
WELCOME
TO
15-213
14-513
18-213
18-613
15-513

Machine-Level Programming II: Control

15-213/18-213/14-513/15-513/18-613: Introduction to Computer Systems
6th Lecture, September 16, 2020

Announcements

- **Lab 1 (datalab)**
  - Due Thurs, Sept. 17, 11:59pm ET
- **Written Assignment 1 peer grading**
  - Due Wed, Sept. 23, 11:59pm ET
- **Written Assignment 2 available on Canvas**
  - Due Wed, Sept. 23, 11:59pm ET
- **Lab 2 (bomblab) will be available at midnight via Autolab**
  - Due Tues, Sept. 29, 11:59 pm ET
- **Recitation on bomblab this Monday**
  - In person: you have been contacted with your recitation info
  - Online: use the zoom links provided on the Canvas homepage

Catching Up

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

LEA: Evaluate Memory Address Expression Without Accessing Memory

- `leaq` *Src*, *Dst*
  - *Src* is address computation expression ⟶ **D(Rb,Ri,S): Reg[Rb]+S*Reg[Ri]+ D**
  - Set *Dst* to address denoted by expression

- **Uses**
  - Computing address/pointer **WITHOUT ACCESSING MEMORY**
    - E.g., translation of `p = &x[i];`
  - Compute arbitrary expressions of form: b+(s*i)+d, where s = 1, 2, 4, or 8
    - **[also w/o accessing memory]**

- **Example**

```
long m12(long x)
{
  return x*12;
}
```

Converted to ASM by compiler:

```
leaq (%rdi,%rdi,2), %rax   # t = x+2*x
salq $2, %rax              # return t<<2
```

LEA vs. other instructions (e.g., MOV)

- `leaq` D(Rb,Ri,S), ***dst***
  - *dst* ⟵ **Reg[Rb]+S*Reg[Ri]+ D**
  - ***NO MEMORY ACCESS HAPPENS!***

- `movq` D(Rb,Ri,S), ***dst***
  - *dst* ⟵ **Mem[Reg[Rb]+S*Reg[Ri]+ D]**
  - ***MEMORY ACCESS HAPPENS!***

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`**: address computation
- **`salq`**: shift
- **`imulq`**: multiplication
  - Curious: only used once…

Understanding 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`

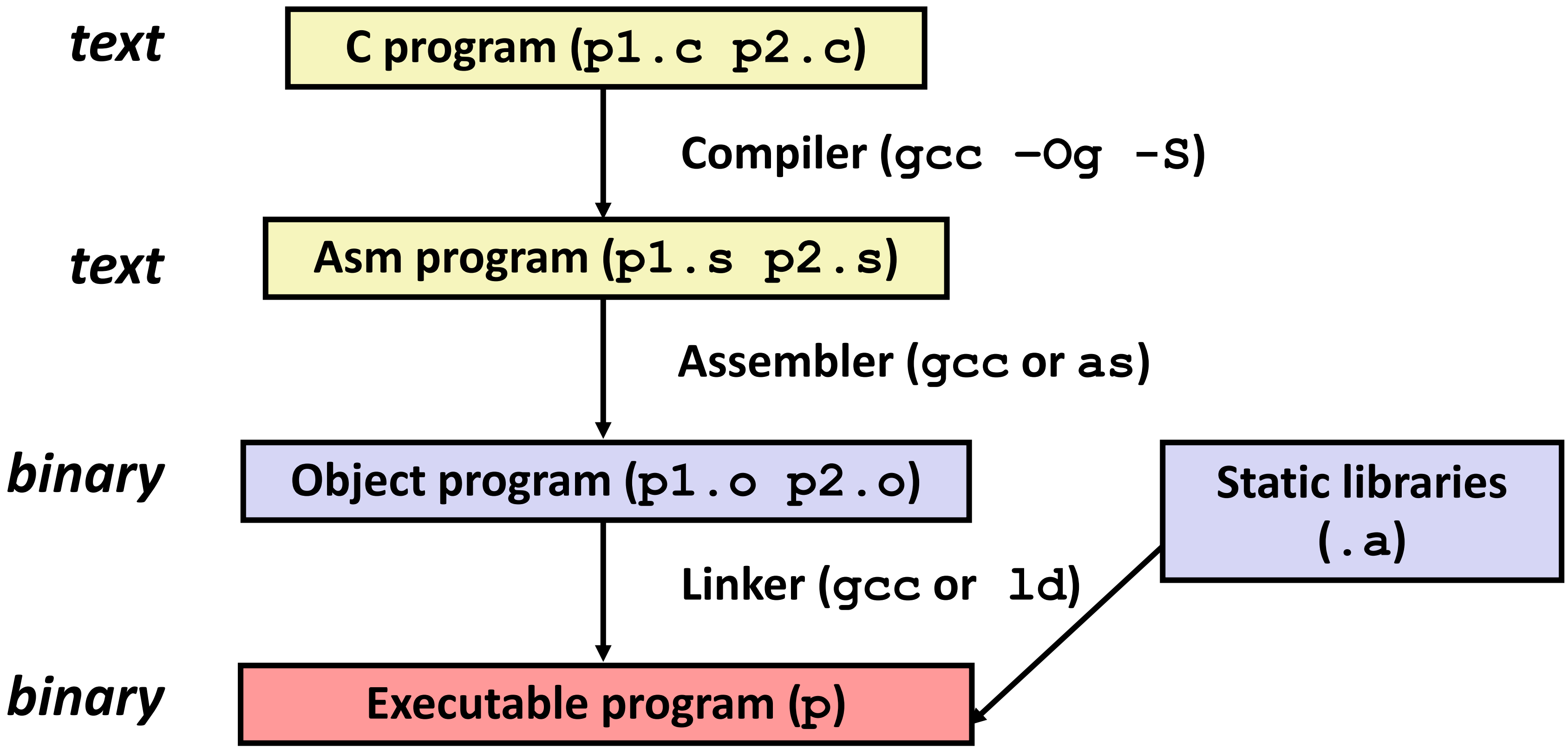
D(Rb,Ri,S): Mem[Reg[Rb]+S*Reg[Ri]+ D]

