Lecture 5: More machine operations

Computer Architecture and
Systems Programming
(252-0061-00)

Timothy Roscoe

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Last time: Machine programming, basics

- History of Intel processors and architectures
- C, assembly, machine code
- Assembly (IA32):
  - Registers
  - Operands
  - Move (what's the `l` in `movl`?)

```
movl $0x4,%eax
movl %eax,%edx
movl (%eax),%edx
```

%eax
%ecx
%edx
%ebx
%esi
%edi
%esp
%ebp

Today

- Complete addressing mode, address computation (`leal`)
- Arithmetic operations
- x86-64
- Control: Condition codes
- Conditional branches
- While loops

Complete memory 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 8 integer registers
- Ri: Index register: Any, except for **%esp**
  - Unlikely you'd use **%ebp**, either
- S: Scale: 1, 2, 4, or 8 (*why these numbers?*)

- 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]]

Address computation examples

%edx	0xf000
%ecx	0x100

Expression	Address Computation	Address
0x8(%edx)	0xf000 + 0x8	0xf008
(%edx,%ecx)	0xf000 + 0x100	0xf100
(%edx,%ecx,4)	0xf000 + 4*0x100	0xf400
0x80(,%edx,2)	2*0xf000 + 0x80	0x1e080

Address computation instruction

- `leal` ***Src,Dest***
  - ***Src*** is address mode expression
  - Set ***Dest*** to address denoted by expression

- Uses
  - Computing addresses without a memory reference
    - E.g., translation of `p = &x[i];`
  - Computing arithmetic expressions of the form x + k*y
    - k = 1, 2, 4, or 8

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Some arithmetic operations

- Two operand instructions:

Format		*Computation*	
`addl`	*Src,Dest*	*Dest ← Dest + Src*	
`subl`	*Src,Dest*	*Dest ← Dest - Src*	
`imull`	*Src,Dest*	*Dest ← Dest * Src*	
`sall`	*Src,Dest*	*Dest ← Dest << Src*	*Also called shll*
`sarl`	*Src,Dest*	*Dest ← Dest >> Src*	*Arithmetic*
`shrl`	*Src,Dest*	*Dest ← Dest >> Src*	*Logical*
`xorl`	*Src,Dest*	*Dest ← Dest ^ Src*	
`andl`	*Src,Dest*	*Dest ← Dest & Src*	
`orl`	*Src,Dest*	*Dest ← Dest | Src*	

- No distinction between signed and unsigned int (why?)

Some arithmetic operations

- One operand instructions

Format		*Computation*
`incl`	*Dest*	*Dest ← Dest + 1*
`decl`	*Dest*	*Dest ← Dest - 1*
`negl`	*Dest*	*Dest ← -Dest*
`notl`	*Dest*	*Dest ← ~Dest*

- See book for more instructions

Using `leal` for arithmetic expressions

```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```

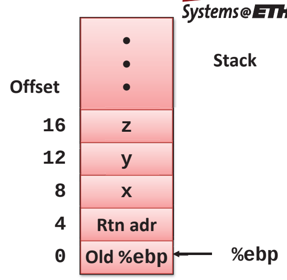
```
arith:
   pushl %ebp                  } Set Up
   movl %esp,%ebp

   movl 8(%ebp),%eax           } Body
   movl 12(%ebp),%edx
   leal (%edx,%eax),%ecx
   leal (%edx,%edx,2),%edx
   sall $4,%edx
   addl 16(%ebp),%ecx
   leal 4(%edx,%eax),%eax
   imull %ecx,%eax

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


Understanding `arith`

```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```




```
movl 8(%ebp),%eax         # eax = x
movl 12(%ebp),%edx        # edx = y
leal (%edx,%eax),%ecx     # ecx = x+y  (t1)
leal (%edx,%edx,2),%edx   # edx = 3*y
sall $4,%edx              # edx = 48*y (t4)
addl 16(%ebp),%ecx        # ecx = z+t1 (t2)
leal 4(%edx,%eax),%eax    # eax = 4+t4+x (t5)
imull %ecx,%eax           # eax = t5*t2 (rval)
```


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;
}
```

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

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

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

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

```
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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- Complete addressing mode, address computation (**leal**)
- Arithmetic operations
- x86-64
- Control: Condition codes
- Conditional branches
- While loops

Data representations: ia32 and x86-64

- Sizes of C objects (in bytes)

C data type	Typical 32-bit	ia32	Intel x86-64
`char`	1	1	1
`short`	2	2	2
`int`	4	4	4
`long`	4	4	8
`long long`	8	8	8
`float`	4	4	4
`double`	8	8	8
`long double`	8	10/12	10/16
`char *` (or any other pointer	4	4	8

x86-64 integer registers

`%rax`	`%eax`	`%r8`	`%r8d`
`%rbx`	`%ebx`	`%r9`	`%r9d`
`%rcx`	`%ecx`	`%r10`	`%r10d`
`%rdx`	`%edx`	`%r11`	`%r11d`
`%rsi`	`%esi`	`%r12`	`%r12d`
`%rdi`	`%edi`	`%r13`	`%r13d`
`%rsp`	`%esp`	`%r14`	`%r14d`
`%rbp`	`%ebp`	`%r15`	`%r15d`

- Extend existing registers. Add 8 new ones.
- Make **%ebp/%rbp** general purpose

Instructions

- Long word **l** (4 Bytes) ↔ Quad word **q** (8 Bytes)
- New instructions:
  - **movl** → **movq**
  - **addl** → **addq**
  - **sall** → **salq**
  - etc.
- 32-bit instructions that generate 32-bit results
  - Set higher order bits of destination register to 0
  - Example: **addl**

Swap in 32-bit mode

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
    pushl %ebp
    movl  %esp,%ebp        } Setup
    pushl %ebx

    movl 12(%ebp),%ecx
    movl 8(%ebp),%edx
    movl (%ecx),%eax       } Body
    movl (%edx),%ebx
    movl %eax,(%edx)
    movl %ebx,(%ecx)

    movl -4(%ebp),%ebx
    movl %ebp,%esp         } Finish
    popl %ebp
    ret
```


