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

Machine-Level Programming II: Control

15-213/14-513/15-513: Introduction to Computer Systems
4th Lecture, Sept 7, 2023

Announcements

- **Written 1 out yesterday, due Wed 9/13**
- **GDB & Debugging Bootcamp this Sun 9/10**
  - Watch for Piazza posting on the details
- **Lab 1 (datalab) due Tues 9/12**
- **Lab 2 (bomblab) out today, due Thurs 9/21**
  - Turns in automatically via Autolab

Recall: Machine Instructions

```
*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

Recall: Move & Arithmetic Operations

- Some Two Operand Instructions:

Format	*Computation*		
`movq`	*Src,Dest*	Dest = Src (Src can be $const)	
`leaq`	***Src,Dest***	**Dest = address computed by expression Src**	
`addq`	*Src,Dest*	Dest = Dest + Src	
`subq`	*Src,Dest*	Dest = Dest – Src	
`imulq`	*Src,Dest*	Dest = Dest * Src	
`salq`	*Src,Dest*	Dest = Dest << Src	***Also called shlq***
`sarq`	*Src,Dest*	Dest = Dest >> Src	***Arithmetic***
`shrq`	*Src,Dest*	Dest = Dest >> Src	***Logical***
`xorq`	*Src,Dest*	Dest = Dest ^ Src	
`andq`	*Src,Dest*	Dest = Dest & Src	
`orq`	*Src,Dest*	Dest = Dest | Src	

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

Which numbers are pointers?

- They aren’t labeled
- You have to figure it out from context

```
(gdb) info registers
rax       0x40057d          4195709
rbx       0x0               0
rcx       0x4005e0          4195808
rdx       0x7fffffffdc28    140737488346152
rsi       0x7fffffffdc18    140737488346136
rdi       0x1               1
rbp       0x0               0x0
rsp       0x7fffffffdb38    0x7fffffffdb38
r8        0x7ffff7dd5e80    140737351868032
r9        0x0               0
r10       0x7fffffffd7c0    140737488345024
r11       0x7ffff7a2f460    140737348039776
r12       0x400490          4195472
r13       0x7fffffffdc10    140737488346128
r14       0x0               0
r15       0x0               0
rip       0x40057d          0x40057d
```

Which numbers are pointers?

- They aren't labeled
- You have to figure it out from context

- %rsp and %rip always hold pointers
  - Register values that are "close" to %rsp or %rip are *probably* also pointers

```
(gdb) info registers
rax      0x40057d         4195709
rbx      0x0              0
rcx      0x4005e0         4195808
rdx      0x7fffffffdc28   140737488346152
rsi      0x7fffffffdc18   140737488346136
rdi      0x1              1
rbp      0x0              0x0
rsp      0x7fffffffdb38   0x7fffffffdb38
r8       0x7ffff7dd5e80   140737351868032
r9       0x0              0
r10      0x7fffffffd7c0   140737488345024
r11      0x7ffff7a2f460   140737348039776
r12      0x400490         4195472
r13      0x7fffffffdc10   140737488346128
r14      0x0              0
r15      0x0              0
rip      0x40057d         0x40057d
```

Which numbers are pointers?

- If a register is being *used* as a pointer…

```
Dump of assembler code for function main:
=> 0x40057d <+0>:   sub    $0x8,%rsp
   0x400581 <+4>:   mov    (%rsi),%rsi
   0x400584 <+7>:   mov    $0x400670,%edi
   0x400589 <+12>:  mov    $0x0,%eax
   0x40058e <+17>:  call   0x400460
```

Which numbers are pointers?

- **If a register is being *used* as a pointer…**
  - mov (%rsi), %rsi
  - …Then its value is *expected* to be a pointer.
    - There might be a bug that makes its value incorrect.