Today: Machine Programming I: Basics

- History of Intel processors and architectures
- Assembly Basics: Registers, operands, move
- Arithmetic & logical operations
- **C, assembly, machine code**

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.**

What it really looks like

```
        .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
```

What it really looks like

```
        .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
```

Things that look weird and are preceded by a '.' are generally directives.

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

Object Code

Code for `sumstore`

```
0x0400595:
    0x53
    0x48
    0x89
    0xd3
    0xe8
    0xf2
    0xff
    0xff
    0xff
    0x48
    0x89
    0x03
    0x5b
    0xc3
```

- **Total of 14 bytes**
- **Each instruction 1, 3, or 5 bytes**
- **Starts at address `0x0400595`**

- **Assembler**
  - Translates `.s` into `.o`
  - Binary encoding of each instruction
  - Nearly-complete image of executable code
  - Missing linkages between code in different files
- **Linker**
  - Resolves references between files
  - Combines with static run-time libraries
    - E.g., code for **`malloc`**, **`printf`**
  - Some libraries are *dynamically linked*
    - Linking occurs when program begins execution

Machine Instruction Example

```
*dest = t;
```

```
movq %rax, (%rbx)
```

```
0x40059e:   48 89 03
```

- **C Code**
  - Store value **`t`** where designated by **`dest`**
- **Assembly**
  - Move 8-byte value to memory
    - Quad words in x86-64 parlance
  - Operands:

    `t:` Register **`%rax`**

    `dest:` Register **`%rbx`**

    `*dest:` Memory **`M[%rbx]`**
- **Object Code**
  - 3-byte instruction
  - Stored at address **`0x40059e`**

Disassembling Object Code

Disassembled

```
0000000000400595 <sumstore>:
  400595:  53                push   %rbx
  400596:  48 89 d3          mov    %rdx,%rbx
  400599:  e8 f2 ff ff ff    callq  400590 <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
  - Can be run on either `a.out` (complete executable) or `.o` file

Alternate Disassembly

Disassembled

```
Dump of assembler code for function sumstore:
 0x0000000000400595 <+0>: push   %rbx
 0x0000000000400596 <+1>: mov    %rdx,%rbx
 0x0000000000400599 <+4>: callq  0x400590 <plus>
 0x000000000040059e <+9>: mov    %rax,(%rbx)
 0x00000000004005a1 <+12>:pop    %rbx
 0x00000000004005a2 <+13>:retq
```

- **Within gdb Debugger**
  - Disassemble procedure

