Machine-Level Programming II: Control

15-213/14-513/15-513: Introduction to Computer Systems

5th Lecture, September 14, 2021

Today

- From last week: Turning C into machine code
- From last week: Review of a few tricky bits
- Basics of control flow
- Condition codes
- Conditional branches
- Loops
- Switch Statements

Reminder about office hours

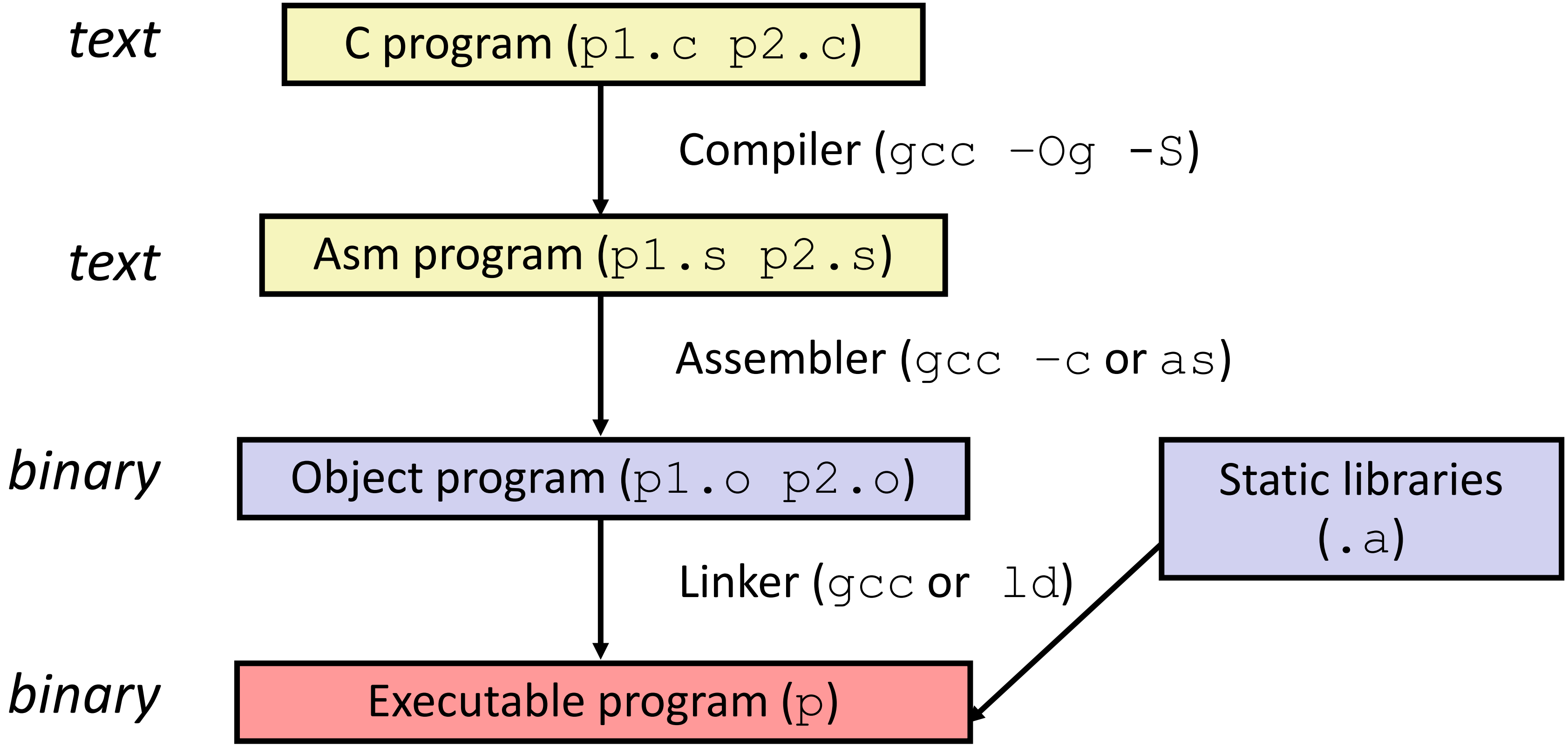
- **6–10PM** on Zoom and in-person (Sun–Fri)
- **11:30AM – 1:30PM** (Wed, Fri)
- **Queue: https://cmqueue.xyz/**
  - New queuing system—do not use the link from last year
  - You must be on the queue even if you are attending in person
- **More details on Piazza:** https://piazza.com/class/kr9vqwncw253c4?cid=284

