Computer Systems

CSE 410 Spring 2012

6 – x86 Machine-Level Programming

Machine Programming II: C to assembly

- Move instructions, registers, and operands
- Complete addressing mode, address computation (`leal`)
- Arithmetic operations (including some x86-64 instructions)
- Condition codes
- Control, unconditional and conditional branches
- While loops

Three Kinds of Instructions

- **Perform arithmetic function on register or memory data**
  - c = a + b;
- **Transfer data between memory and register**
  - Load data from memory into register
    - %reg = Mem[address]
  - Store register data into memory
    - Mem[address] = %reg
- **Transfer control (control flow)**
  - Unconditional jumps to/from procedures
  - Conditional branches

Moving Data: IA32

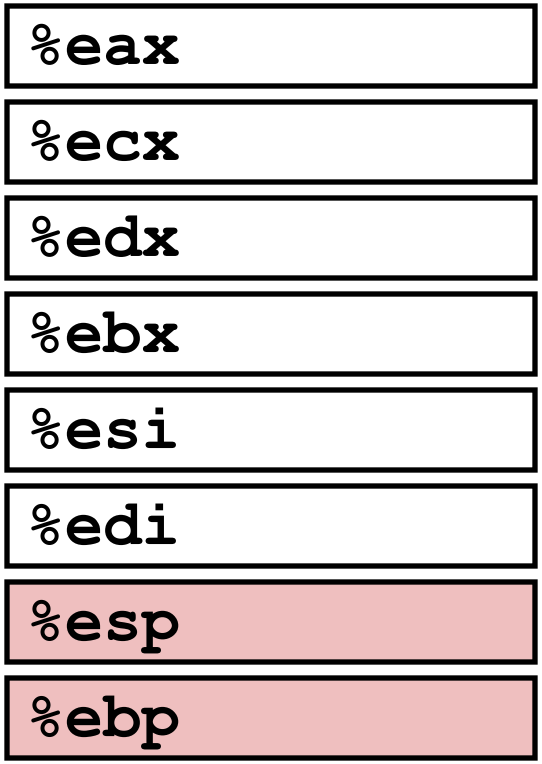
- **Moving Data**
  - **`movx`** ***Source, Dest***
  - **`x`** is one of {**`b, w, l`**}

  - **`movl`** ***Source, Dest*:**
    Move 4-byte "long word"
  - **`movw`** ***Source, Dest*:**
    Move 2-byte "word"
  - **`movb`** ***Source, Dest*:**
    Move 1-byte "byte"

- **Lots of these in typical code**

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

Moving Data: IA32



- **Moving Data**

  `movl` ***Source*, *Dest***:

- **Operand Types**
  - ***Immediate:*** Constant integer data
    - Example: **`$0x400, $-533`**
    - Like C constant, but prefixed with **`'$'`**
    - Encoded with 1, 2, or 4 bytes
  - ***Register:*** One of 8 integer registers
    - Example: **`%eax, %edx`**
    - But **`%esp`** and **`%ebp`** reserved for special use
    - Others have special uses for particular instructions
  - ***Memory:*** 4 consecutive bytes of memory at address given by register
    - Simplest example: **`(%eax)`**
    - Various other "address modes"

`movl` Operand Combinations

	Source	Dest	Src,Dest	C Analog
`movl`	*Imm*	*Reg*	`movl $0x4,%eax`	
		Mem	`movl $-147,(%eax)`	
	Reg	*Reg*	`movl %eax,%edx`	
		Mem	`movl %eax,(%edx)`	
	Mem	*Reg*	`movl (%eax),%edx`	

Cannot do memory-memory transfer with a single instruction.

How do you copy from a memory location to another then?

`movl` Operand Combinations

	Source	Dest	Src,Dest	C Analog
`movl`	*Imm*	*Reg*	`movl $0x4,%eax`	`temp = 0x4;`
		Mem	`movl $-147,(%eax)`	`*p = -147;`
	Reg	*Reg*	`movl %eax,%edx`	`temp2 = temp1;`
		Mem	`movl %eax,(%edx)`	`*p = temp;`
	Mem	*Reg*	`movl (%eax),%edx`	`temp = *p;`

Memory vs. registers

- Why both?

- Performance?

- Usage difference?

