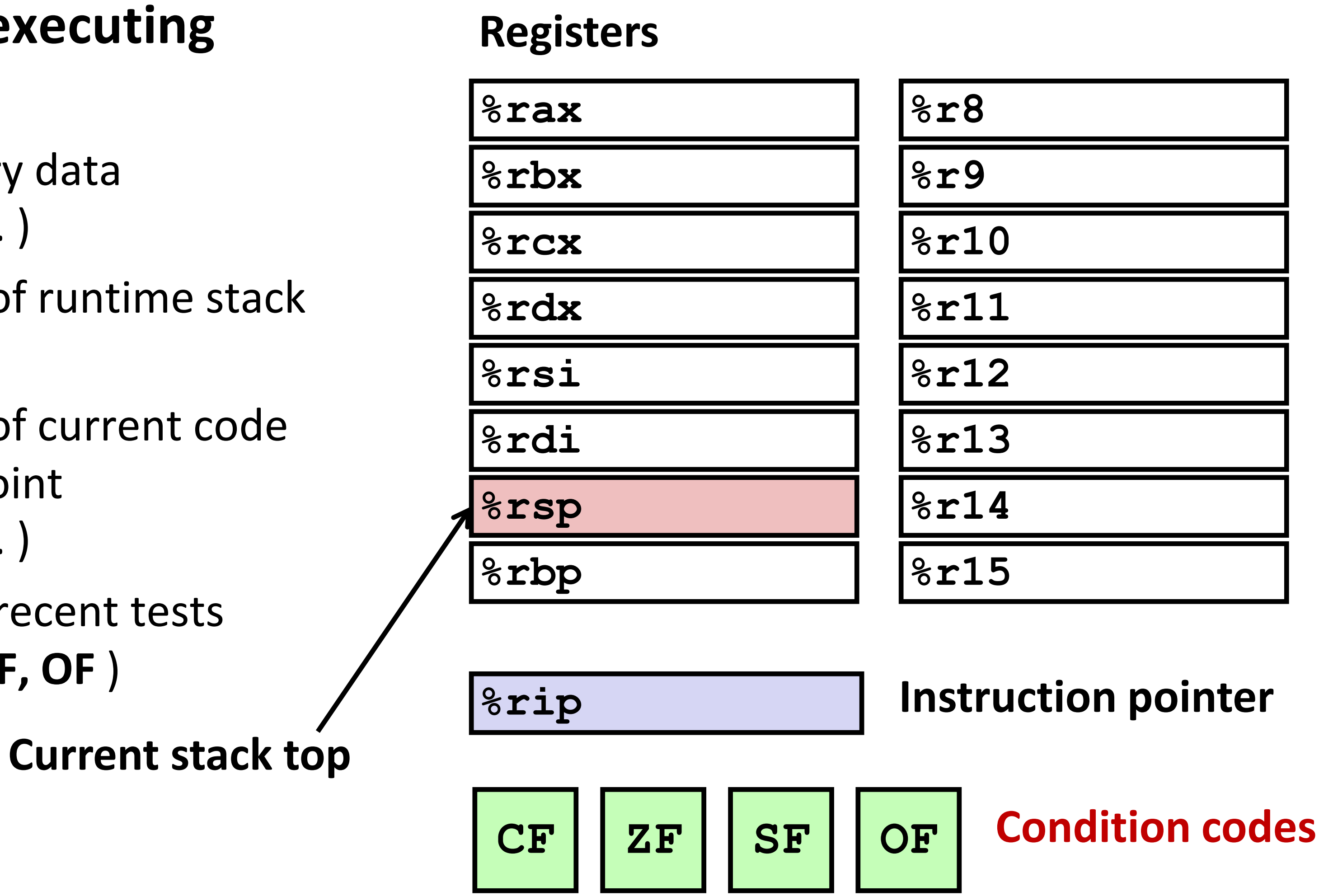
  - Useful tool for examining object code
  - Analyzes bit pattern of series of instructions
  - Produces approximate rendition of assembly code

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 (as side effect) of arithmetic operations**

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

  CF set if carry/borrow 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 `lea` 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...                Carry
 ---------------------
 1  xxxxxxxxxxxxxx...