```
Dump of assembler code for function main:
=> 0x40057d <+0>:   sub    $0x8,%rsp
   0x400581 <+4>:   mov    (%rsi),%rsi
   0x400584 <+7>:   mov    $0x400670,%edi
   0x400589 <+12>:  mov    $0x0,%eax
   0x40058e <+17>:  call   0x400460
```

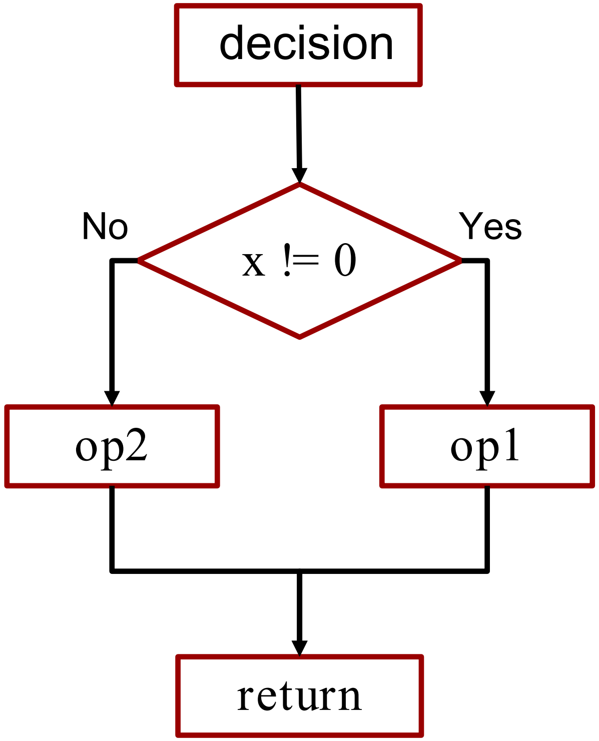
- **Not as obvious with complicated address "modes"**
  - (%rsi, %rbx) – *One* of these is a pointer, we don't know which.
  - (%rsi, %rbx, 2) – %rsi is a pointer, %rbx isn't (why?)
  - 0x400570(, %rbx, 2) – 0x400570 is a pointer, %rbx isn't (why?)
  - lea (anything), %rax – (anything) *may or may not* be a pointer

Today

Control: Condition codes	CSAPP 3.6.1 - 3.6.2
Conditional branches	CSAPP 3.6.3 - 3.6.6
Loops	CSAPP 3.6.7
Switch Statements	CSAPP 3.6.8

Control flow

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

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



Control flow in assembly language

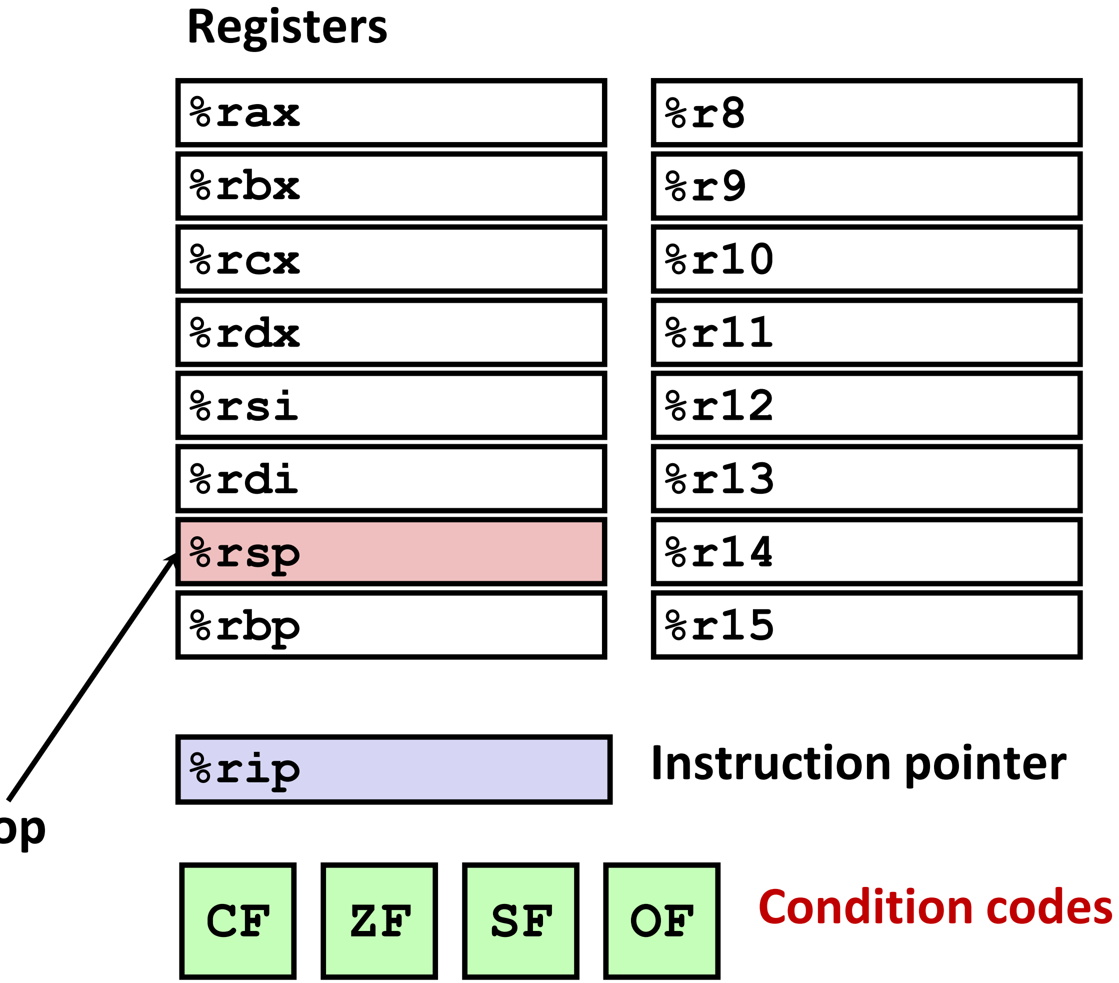
```
extern void op1(void);
extern void op2(void);

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
```

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**)



Current stack top

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)
  - **GDB prints these as one "eflags" register**