Simple Memory Addressing Modes

- **Normal (R) Mem[Reg[R]]**
  - Register R specifies memory address

```
movl (%ecx),%eax
```

- **Displacement D(R) Mem[Reg[R]+D]**
  - Register R specifies start of memory region
  - Constant displacement D specifies offset

```
movl 8(%ebp),%edx
```

Using Simple Addressing Modes

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

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

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

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

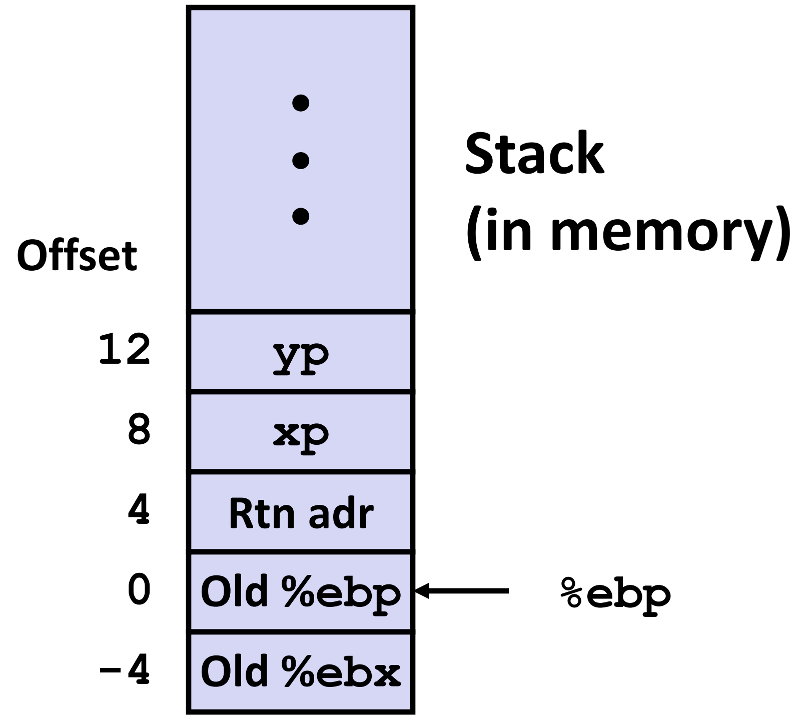
Set Up

Body

Finish

Understanding Swap

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



Register	Value
%ecx	yp
%edx	xp
%eax	t1
%ebx	t0

```
movl 12(%ebp),%ecx   # ecx = yp
movl 8(%ebp),%edx    # edx = xp
movl (%ecx),%eax     # eax = *yp (t1)
movl (%edx),%ebx     # ebx = *xp (t0)
movl %eax,(%edx)     # *xp = eax
movl %ebx,(%ecx)     # *yp = ebx
```

Understanding Swap

Register	Value
%eax	
%edx	
%ecx	
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset	Contents	Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
xp	8	0x124	0x10c
	4	Rtn adr	0x108
%ebp →	0		0x104
	-4		0x100

```
movl 12(%ebp),%ecx      # ecx = yp
movl 8(%ebp),%edx       # edx = xp
movl (%ecx),%eax        # eax = *yp (t1)
movl (%edx),%ebx        # ebx = *xp (t0)
movl %eax,(%edx)        # *xp = eax
movl %ebx,(%ecx)        # *yp = ebx
```

Understanding Swap

%eax	
%edx	
%ecx	0x120
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
			0x118
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movl %eax,(%edx)       # *xp = eax
movl %ebx,(%ecx)       # *yp = ebx
```

Understanding Swap

Register	Value
%eax	
%edx	0x124
%ecx	0x120
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset	Value	Address
		123	0x124
		456	0x120
			0x11c
			0x118
			0x114
yp	12	0x120	0x110
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movl 12(%ebp),%ecx     # ecx = yp
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movl (%edx),%ebx       # ebx = *xp (t0)
movl %eax,(%edx)       # *xp = eax
movl %ebx,(%ecx)       # *yp = ebx
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Understanding Swap

Register	Value
%eax	456
%edx	0x124
%ecx	0x120
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
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movl %eax,(%edx)        # *xp = eax
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```

Understanding Swap

%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
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Understanding Swap

Register	Value
%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset	Value	Address
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movl %eax,(%edx)       # *xp = eax
movl %ebx,(%ecx)       # *yp = ebx
```

