Machine-Level Programming II: Control

Introduction to Computer Systems
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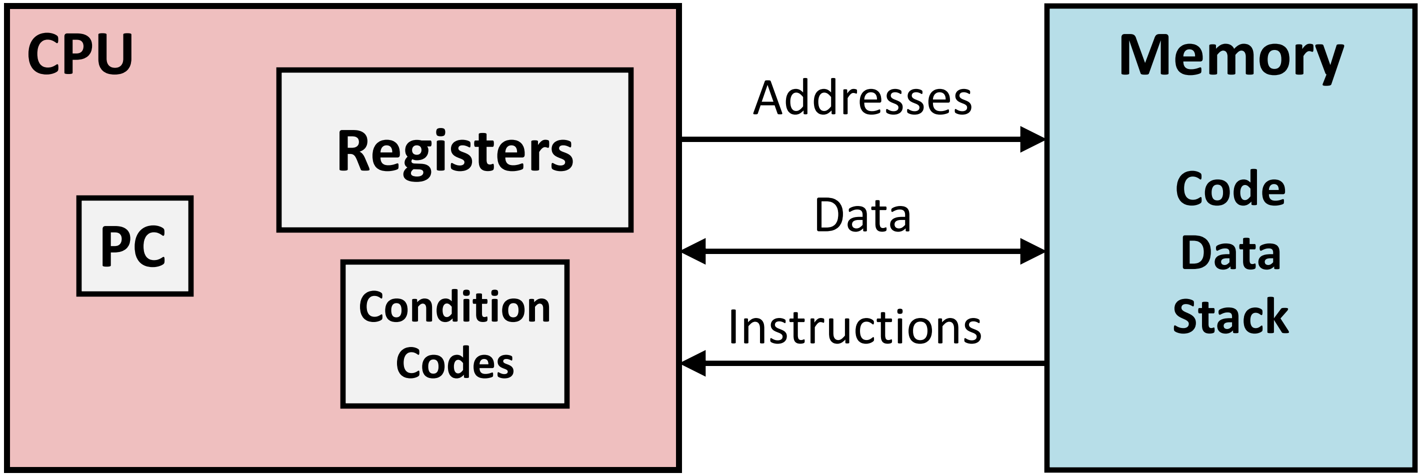
Recall: ISA = Assembly/Machine Code View