```
eflags   0x246   [ PF ZF IF ]
```
Z set, CSO clear

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

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

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

  ZF set if `t == 0`

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

  OF set if two's-complement (signed) overflow
  `(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`

- **Not set by `lea` instructions**

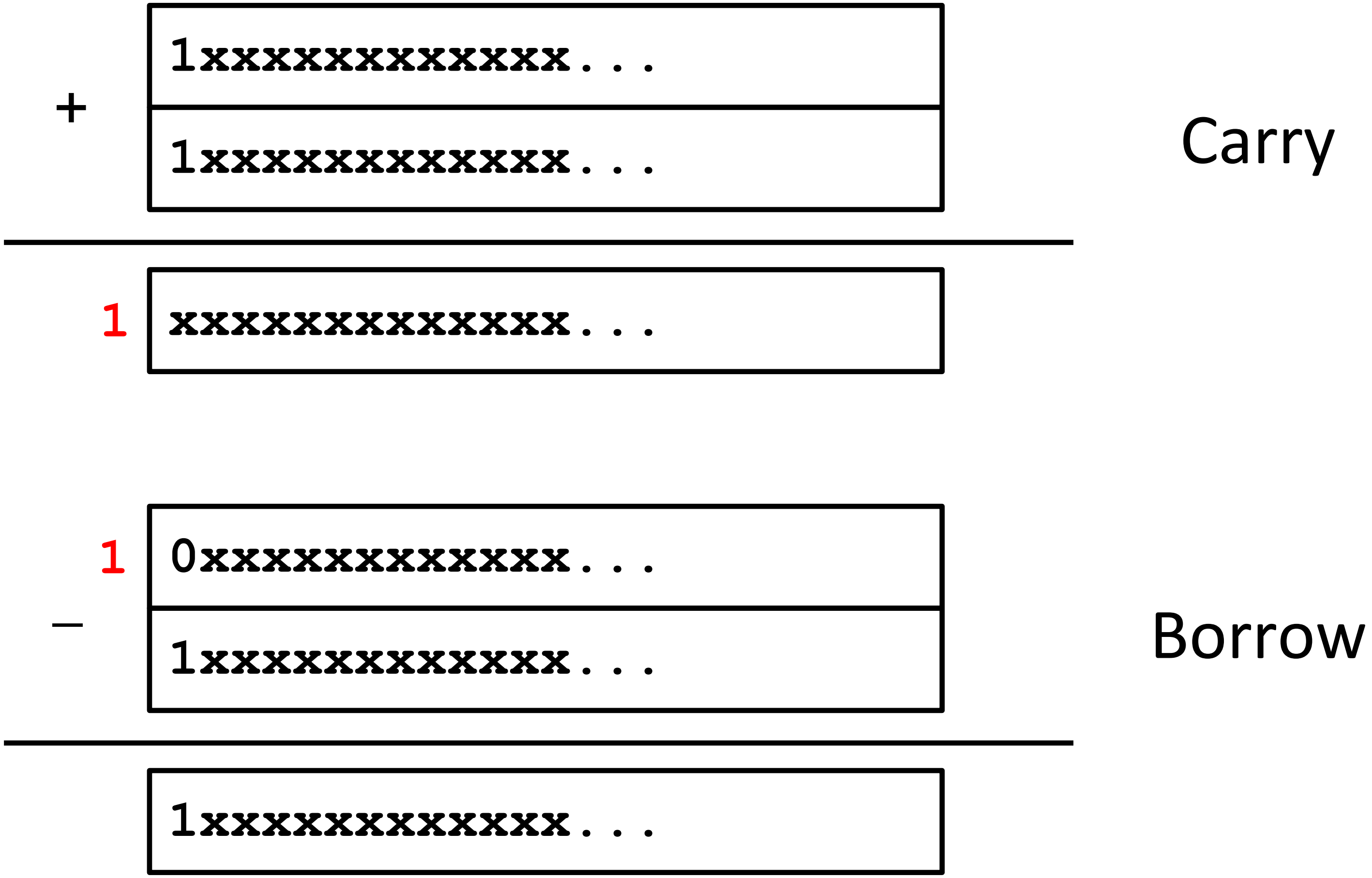
ZF set when

000000000000…00000000000

SF set when

```
1xxxxxxxxxxx...xxxxxxxxxxx
```

CF set when



```
   1xxxxxxxxxxxx...
+  1xxxxxxxxxxxx...
-------------------
1  xxxxxxxxxxxxx...
```

Carry