Swap in 64-bit Mode

```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
    movl    (%rdi), %edx
    movl    (%rsi), %eax
    movl    %eax, (%rdi)
    movl    %edx, (%rsi)
    retq
```

- Operands passed in registers (why useful?)
  - First (**xp**) in **%rdi**, second (**yp**) in **%rsi**
  - 64-bit pointers
- No stack operations required
- 32-bit data
  - Data held in registers **%eax** and **%edx**
  - **movl** operation

Swap Long Ints in 64-bit Mode

```
void swap_l
  (long int *xp, long int *yp)
{
  long int t0 = *xp;
  long int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap_l:
    movq    (%rdi), %rdx
    movq    (%rsi), %rax
    movq    %rax, (%rdi)
    movq    %rdx, (%rsi)
    retq
```

- 64-bit data
  - Data held in registers **%rax** and **%rdx**
  - **movq** operation
  - "**q**" stands for quad-word

Today

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Processor State (ia32, Partial)

- Information about currently executing program
  - Temporary data (**%eax**, …)
  - Location of runtime stack (**%ebp**, **%esp**)
  - Location of current code control point (**%eip**, …)
  - Status of recent tests (**CF**, **ZF**, **SF**, **OF**)

%eax
%ecx
%edx
%ebx
%esi
%edi

General purpose registers

%esp — Current stack top
%ebp — Current stack frame

%eip — 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 (think of it as side effect) by arithmetic operations
  Example: **addl/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** instruction
- Full documentation (ia32), link also on course website

Condition Codes (Explicit Setting: Compare)

- Explicit Setting by Compare Instruction

  cmpl/cmpq ***Src2,Src1***

  cmpl 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

  testl/testq ***Src2,Src1***

  testl b,a like computing **a&b** w/o 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**

Reading Condition Codes

- SetX Instructions
  - Set single byte based on combinations of condition codes

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)

Reading Condition Codes (Cont.)

- **`setx`** Instructions:
  Set single byte based on combination of condition codes
- One of 8 addressable byte registers
  - Does not alter remaining 3 bytes
  - Typically use **`movzbl`** to finish job

`%eax`	`%ah`	`%al`
`%ecx`	`%ch`	`%cl`
`%edx`	`%dh`	`%dl`
`%ebx`	`%bh`	`%bl`
`%esi`		
`%edi`		
`%esp`		
`%ebp`		

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

Body

```
movl 12(%ebp),%eax      # eax = y
cmpl %eax,8(%ebp)       # Compare x : y
setg %al                # al = x > y
movzbl %al,%eax         # Zero rest of %eax
```


Reading Condition Codes: x86-64

- **`setx`** Instructions:
  - Set single byte based on combination of condition codes
  - Does not alter remaining 3 bytes

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

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

Body (same for both)

```
xorl %eax, %eax        # eax = 0
cmpq %rsi, %rdi        # Compare x and y
setg %al               # al = x > y
```

Is **`%rax`** zero?
Yes: 32-bit instructions set high order 32 bits to 0!

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)

Today

- Complete addressing mode, address computation (**`leal`**)
- Arithmetic operations
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Conditional Branch Example

```
int absdiff(int x, int y)
{
    int result;
    if (x > y) {
        result = x-y;
    } else {
        result = y-x;
    }
    return result;
}
```

```
absdiff:
    pushl   %ebp                 } Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx        } Body1
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L7
    subl    %eax, %edx
    movl    %edx, %eax
.L8:
    leave                        } Finish
    ret
.L7:
    subl    %edx, %eax           } Body2
    jmp     .L8
```

Conditional Branch Example

```
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
Exit:
  return result;
Else:
  result = y-x;
  goto Exit;
}
```

```
absdiff:
    pushl   %ebp
    movl    %esp, %ebp
    movl    8(%ebp), %edx
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L7
    subl    %eax, %edx
    movl    %edx, %eax
.L8:
    leave
    ret
.L7:
    subl    %edx, %eax
    jmp     .L8
```

- C allows "goto" as means of transferring control
  - Closer to machine-level programming style
- Generally considered bad coding style