Reminder about office hour etiquette

- **Office hours are for getting ideas on how to debug or better approach your homework.**
  - Conceptual OH coming soon as well so look out for that!
- **Write a description!**
  - If you don't have a description, you may be frozen/removed from the queue.
- **Try to narrow down your problem area as much as possible**
  - Same principles as asking questions on Piazza
  - https://piazza.com/class/kr9vqwncw253c4?cid=352
- **The queue closes early**
  - so everyone can be helped by around 9:30pm
- **Please find the TAs at the carrels**
  - TAs should not need to find you

Turning C into Machine 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`**



Machine Instruction Example

```
*dest = t;
```

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

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

- **C**
  - 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]`**
- **Machine**
  - 3 bytes at address **`0x40059e`**
  - Compact representation of the assembly instruction
  - (Relatively) easy for hardware to interpret

Machine Instruction Example

```
*dest = t;
```

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

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

0100	1	0	0	0	10001011	00	000	011
REX	W	R	X	B	Move	Mod	R	M

- **C**
  - 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]`**
- **Machine**
  - 3 bytes at address **`0x40059e`**
  - Compact representation of the assembly instruction
  - (Relatively) easy for hardware to interpret

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

What an assembly file 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 an assembly file 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* that you can ignore.

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

Object Code

Code for `sumstore`

```
00000000 <sumstore>:
    53
    48 89 d3
    e8 00 00 00 00
    48 89 03
    5b
    c3
```

- **Starts at address `0x0400595`**
- **Total of 14 bytes**
- **Each instruction 1, 3, or 5 bytes**
- **Placeholders (red) for addresses of `sumstore` and `plus`**

- **Assembler**
  - Translates `.s` into `.o`
  - Binary encoding of each instruction
  - Nearly-complete image of executable code
  - Address of each function not yet assigned
  - Placeholders (“relocations”) for uses of code and data defined in other files
- **Linker**
  - Resolves references between files
    - E.g., fills in address of **`plus`**
  - Combines with static run-time libraries
    - E.g., code for **`malloc`**, **`printf`**
  - Some libraries are *dynamically linked*
    - Second pass of linking occurs when program begins execution

Disassembling Object Code

Disassembled

```
0000000000000000 <sumstore>:
       0:    53                              push    %rbx
       1:    48 89 d3                        mov     %rdx,%rbx
       4:    e8 00 00 00 00                  callq   9 <sumstore+0x9>
                          5: R_X86_64_PLT32          plus-0x4
       9:    48 89 03                        mov     %rax,(%rbx)
       c:    5b                              pop     %rbx
       d:    c3                              retq
```

- **Disassembler**

  `objdump -dr sum.o`

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

Disassembling Executable Code

Disassembled

```
0000000000401122 <sumstore>:
  401122:   53                      push   %rbx
  401123:   48 89 d3                mov    %rdx,%rbx
  401126:   e8 05 00 00 00          callq  401130 <plus>

  40112b:   48 89 03                mov    %rax,(%rbx)
  40112e:   5b                      pop    %rbx
  40112f:   c3                      retq
```

- **Disassembler**

  `objdump -dr a.out`

  - Can be applied to executables too
- **Changes made by linker**
  - **`sumstore`** has an address
  - Call instruction has a destination address instead of a relocation

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
```

  - Same information, different format

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
```