```
1  0xxxxxxxxxxxx...
–  1xxxxxxxxxxxx...
-------------------
   1xxxxxxxxxxxx...
```

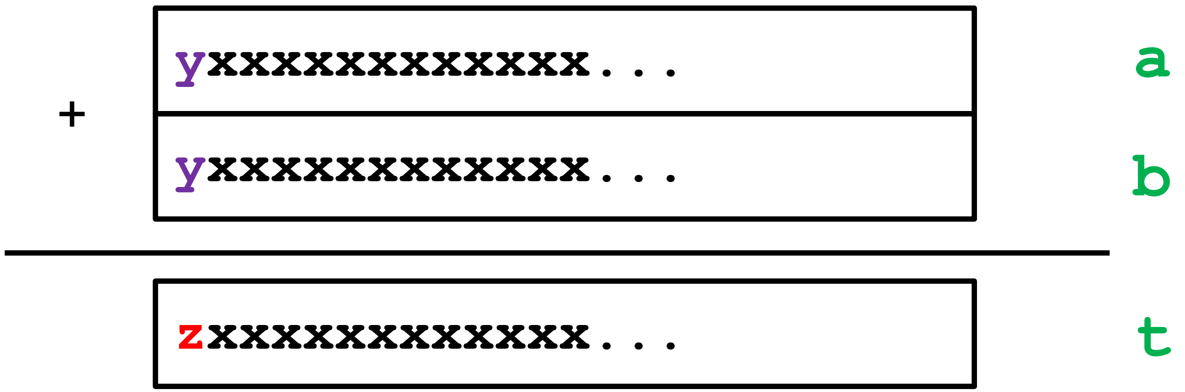
Borrow

For unsigned arithmetic, this reports overflow

OF set when

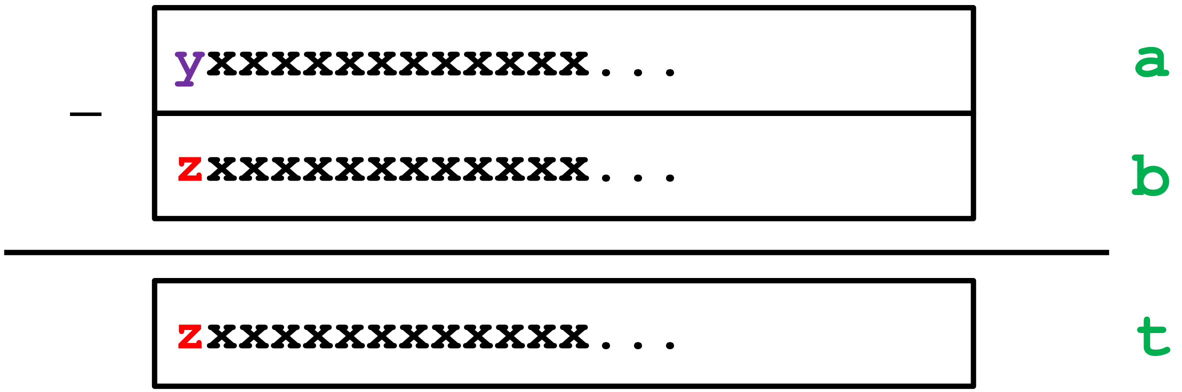
For signed arithmetic, this reports overflow

z = ~y



Positive Overflow

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



Negative Overflow

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

Compare Instruction

- **`cmp a, b`**
  - Computes $b - a$ (just like **`sub`**)
  - Sets condition codes based on result, but…
  - **Does not change *b***

  - Used for **`if (a < b) { … }`**
    whenever $b - a$ isn't needed for anything else

Test Instruction

- `test a, b`
  - Computes $b\&a$ (just like **`and`**)
  - Sets condition codes (only SF and ZF) based on result, but…
  - **Does not change *b***
  - Most common use: `test %rX, %rX`
    to compare `%rX` to zero
  - Second most common use: `test %rX, %rY`
    tests if any of the 1-bits in `%rY` are also 1 in `%rX` (or vice versa)

Today

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

Jumping

jX Instructions

- Jump to different part of code depending on condition codes

jX	Condition	Description
jmp	1	Unconditional
je	ZF	Equal / Zero
jne	~ZF	Not Equal / Not Zero
js	SF	Negative
jns	~SF	Nonnegative
jg	~(SF^OF)&~ZF	Greater (Signed)
jge	~(SF^OF)	Greater or Equal (Signed)
jl	(SF^OF)	Less (Signed)
jle	(SF^OF)|ZF	Less or Equal (Signed)
ja	~CF&~ZF	Above (unsigned)
jb	CF	Below (unsigned)

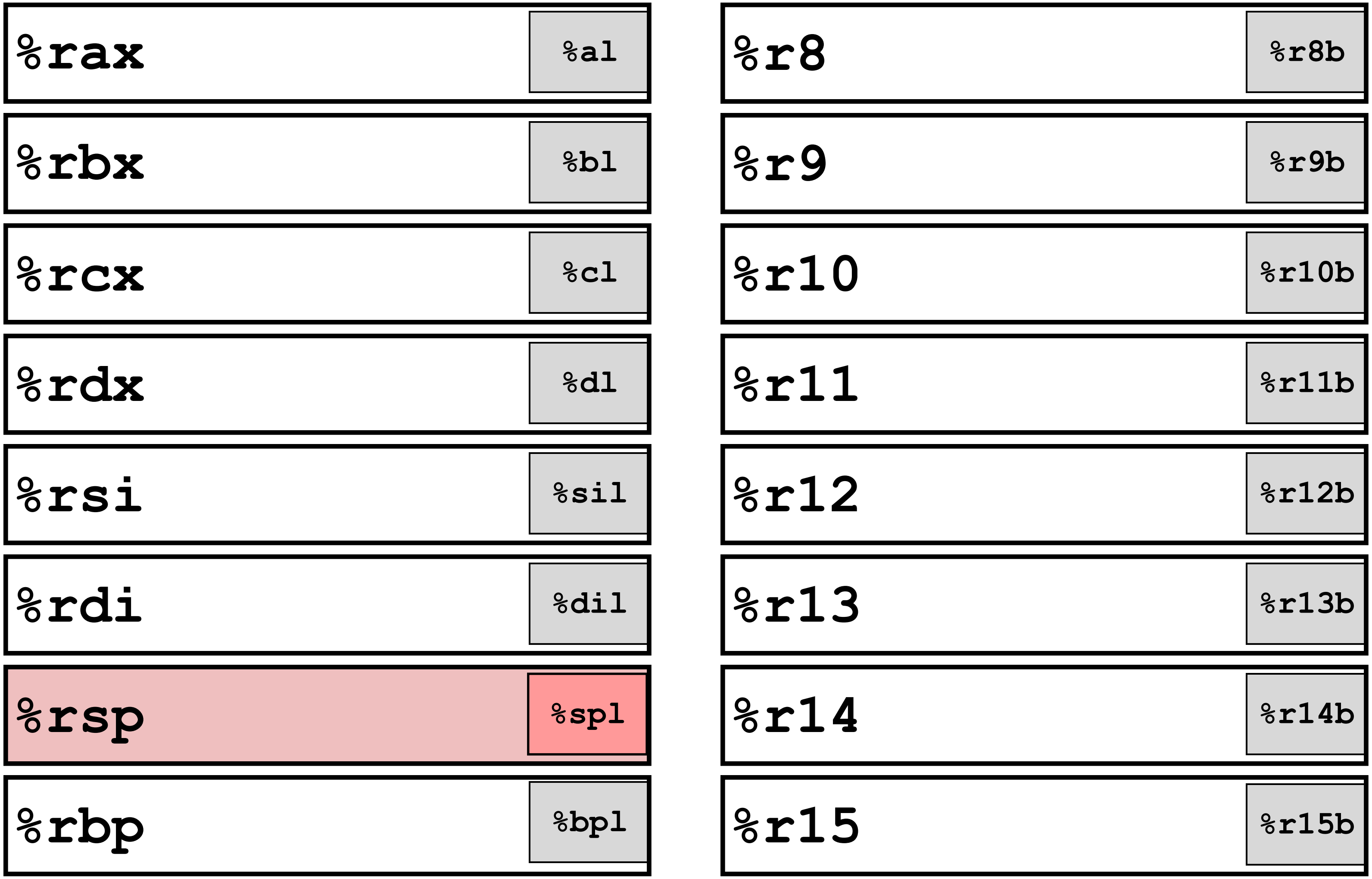
Reading Condition Codes

SetX Instructions

- Set low-order byte of destination to 0 or 1 based on *combinations* of condition codes
- Does not alter remaining 7 bytes

SetX	Condition	Description
`sete`	`ZF`	Equal / Zero
`setne`	`~ZF`	Not Equal / Not Zero
`sets`	`SF`	Negative
`setns`	`~SF`	Nonnegative
`setg`	`~(SF^OF)&~ZF`	Greater (Signed)
`setge`	`~(SF^OF)`	Greater or Equal (Signed)
`setl`	`(SF^OF)`	Less (Signed)
`setle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`seta`	`~CF&~ZF`	Above (unsigned)
`setb`	`CF`	Below (unsigned)

x86-64 Integer Registers

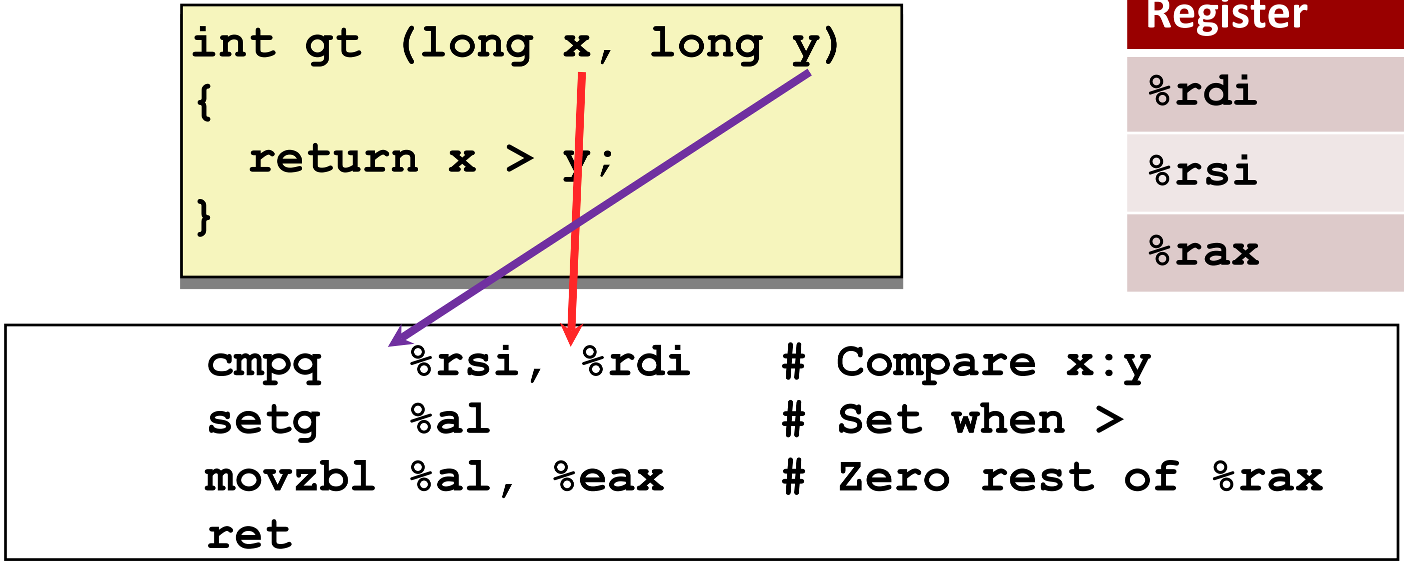


%rax	%al	%r8	%r8b
%rbx	%bl	%r9	%r9b
%rcx	%cl	%r10	%r10b
%rdx	%dl	%r11	%r11b
%rsi	%sil	%r12	%r12b
%rdi	%dil	%r13	%r13b
%rsp	%spl	%r14	%r14b
%rbp	%bpl	%r15	%r15b

- SetX argument is always a low byte (%al, %r8b, etc.)

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;
}
```