 1  0xxxxxxxxxxxxx...
 -  1xxxxxxxxxxxxx...                Borrow
 ---------------------
    1xxxxxxxxxxxxx...
```

For unsigned arithmetic, this reports overflow

OF set when

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

z = ~y

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

For signed arithmetic, this reports overflow

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/borrow 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`**

Very often:

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

Condition Codes (Explicit Reading: Set)

- **Explicit Reading by Set Instructions**
  - **`setX`** *Dest*: Set low-order byte of destination *Dest* to 0 or 1 based on combinations of condition codes
  - Does not alter remaining 7 bytes of *Dest*

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)

Explicit 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 lt (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
    setl   %al           # Set when <
    movzbl %al, %eax     # Zero rest of %rax
    ret
```

Example: setl (Signed <)

- Condition: SF^OF

SF	OF	SF ^ OF	Implication
0	0	0	No overflow, so SF implies not <
1	0	1	No overflow, so SF implies <
0	1	1	Overflow, so SF implies negative overflow, i.e. <
1	1	0	Overflow, so SF implies positive overflow, i.e. not <

negative overflow case

```
  1xxxxxxxxxxxxx...   a
- 0xxxxxxxxxxxxx...   b
---------------------
  0xxxxxxxxxxxxx...   t
```

x86-64 Integer Registers

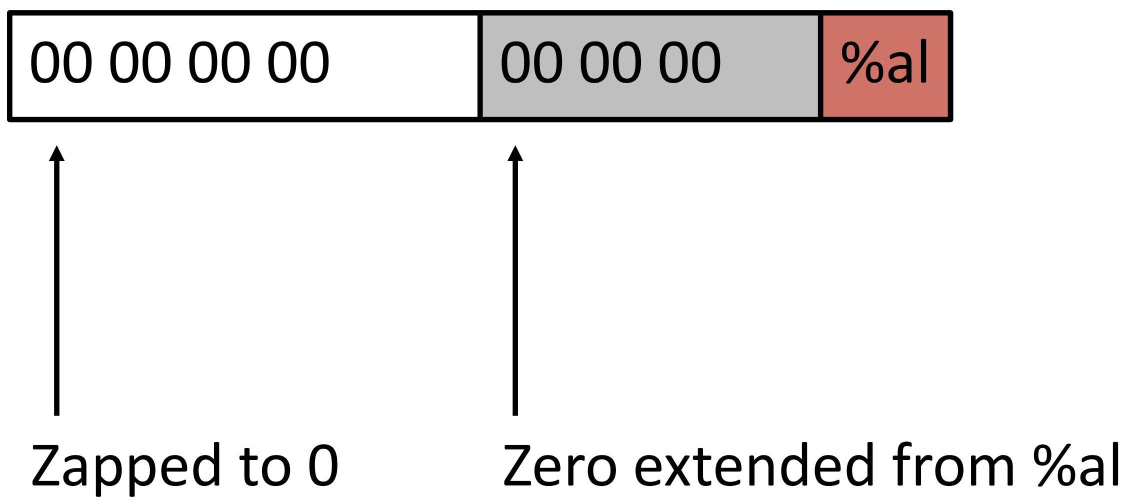
%rax	%al	%r8	%r8b
%rbx	%bl	%r9	%r9b
%rcx	%cl	%r10	%r10b
%rdx	%dl	%r11	%r11b
%rsi	%sil	%r12	%r12b
%rdi	%dil	%r13	%r13b
%rsp	%spl	%r14	%r14b
%rbp	%bpl	%r15	%r15b

- Can reference low-order byte

An x86-64 quirk to watch out for

Most instructions with a 32-bit destination zero the upper 32 bits of the register!

```
movzbl %al, %eax
```



Today

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

Jumping

- **jX Instructions**
  - Jump to different part of code depending on condition codes
  - Implicit reading of 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)

Get to this shortly

- **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, 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
```

When is this bad?

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

`cmpq b,a` like computing `a-b` w/o setting dest

- **CF set** if carry/borrow 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

SetX	Condition	Description
`sete`	`ZF`	Equal / Zero
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`setl`	`SF^OF`	Less (signed)
`setle`	`(SF^OF)|ZF`	Less or Equal (signed)
`seta`	`~CF&~ZF`	Above (unsigned)
`setb`	`CF`	Below (unsigned)

```
xorq    %rax, %rax
subq    $1, %rax
cmpq    $2, %rax
setl    %al
movzbl  %al, %eax
```

`%rax`	SF	CF	OF	ZF

Note: **`setl`** and **`movzbl`** do not modify condition codes

Exercise

`cmpq b,a` like computing `a-b` w/o setting dest

- **CF set** if carry/borrow out from most significant bit (used for unsigned comparisons)
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`seta`	`~CF&~ZF`	Above (unsigned)
`setb`	`CF`	Below (unsigned)

```
xorq    %rax, %rax
subq    $1, %rax
cmpq    $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

Note: **`setl`** and **`movzblq`** do not modify condition codes

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

```
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
```

Quiz Time!