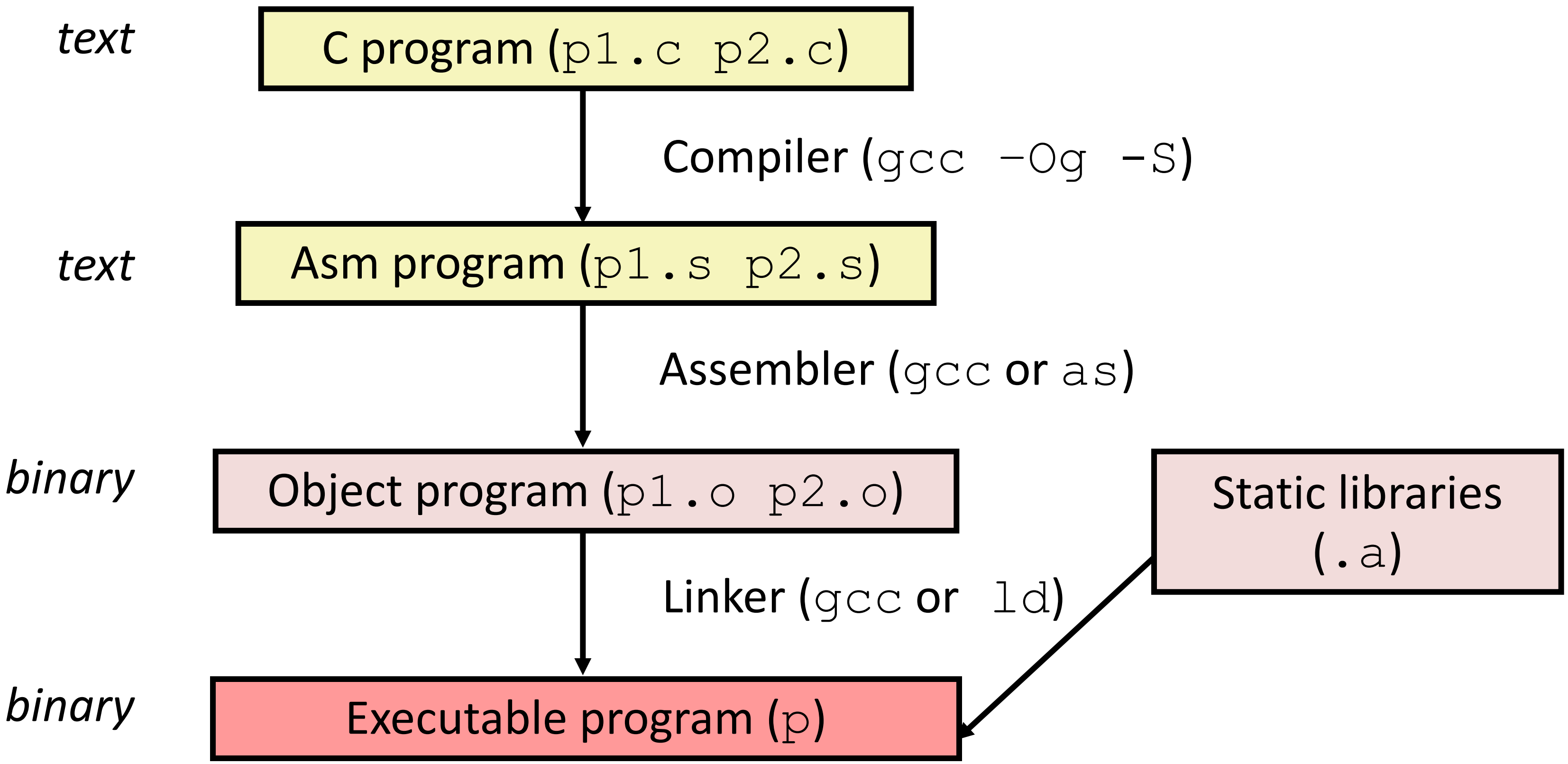
Programmer-Visible State

- **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: 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`**



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

- **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**

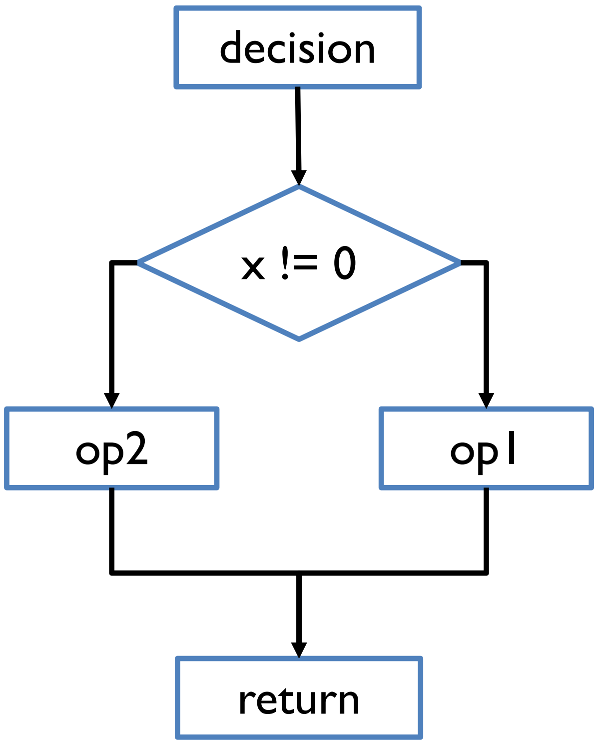
Today

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

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) by 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…0000000000