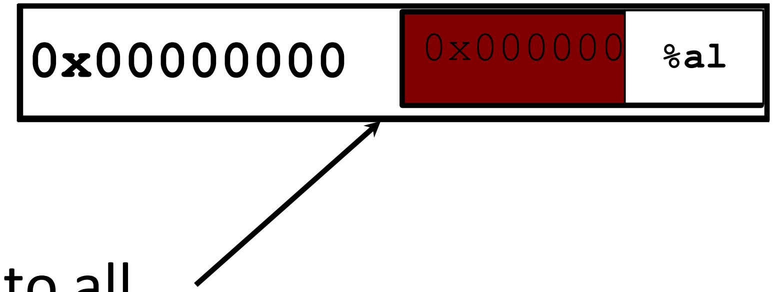
```
        cmpq    %rsi, %rdi    # Compare x:y
        setg    %al           # Set when >
        movzbl  %al, %eax     # Zero rest of %rax
        ret
```

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

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
```

Activity Time!

To obtain a copy of today's activity, log into a shark machine and do the following:

```
$ wget http://www.cs.cmu.edu/~213/activities/machine-control.tar
$ tar xf machine-control.tar
$ cd machine-control
```

Do (only) "3 Basic Control Flow", problems 1, 2, and 3

Conditional Branch Example (Old Style)

- Generation

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

I'll 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);
```

- 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

Today

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

“Do-While” Loop Example

C Code

```
long pcount_do
  (unsigned long x) {
  long result = 0;
  do {
    result += x & 0x1;
    x >>= 1;
  } while (x);
  return result;
}
```

Goto Version

```
long pcount_goto
  (unsigned long x) {
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
  return result;
}
```

- Count number of 1’s in argument **x** (“popcount”)
- Use conditional branch to either continue looping or to exit loop

“Do-While” Loop Compilation

Goto Version

```
long pcount_goto
  (unsigned long x) {
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
  return result;
}
```

Register	Use(s)
`%rdi`	Argument **`x`**
`%rax`	**`result`**

```
    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!

Canvas Quiz: Day 4 - Machine Control

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 → Do-While Loop

For version

```
  for  (Init;  Test;  Update )

             Body
```

- Initial test can often be optimized away – why?

Do-While Version

```
   if  (!Test)
     goto done;
   do {
     Body
     Update
   } while(Test);
done:
```

Goto Version

```
   if  (!Test)
     goto done;
loop:
   Body
   Update
   if  (Test)
     goto loop;
done:
```

"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;
  ~~if (!(i < WSIZE))~~
    ~~goto done;~~
 loop:
  {
    unsigned bit =
       (x >> i) & 0x1;
    result += bit;
  }
  i++;
  if (i < WSIZE)
    goto loop;
 done:
  return result;
}
```

Init

!Test

Body

Update

Test

- Initial test can be optimized away

Activity Time!

