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CS 270: Computer Organization

Machine Representation of Programs II

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Instruction Suffixes

- **Byte `(b)` means 1 Byte**
  Word `(w)` means 2 Bytes
  Long word `(l)` means 4 Bytes
  Quad word `(q)` means 8 Bytes

- **Instruction suffixes:**
  `movb, movw, movl, movq`
  `addb, addw, addl, addq`
  `salb, salw, sall, salq`
  etc.

- **32-bit instructions generate 32-bit results**
  - Set higher order bits of destination register to 0
  - Example: `addl`

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Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

$2^{13} = 8192, 2^{13} - 7 = 8185$

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	t1, t2, rval

```
Logical:
  movl %rdi, %rax
  xorl %rsi,%rax # rax = x^y
  sarl $17,%rax  # rax = t1>>17
  # compiler precomputes 1<<13-7
  # rax = t2 & mask
  andl $8185,%rax
  ret
```

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Another Example

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

$2^{13} = 8192, 2^{13} - 7 = 8185$

```
logical:
   pushl %ebp              } Set
   movl %esp,%ebp          } Up

   movl 8(%ebp),%eax       }
   xorl 12(%ebp),%eax      }
   sarl $17,%eax           }
   andl $8185,%eax         } Body

   movl %ebp,%esp          }
   popl %ebp               } Finish
   ret                     }
```

```
movl 8(%ebp),%eax      eax = x
xorl 12(%ebp),%eax     eax = x^y     (t1)
sarl $17,%eax          eax = t1>>17  (t2)
andl $8185,%eax        eax = t2 & 8185
```

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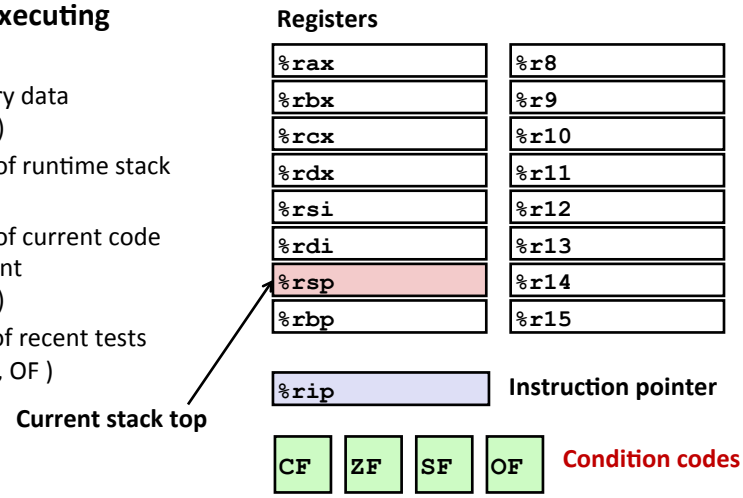
Processor State (x86-64, Partial)

Information about currently executing program

- Temporary data (`%rax`, …)
- Location of runtime stack (`%rsp`)
- Location of current code control point (`%rip`, …)
- -m Status of recent tests (CF, ZF, SF, OF)



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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 (think of it as side effect) by 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 `leaq` instruction**

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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)
```

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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`

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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)

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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

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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
```

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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)

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Conditional Branch Example (Old Style)

Generation

```
$ 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
   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

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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;
}
```

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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

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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;
```

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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
```

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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

Risky Computations

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

- Both values get computed
- May have undesirable effects

Computations with side effects

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

- Both values get computed
- Must be side-effect free

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"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

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"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
```

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General "Do-While" Translation

C Code

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

Goto Version

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

Body:

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

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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:
```

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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

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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:
```

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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

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"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;
}
```

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"For" Loop → While Loop

For Version

```
for (Init; Test; Update)
    Body
```

While Version

```
Init;
while (Test) {
    Body
    Update;
}
```

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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;
}
```

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"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

Goto Version

```
long pcount_for_goto_dw
  (unsigned long x) {
  size_t i;
  long result = 0;
  i = 0;                          Init
  if (!(i < WSIZE))               !Test
    goto done;
 loop:
  {
    unsigned bit =
      (x >> i) & 0x1;             Body
    result += bit;
  }
  i++;                            Update
  if (i < WSIZE)                  Test
    goto loop;
 done:
  return result;
}
```

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Implementing Loops

IA32

- All loops translated into form based on "do-while"

x86-64

- Also make use of "jump to middle"

Why the difference?

- IA32 compiler developed for machine where all operations costly
- x86-64 compiler developed for machine where unconditional branches incur (almost) no overhead