```
gdb sum
disassemble sumstore
```

Alternate Disassembly

Object Code

```
0x0400595:
    0x53
    0x48
    0x89
    0xd3
    0xe8
    0xf2
    0xff
    0xff
    0xff
    0x48
    0x89
    0x03
    0x5b
    0xc3
```

Disassembled

```
Dump of assembler code for function sumstore:
 0x0000000000400595 <+0>: push   %rbx
 0x0000000000400596 <+1>: mov    %rdx,%rbx
 0x0000000000400599 <+4>: callq  0x400590 <plus>
 0x000000000040059e <+9>: mov    %rax,(%rbx)
 0x00000000004005a1 <+12>:pop    %rbx
 0x00000000004005a2 <+13>:retq
```

- **Within gdb Debugger**
  - Disassemble procedure

```
gdb sum
disassemble sumstore
```

  - Examine the 14 bytes starting at `sumstore`

```
x/14xb sumstore
```

What Can be Disassembled?

```
% objdump -d WINWORD.EXE

WINWORD.EXE:    file format pei-i386

No symbols in "WINWORD.EXE".
Disassembly of section .text:

30001000 <.text>:
30001000:
30001001:
30001003:
30001005:
3000100a:
```

Reverse engineering forbidden by Microsoft End User License Agreement

- **Anything that can be interpreted as executable code**
- **Disassembler examines bytes and reconstructs assembly source**

Machine Programming I: Summary

- **History of Intel processors and architectures**
  - Evolutionary design leads to many quirks and artifacts
- **C, assembly, machine code**
  - New forms of visible state: program counter, registers, ...
  - Compiler must transform statements, expressions, procedures into low-level instruction sequences
- **Assembly Basics: Registers, operands, move**
  - The x86-64 move instructions cover wide range of data movement forms
- **Arithmetic**
  - C compiler will figure out different instruction combinations to carry out computation

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**)

Registers

`%rax`	`%r8`
`%rbx`	`%r9`
`%rcx`	`%r10`
`%rdx`	`%r11`
`%rsi`	`%r12`
`%rdi`	`%r13`
`%rsp`	`%r14`
`%rbp`	`%r15`

Current stack top

`%rip` **Instruction pointer**

CF	ZF	SF	OF

Condition codes

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 `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 = ~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)

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

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 gt (long x, long y)
{
  return x > y;
}
```

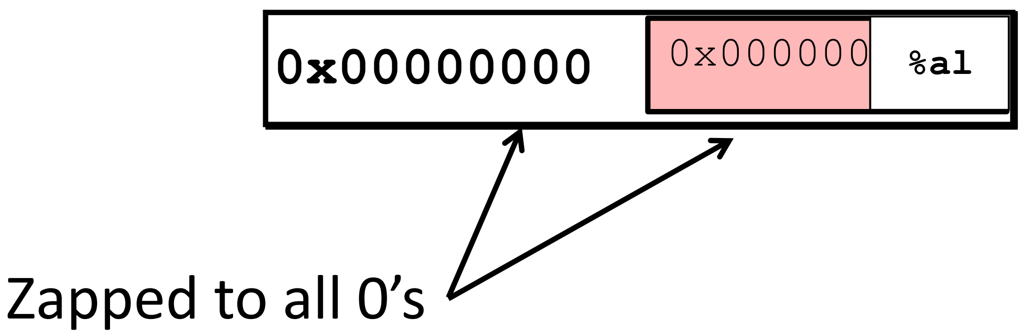
Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rax`	Return value

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

Explicit Reading Condition Codes (Cont.)