Understanding Swap

Register	Value
%eax	456
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		456	0x124
		123	0x120
			0x11c
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movl 8(%ebp),%edx       # edx = xp
movl (%ecx),%eax        # eax = *yp (t1)
movl (%edx),%ebx        # ebx = *xp (t0)
movl %eax,(%edx)        # *xp = eax
movl %ebx,(%ecx)        # *yp = ebx
```

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`

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

Expression	Address Computation	Address
`0x8(%edx)`		
`(%edx,%ecx)`		
`(%edx,%ecx,4)`		
`0x80(%edx,2)`		

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*i
    - k = 1, 2, 4, or 8

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*	

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**

`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
    movl %esp,%ebp                } Up

    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;
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}
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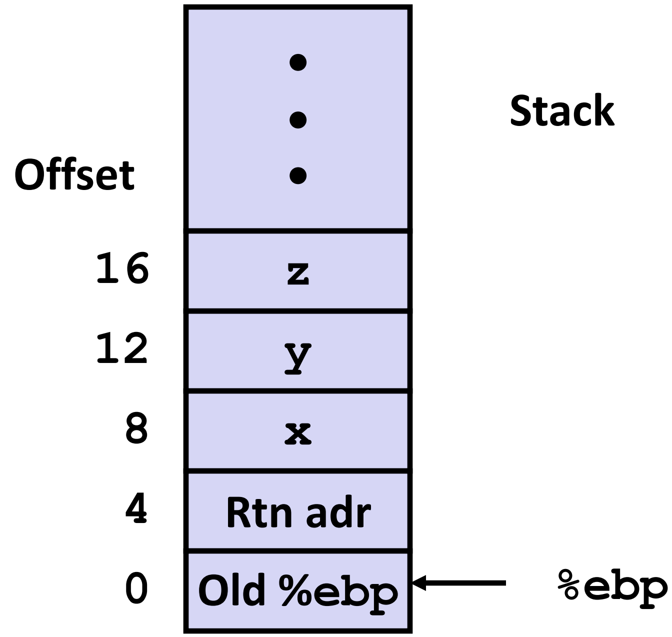


```
movl  8(%ebp),%eax
movl  12(%ebp),%edx
leal  (%edx,%eax),%ecx
leal  (%edx,%edx,2),%edx
sall  $4,%edx
addl  16(%ebp),%ecx
leal  4(%edx,%eax),%eax
imull  %ecx,%eax
```

What does each of these instructions mean?

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;
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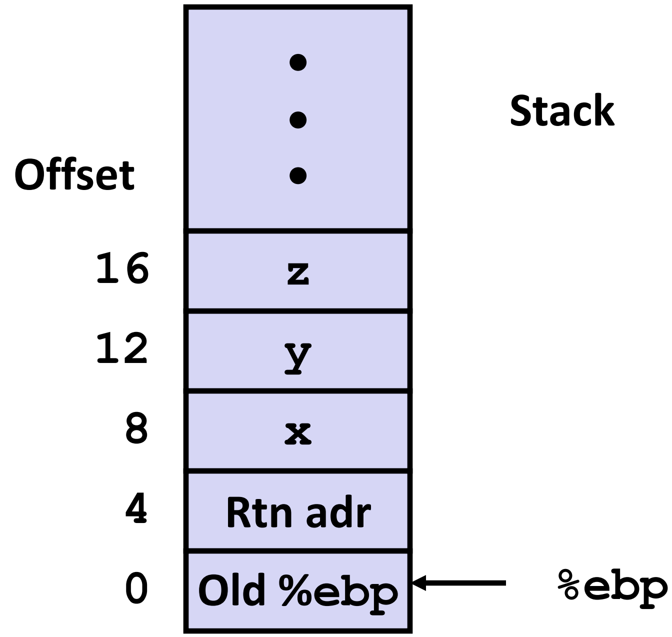
  int rval = t2 * t5;
  return rval;
}
```




```
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)
```