Check out:

https://canvas.cmu.edu/courses/17808

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;
}
```

- **Initial conditional guards entrance to loop**
- **Compare to do-while version of function**
  - Removes jump to middle. When is this good or bad?

"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 – **why?**

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 my_switch
   (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;
}
```

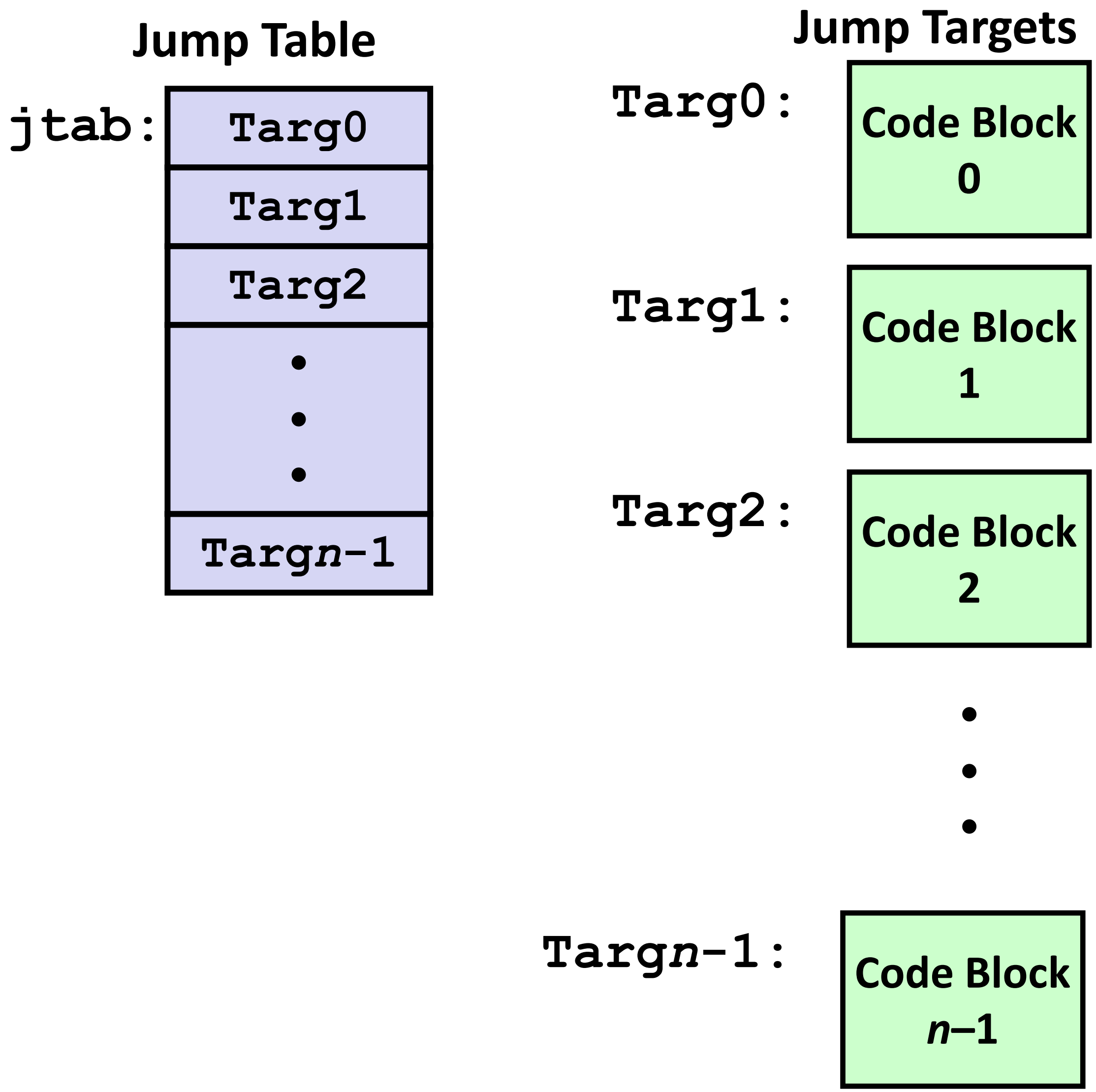
Switch Statement Example

- **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 my_switch
   (long x, long y, long z)
{
    long w = 1;
    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;
    }
    return w;
}
```

```
my_switch:
   cmpq     $6, %rdi    # x:6
   ja       .L8    # if x > 6 jump
                   # to default
   jmp      *.L4(,%rdi,8)
```

```
.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`**
- **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

```
.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
```

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                 # sign extend
                        # rax to rdx:rax
   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`
`%rcx`	`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

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
```