Beware weirdness **`movzbl`** (and others)

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



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: 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)

- **Generation**

Get to this shortly

```
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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`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)

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

`%rax`	SF	CF	OF	ZF

Note: **`setl`** and **`movzblq`** 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)
- **ZF set** if `a == b`
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SetX	Condition	Description
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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)

Instruction	`%rax`	SF	CF	OF	ZF
`xorq %rax, %rax`	`0x0000 0000 0000 0000`	0	0	0	1
`subq $1, %rax`	`0xFFFF FFFF FFFF FFFF`	1	1	0	0
`cmpq $2, %rax`	`0xFFFF FFFF FFFF FFFF`	1	0	0	0
`setl %al`	`0xFFFF FFFF FFFF FF01`	1	0	0	0
`movzblq %al, %eax`	`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

- "Do-while" conversion
- Used with –O1

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:
```

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;
}
```

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 – **why?**

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;
}
```

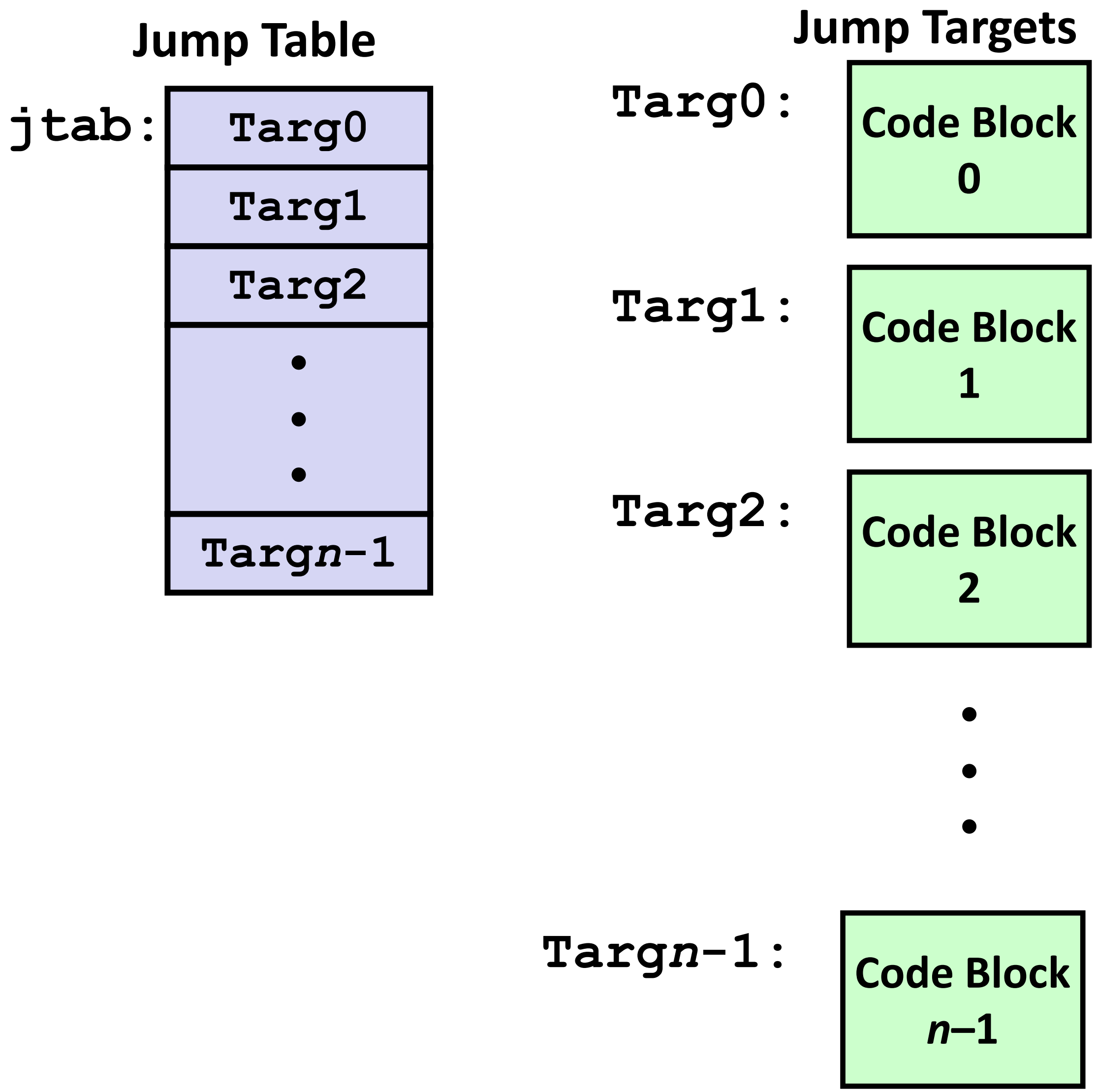
Switch Statement Example

- **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
```