Understanding `arith`

```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
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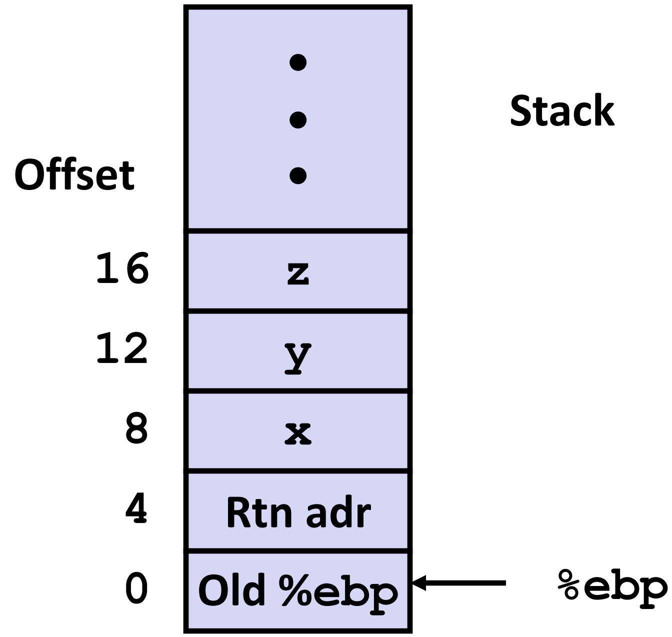


```
movl  8(%ebp),%eax          # eax = x
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leal  (%edx,%edx,2),%edx    # edx = 3*y
sall  $4,%edx               # edx = 48*y (t4)
addl  16(%ebp),%ecx         # ecx = z+t1 (t2)
leal  4(%edx,%eax),%eax     # eax = 4+t4+x (t5)
imull %ecx,%eax          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

Understanding `arith`

```
int arith
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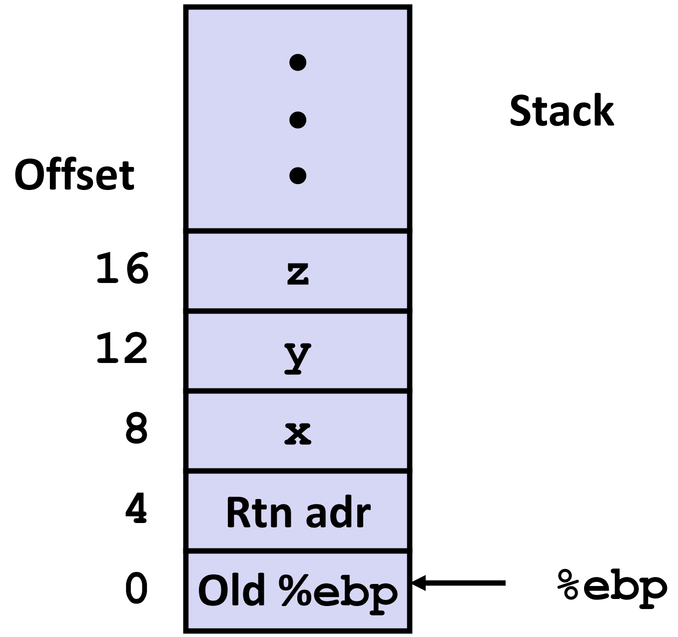


```
movl  8(%ebp),%eax          # eax = x
movl  12(%ebp),%edx         # edx = y
leal  (%edx,%eax),%ecx      # ecx = x+y   (t1)
leal  (%edx,%edx,2),%edx    # edx = 3*y
sall  $4,%edx               # edx = 48*y (t4)
addl  16(%ebp),%ecx         # ecx = z+t1 (t2)
leal  4(%edx,%eax),%eax     # eax = 4+t4+x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