General Conditional Expression Translation

C Code

```
val = Test ? Then-Expr : Else-Expr;
```

```
val = x>y ? x-y : y-x;
```

- Test is expression returning integer
  - = 0 interpreted as false
  - ≠0 interpreted as true
- Create separate code regions for then & else expressions
- Execute appropriate one

Goto Version

```
  nt = !Test;
  if (nt) goto Else;
  val = Then-Expr;
Done:
  . . .
Else:
  val = Else-Expr;
  goto Done;
```


Conditionals: x86-64

```
int absdiff(
    int x, int y)
{
    int result;
    if (x > y) {
        result = x-y;
    } else {
        result = y-x;
    }
    return result;
}
```

```
absdiff: # x in %edi, y in %esi
  movl   %edi, %eax  # eax = x
  movl   %esi, %edx  # edx = y
  subl   %esi, %eax  # eax = x-y
  subl   %edi, %edx  # edx = y-x
  cmpl   %esi, %edi  # x:y
  cmovle %edx, %eax  # eax=edx if <=
  ret
```

- Conditional move instruction
  - `cmov`*C* ***src, dest***
  - Move value from ***src*** to ***dest*** if condition *C* holds
  - More efficient than conditional branching (simple control flow)
  - But overhead: both branches are evaluated

General Form with Conditional Move

C Code

```
val = Test ? Then-Expr : Else-Expr;
```

Conditional Move Version

```
val1  = Then-Expr;
val2  = Else-Expr;
val1  = val2 if  !Test;
```

- Both values get computed
- Overwrite then-value with else-value if condition doesn't hold
- Don't use when:
  - Then or else expressions have side effects
  - Then and else expressions are too expensive

Today

- Complete addressing mode, address computation (`leal`)
- Arithmetic operations
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"Do-While" Loop Example

C Code

```
int fact_do(int x)
{
  int result = 1;
  do {
    result *= x;
    x = x-1;
  } while (x > 1);

  return result;
}
```

Goto Version

```
int fact_goto(int x)
{
  int result = 1;
loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto loop;
  return result;
}
```

- Use backward branch to continue looping
- Only take branch when "while" condition holds

"Do-While" Loop Compilation

Registers:

%edx	x
%eax	result

Goto Version

```
int
fact_goto(int x)
{
  int result = 1;


loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto loop;

  return result;
}
```

Assembly

```
fact_goto:
  pushl %ebp           # Setup
  movl %esp,%ebp       # Setup
  movl $1,%eax         # eax = 1
  movl 8(%ebp),%edx    # edx = x

.L11:
  imull %edx,%eax      # result *= x
  decl %edx            # x--
  cmpl $1,%edx         # Compare x : 1
  jg .L11              # if > goto loop

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


General "Do-While" Translation

C Code

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

Goto Version

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

- Body: {
  Statement$_1$;
  Statement$_2$;
  …
  Statement$_n$;
  }
- Test returns integer
  = 0 interpreted as false
  ≠0 interpreted as true

"While" Loop Example

C Code

```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {


    result *= x;
    x = x-1;
  };

  return result;
}
```

Goto Version #1

```
int fact_while_goto(int x)
{
  int result = 1;
loop:
  if (!(x > 1))
    goto done;
  result *= x;
  x = x-1;
  goto loop;
done:
  return result;
}
```

- Is this code equivalent to the do-while version?
- Must jump out of loop if test fails

Alternative "While" Loop Translation

C Code

```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {
    result *= x;
    x = x-1;
  };
  return result;
}
```

- Historically used by GCC
- Uses same inner loop as do-while version
- Guards loop entry with extra test

Goto Version #2

```
int fact_while_goto2(int x)
{
  int result = 1;
  if (!(x > 1))
    goto done;
loop:
  result *= x;
  x = x-1;
  if (x > 1)
    goto loop;
done:
  return result;
}
```


General "While" Translation

While version

```
while (Test)
  Body
```

Do-While Version

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

Goto Version

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


New Style "While" Loop Translation

C Code

```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {
    result *= x;
    x = x-1;
  };
  return result;
}
```

- Recent technique for GCC
  - Both IA32 & x86-64
- First iteration jumps over body computation within loop

Goto Version

```
int fact_while_goto3(int x)
{
  int result = 1;
  goto middle;
loop:
  result *= x;
  x = x-1;
middle:
  if (x > 1)
    goto loop;
  return result;
}
```

Jump-to-Middle While Translation

C Code

```
while (Test)
  Body
```

- Avoids duplicating test code
- Unconditional **goto** incurs no performance penalty
- **for** loops compiled in similar fashion

Goto Version

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

Goto (Previous) Version

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


Jump-to-Middle Example

```
int fact_while(int x)
{
  int result = 1;
  while (x > 1) {
    result *= x;
    x--;
  };
  return result;
}
```

```
# x in %edx, result in %eax
  jmp   .L34        #   goto Middle
.L35:               # Loop:
  imull %edx, %eax  #   result *= x
  decl  %edx        #   x--
.L34:               # Middle:
  cmpl  $1, %edx    #   x:1
  jg    .L35        #   if >, goto Loop
```


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

Next time

- For loops
- Switch statements
- Procedures