Do “6 Loops”, problems 15, 16, and 17

Today

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

Switch Statement Example

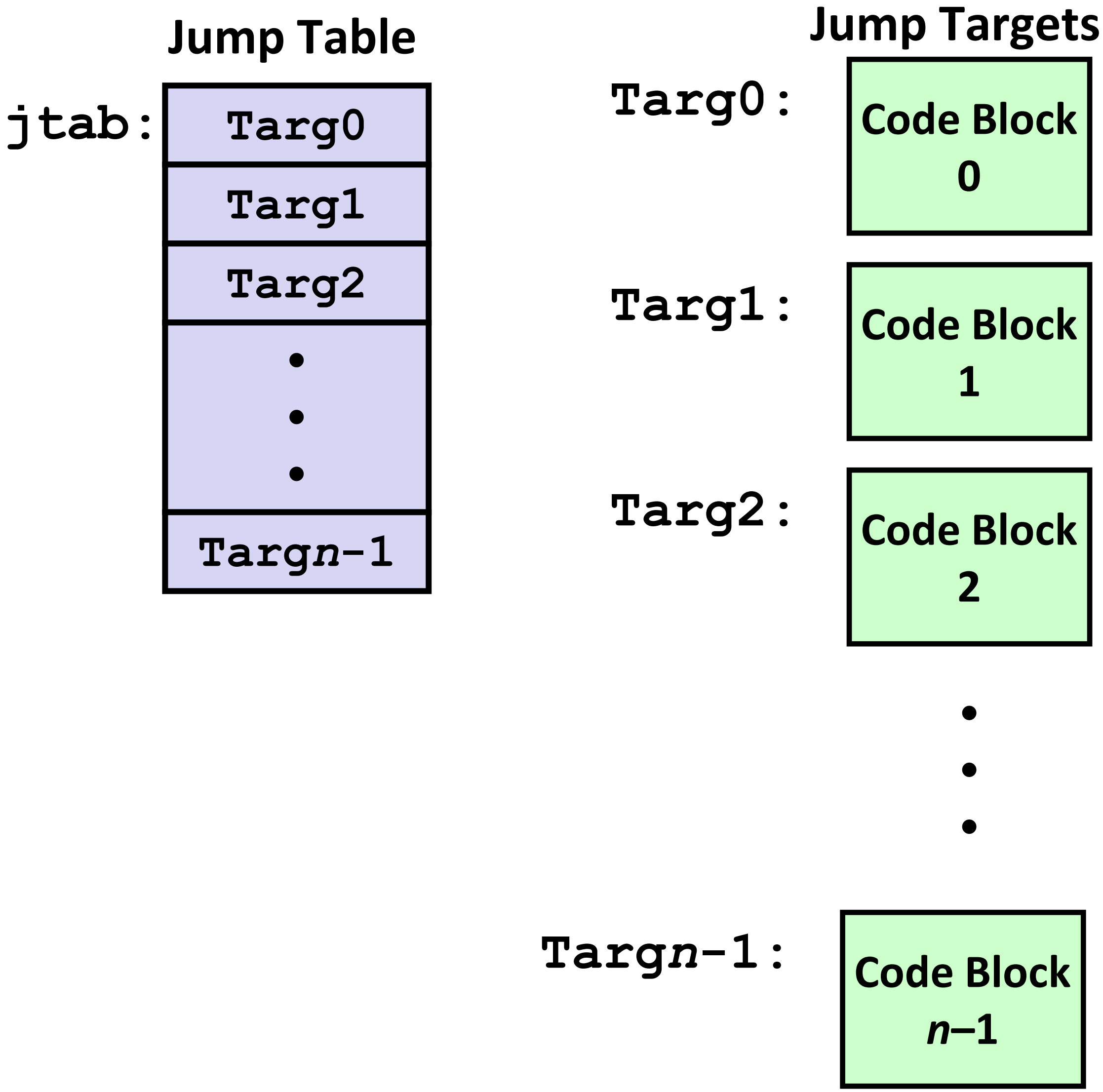
```
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

- 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
}
```