SF set when

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

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

CF set when

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


 1   0xxxxxxxxxxxx...
 -   1xxxxxxxxxxxx...        Borrow
 ---------------------
     1xxxxxxxxxxxx...
```

For unsigned arithmetic, this reports overflow

OF set when

```
   yxxxxxxxxxxxxx...      a
+  yxxxxxxxxxxxxx...      b
------------------------
   zxxxxxxxxxxxxx...      t
```

$$z = \sim y$$

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

For signed arithmetic, this reports overflow

Condition Codes (Explicit Setting: Compare)

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

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

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

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
```

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)

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

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;
}
```

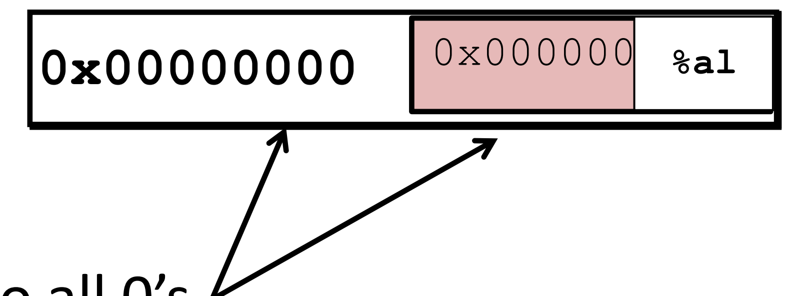
Register	Use(s)
%rdi	Argument **x**
%rsi	Argument **y**
%rax	Return value

```
    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

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**

```
server> 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
```

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

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

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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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`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
0x0000 0000 0000 0000	0	0	0	1
0xFFFF FFFF FFFF FFFF	1	1	0	0
0xFFFF FFFF FFFF FFFF	1	0	0	0
0xFFFF FFFF FFFF FF01	1	0	0	0
0x0000 0000 0000 0001	1	0	0	0

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

Today

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

"Do-While" Loop Example

C Code

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

Goto Version

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

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

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:**
```
{
  Statement_1;
  Statement_2;
    …
  Statement_n;
}
```

"Do-While" Loop Compilation

Goto Version

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

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

```
        movl    $0, %eax     #  result = 0
.L2:                         # loop:
        movq    %rdi, %rdx
        andl    $1, %edx     #  t = x & 0x1
        addq    %rdx, %rax   #  result += t
        shrq    %rdi         #  x >>= 1
        jne     .L2          #  if (x) goto loop
        rep; ret
```

General "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)
    goto loop;                Test
 done:
  return result;
}
```

Today

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

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

Switch Statement Example

- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

Jump Table Structure

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```

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

Setup:

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

What range of values takes default?

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

Note that **w** not initialized here

Switch Statement Example

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

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad     .L8   # x = 0
  .quad     .L3   # x = 1
  .quad     .L5   # x = 2
  .quad     .L9   # x = 3
  .quad     .L8   # x = 4
  .quad     .L7   # x = 5
  .quad     .L7   # x = 6
```

Setup:

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

Indirect jump

Assembly Setup Explanation

- **Table Structure**
  - Each target requires 8 bytes
  - Base address at `.L4`

- **Jumping**
  - Direct: `jmp .L8`
  - Jump target is denoted by label `.L8`

  - Indirect: `jmp *.L4(,%rdi,8)`
  - Start of jump table: `.L4`
  - Must scale by factor of 8 (addresses are 8 bytes)
  - Fetch target from effective Address `.L4 + x*8`
    - Only for $0 \le x \le 6$

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
   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)

Summary

- **Today**
  - Control: Condition codes
  - Conditional branches & conditional moves
  - Loops
  - Switch statements
- **Next Time**
  - Stack
  - Call / return
  - Procedure call discipline

Additional Slides

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
```