Understanding arith

```
int arith
   (int x, int y, int z)
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   return rval;
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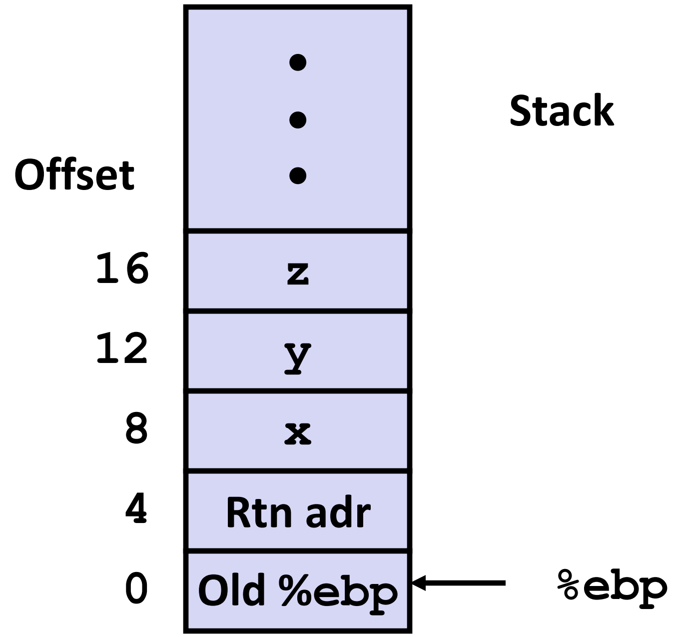


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leal  (%edx,%eax),%ecx      # ecx = x+y   (t1)
leal  (%edx,%edx,2),%edx    # edx = 3*y
sall  $4,%edx               # edx = 48*y  (t4)
addl  16(%ebp),%ecx         # ecx = z+t1  (t2)
leal  4(%edx,%eax),%eax     # eax = 4+t4+x (t5)
imull %ecx,%eax   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

Another Example

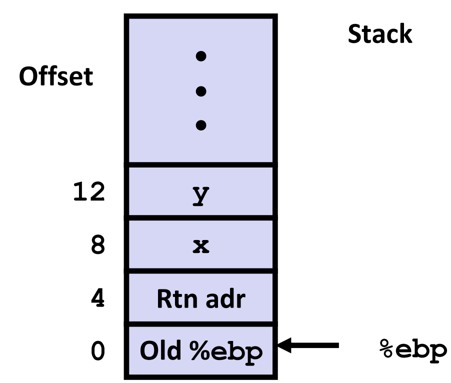
```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
    pushl %ebp            } Set
    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
sarl $17,%eax          # eax = t1>>17
andl $8185,%eax        # eax = t2 & 8185
```



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    movl 8(%ebp),%eax       }
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    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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Another Example

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    pushl %ebp              } Set Up
    movl %esp,%ebp

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

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

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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
```

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
    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                   }
```

$2^{13} = 8192$, $2^{13} – 7 = 8185$

```
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
```

Control-Flow/Conditionals

- **Unconditional**

```
while(true) {
  do_something;
}
...
```

- **Conditional**

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

Conditionals and Control Flow

- **A test / conditional branch is sufficient to implement most control flow constructs offered in higher level languages**
  - if (condition) then {...} else {…}
  - while(condition) {…}
  - do {…} while (condition)
  - for (initialization; condition; iterative) {...}

- **Unconditional branches implemented some related control flow constructs**
  - break, continue

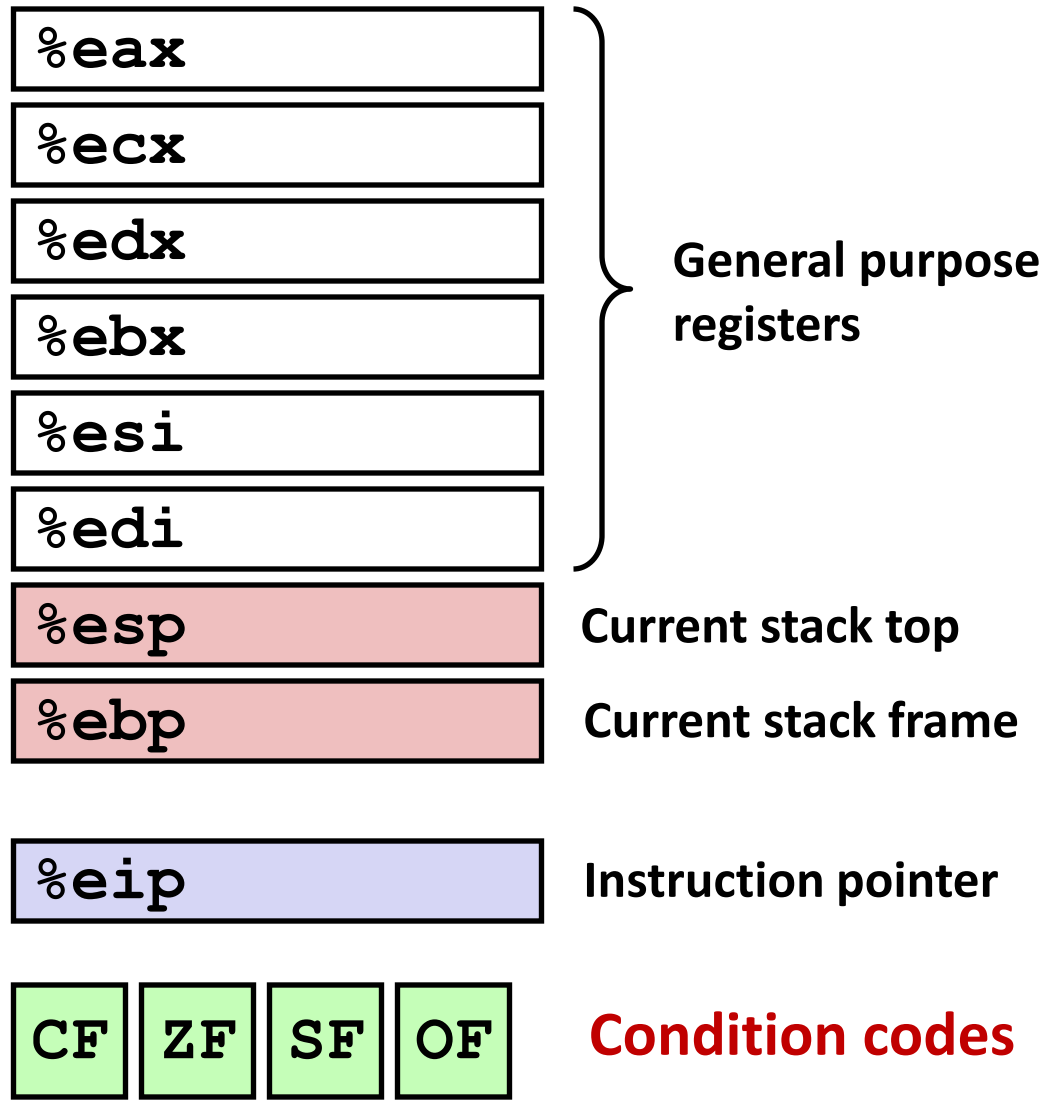
Jumping

- **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)

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`)



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 (beware!)**

- **Full documentation (IA32)** **http://www.jegerlehner.ch/intel/IntelCodeTable.pdf**

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`** 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`**

  - **`testl %eax, %eax`**
    - Sets SF and ZF, check if eax is +,0,-

Reading Condition Codes

- **SetX Instructions**
  - Set a 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

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

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

Body