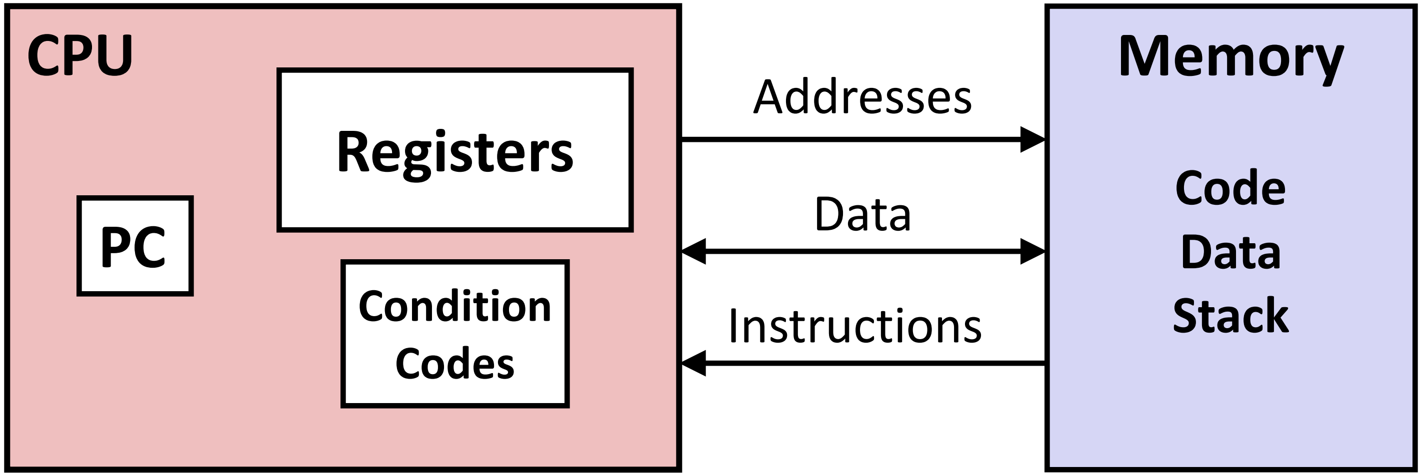
- **Within gdb Debugger**
  - Disassemble procedure

```
gdb sum
disassemble sumstore
```

  - Examine the 14 bytes starting at `sumstore`

```
x/14xb sumstore
```

Recall: ISA = Assembly/Machine Code View



Programmer-Visible State

- **PC: Program counter**
  - Address of next instruction
- **Register file**
  - Heavily used program data
- **Condition codes**
  - Store status information about most recent arithmetic or logical operation
  - Used for conditional branching

- **Memory**
  - Byte addressable array
  - Code and user data
  - Stack to support procedures

Recall: Addressing Modes

- **Most General Form**

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

  - D: Constant "displacement" 1, 2, or 4 bytes
  - Rb: Base register: Any of 16 integer registers
  - Ri: Index register: Any, except for `%rsp`
  - S: Scale: 1, 2, 4, or 8

- **Special Cases**

  (Rb,Ri) Mem[Reg[Rb]+Reg[Ri]]

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

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

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

Sidebar: instruction suffixes

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

There's no difference!