Jump Table

jtab: Targ0 | Targ1 | Targ2 | • • • | Targn-1

Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

• • •

Targn-1: Code 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 ≤ `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
```

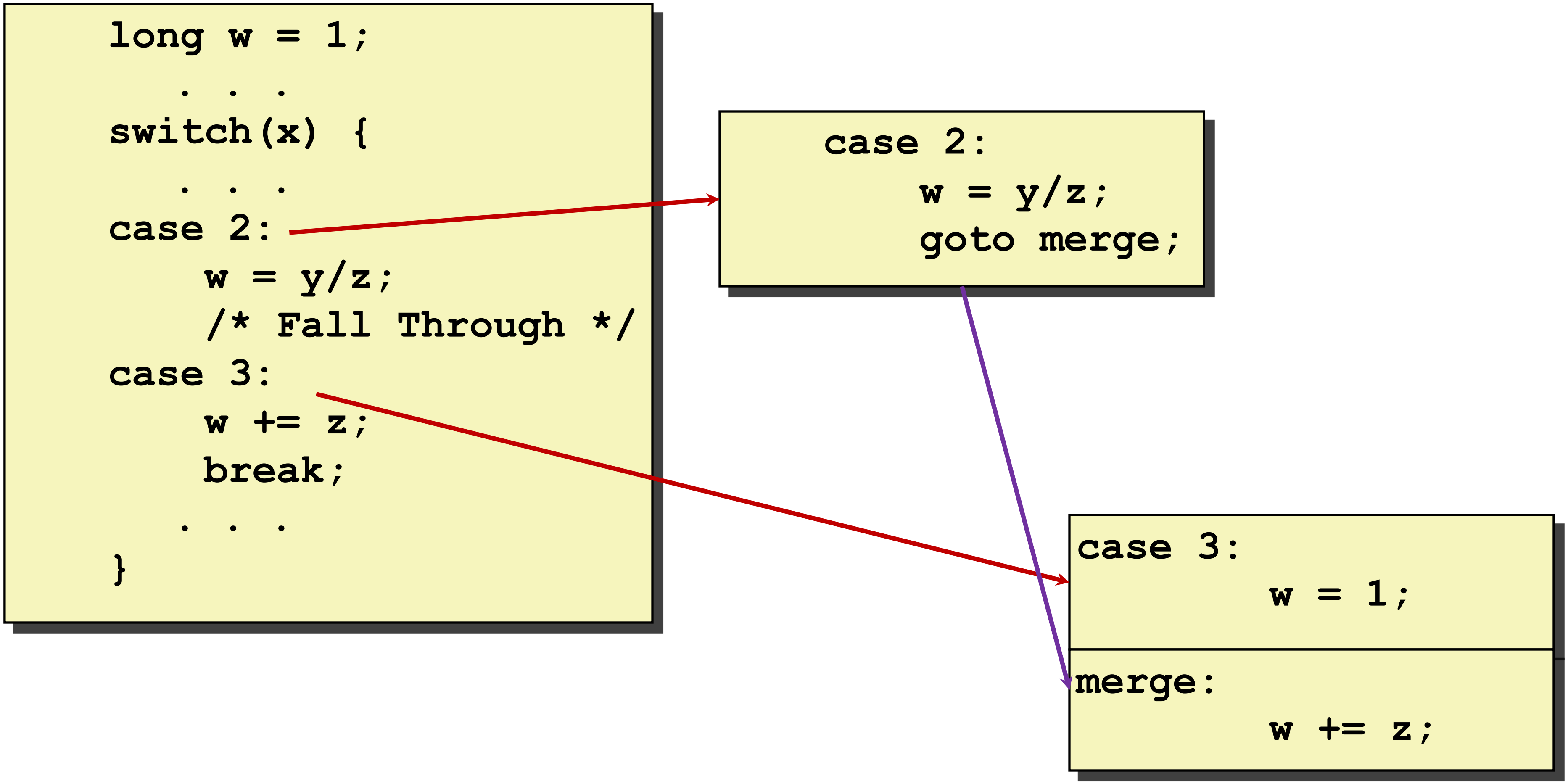
Code Blocks (x == 1)

```
  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

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)

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
`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)

```
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

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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
`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 **`movzbl`** do not modify condition codes

Switch Statement Example

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

Setup:

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

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

What range of values takes default?

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
```

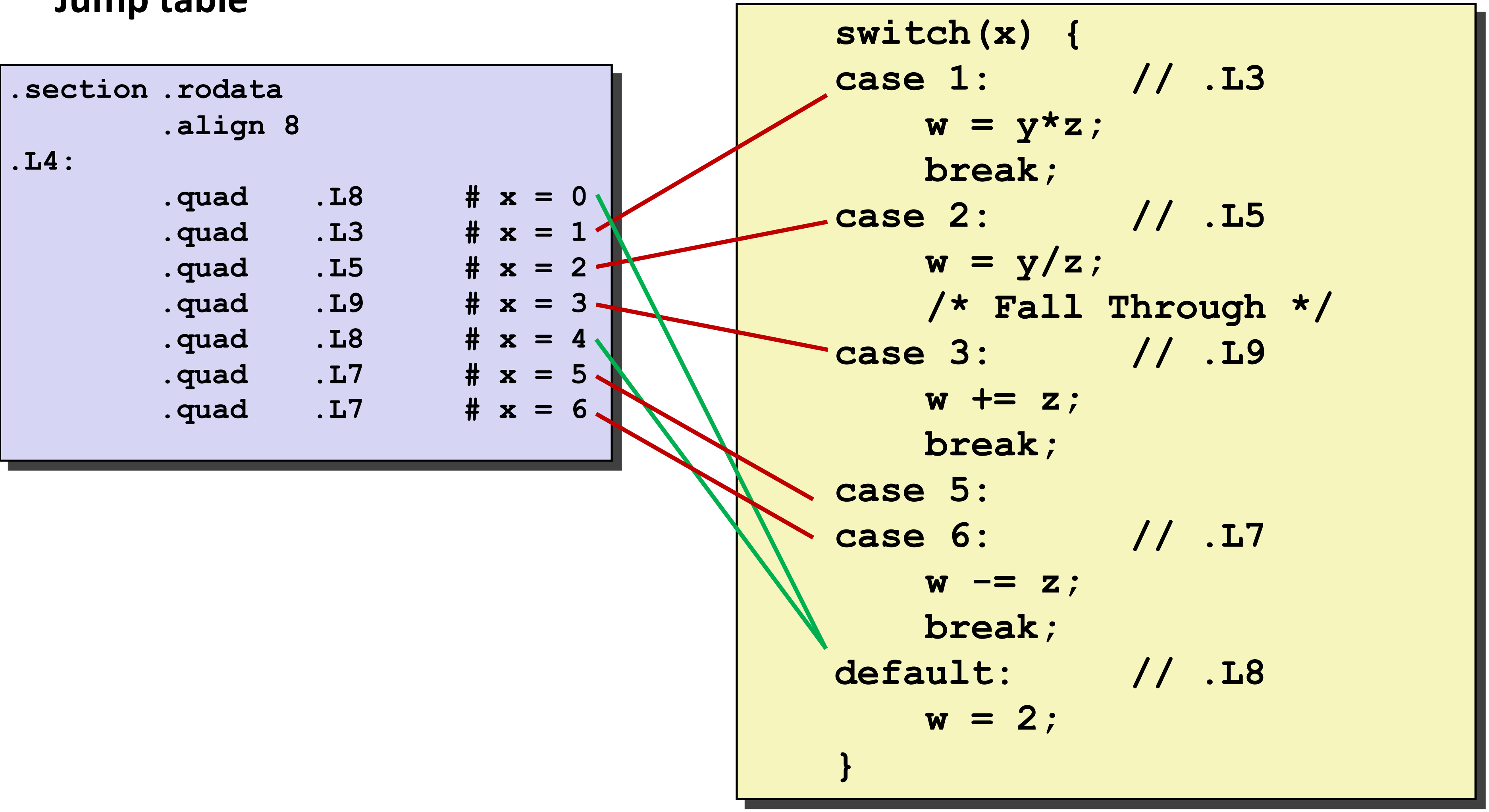
Setup:

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

Indirect jump → jmp

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;
}
```

Finding Jump Table in Binary

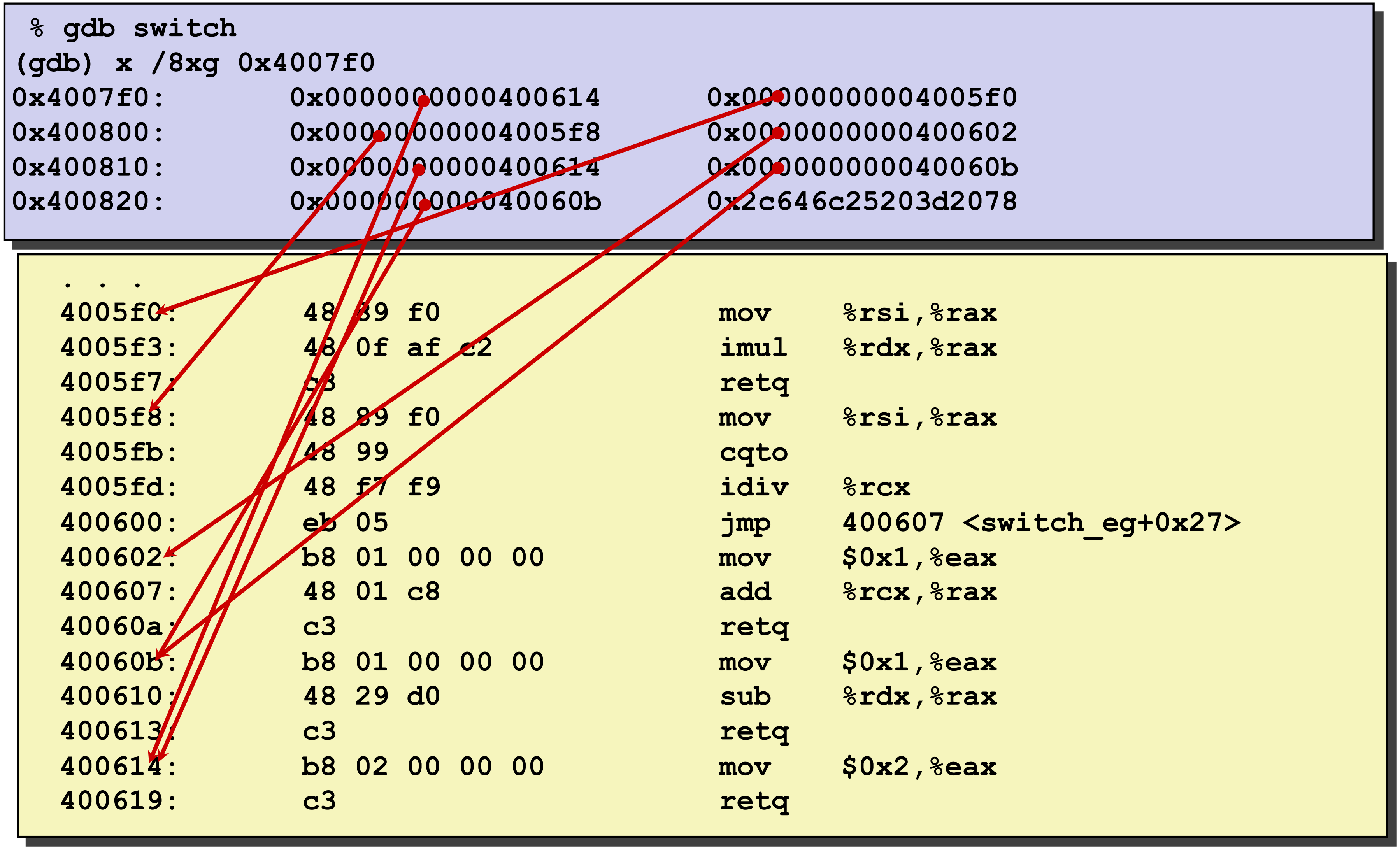
```
 00000000004005e0 <switch_eg>:
4005e0:       48 89 d1                mov    %rdx,%rcx
4005e3:       48 83 ff 06             cmp    $0x6,%rdi
4005e7:       77 2b                   ja     400614 <switch_eg+0x34>
4005e9:       ff 24 fd f0 07 40 00    jmpq   *0x4007f0(,%rdi,8)
4005f0:       48 89 f0                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
```

Reminder: Machine Instructions

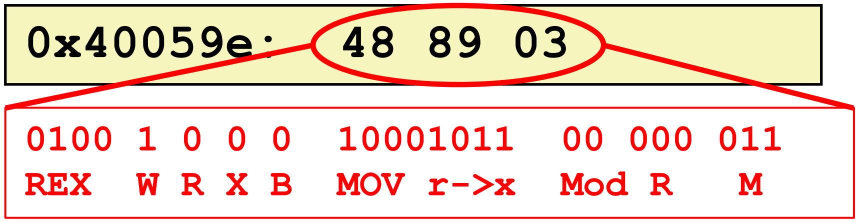
```
*dest = t;
```

- **C**
  - Store value **t** where designated by **dest**

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

- **Assembly**
  - Move 8-byte value to memory
    - Quad words in x86-64 parlance
  - Operands:

t:	Register **%rax**
dest:	Register **%rbx**
***dest:**	Memory **M[%rbx]**



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

```
0100 1 0 0 0  10001011  00 000 011
REX  W R X B  MOV r->x  Mod R   M
```

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

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**