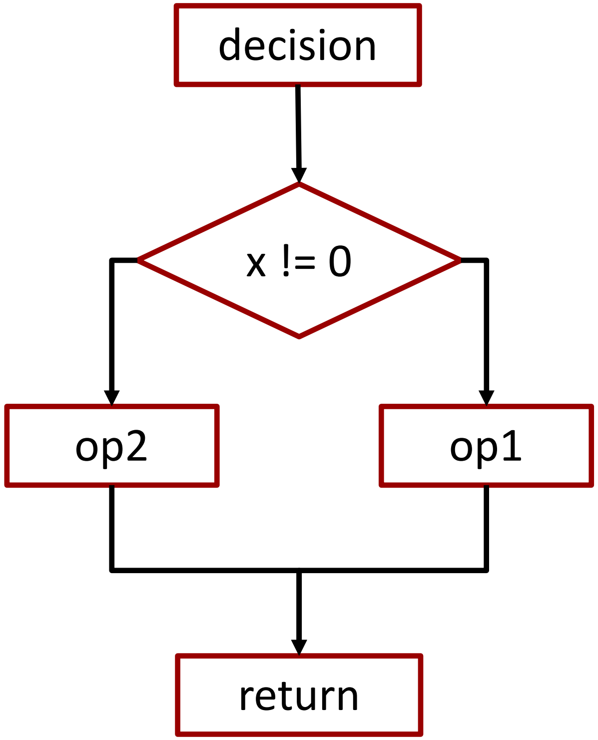
- **The suffix indicates the operation size**
  - b=byte, w=short, l=int, q=long
  - If present, must match register names
- **Assembly output from the compiler (gcc –S) usually has suffixes**
- **Disassembly dumps (objdump –d, gdb 'disas') usually omit suffixes**
- **Intel's manuals always omit the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


CONTROL... CONTROL...
YOU MUST LEARN CONTROL

Control flow

```
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```



Control flow in assembly language

```
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```

```
decision:
        subq    $8, %rsp
        testl   %edi, %edi
        je      .L2
        call    op1
        jmp     .L1
.L2:
        call    op2
.L1:
        addq    $8, %rsp
        ret
```

Control flow in assembly language

```
extern void op1(void);
extern void op2(void);

void decision(int x) {
    if (x) {
        op1();
    } else {
        op2();
    }
}
```

```
decision:
        subq    $8, %rsp
        testl   %edi, %edi
        je      .L2
        call    op1
        jmp     .L1
.L2:
        call    op2
.L1:
        addq    $8, %rsp
        ret
```

It's all done with GOTO!

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;
}
```

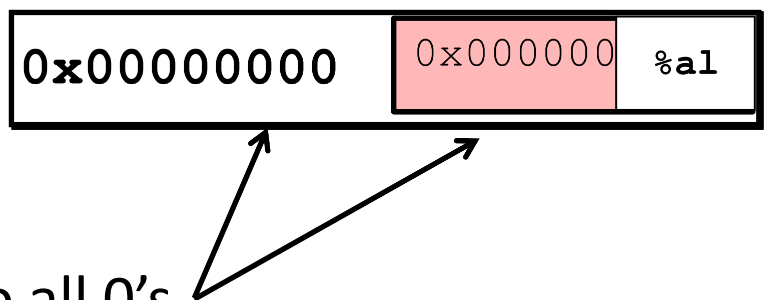
Register	Use(s)
`%rdi`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rax`	Return value

```
    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



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: 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**

```
shark> gcc –Og -S –fno-if-conversion control.c
```

Get to this shortly

```
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
```

When is this bad?

Bad Cases for Conditional Move

Expensive Computations

```
val = Test(x) ? Hard1(x) : Hard2(x);
```

Bad Performance

- Both values get computed
- Only makes sense when computations are very simple

Risky Computations

```
val = p ? *p : 0;
```

Unsafe

- Both values get computed
- May have undesirable effects

Computations with side effects

```
val = x > 0 ? x*=7 : x+=3;
```

Illegal

- 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

x86 being CISC has a popcount instruction

General "Do-While" Translation

C Code

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

Goto Version

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

- **Body:**

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

"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/24383/quizzes/67235

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))
    goto done;              ! Test
 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;
}
```

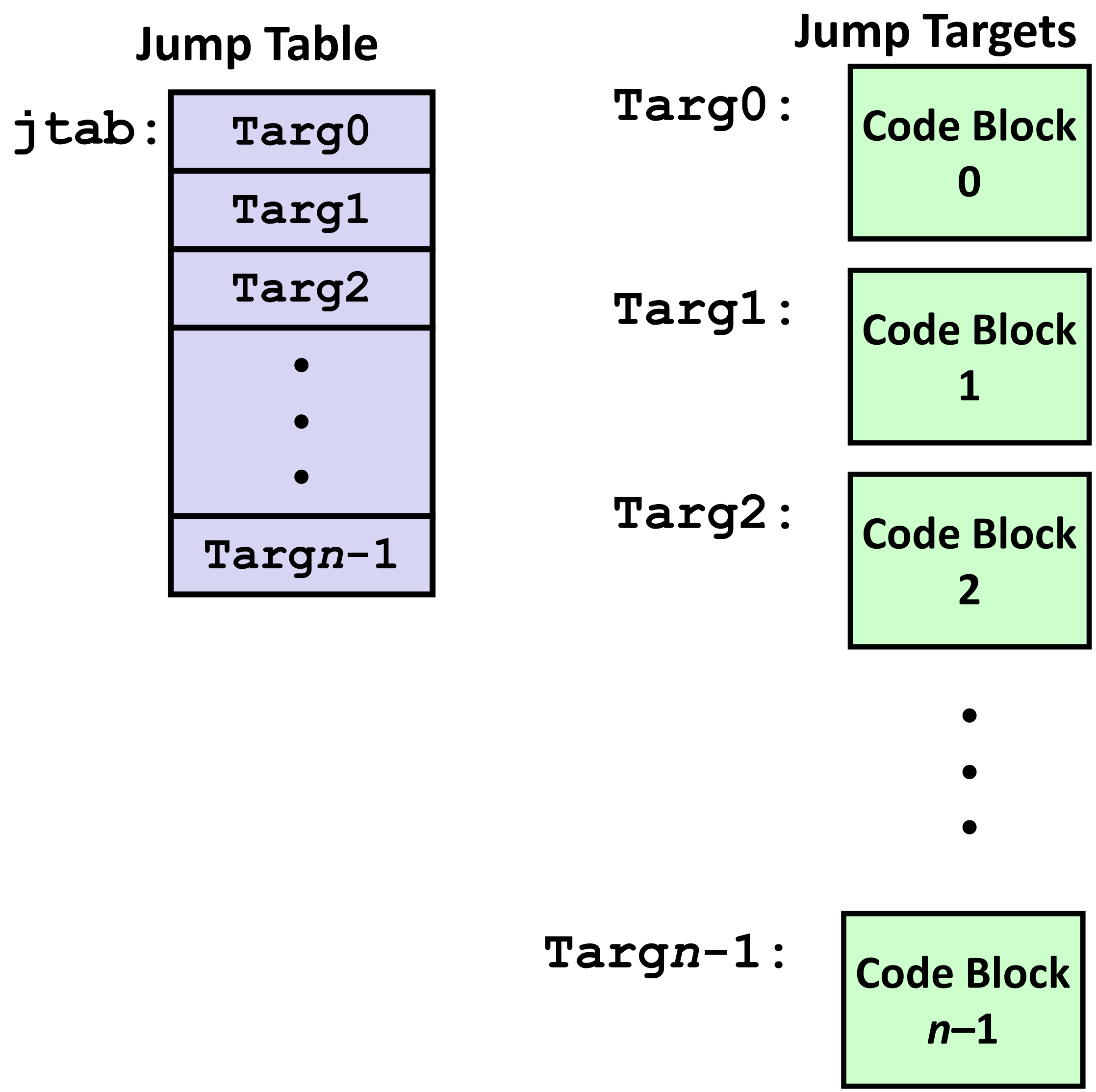
Switch Statement Example

- **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) {
      . . .
    }
    return w;
}
```

Setup

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

Setup

```
my_switch:
    movq    %rdx, %rcx
    cmpq    $6, %rdi     # x:6
    ja      .L8          # use default
    jmp     *.L4(,%rdi,8)  # goto *Jtab[x]
```

Indirect jump

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
```

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
```

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                   # 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
```