```
movl  12(%ebp),%eax
cmpl  %eax,8(%ebp)
setg  %al
movzbl  %al,%eax
```

What does each of these instructions do?

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

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

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

Body

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

Note inverted ordering!

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

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

Setup: pushl %ebp; movl %esp, %ebp
Body1: movl 8(%ebp), %edx through movl %edx, %eax
Finish: leave; ret
Body2: subl %edx, %eax; jmp .L8

Conditional Branch Example (Cont.)

```
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**

Conditional Branch Example (Cont.)

```
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
```

Conditional Branch Example (Cont.)

```
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
```

Conditional Branch Example (Cont.)

```
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
```

Conditional Branch Example (Cont.)

```
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
```

General Conditional Expression Translation

C Code

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

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

Goto Version

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

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

- How would you make this efficient?

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**
  - **`cmovC`** 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

PC Relative Addressing

```
0x100     cmp   r2, r3       0x1000
0x102     je    0x70         0x1002
0x104     …                  0x1004
…         …                  …
0x172     add   r3, r4       0x1072
```

- PC relative branches are <u>relocatable</u>
- Absolute branches are not

Compiling Loops

C/Java code

```
while ( sum != 0 ) {
   <loop body>
}
```

Machine code

```
loopTop:    cmp   r3, $0
            be    loopDone
                <loop body code>
            jmp loopTop
loopDone:
```

- **How to compile other loops should be clear to you**
  - The only slightly tricky part is to be sure where the conditional branch occurs: top or bottom of the loop
- **Q: How is `for(i=0; i<100; i++)` implemented?**
- **Q: How are `break` and `continue` implemented?**

Machine Programming II: Instructions (cont'd)

- Move instructions, registers, and operands
- Complete addressing mode, address computation (`leal`)
- Arithmetic operations (including some x86-64 instructions)
- Condition codes
- Control, unconditional and conditional branches
- While loops
- For loops
- Switch statements

"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
  movl %esp,%ebp
  movl $1,%eax
  movl 8(%ebp),%edx

.L11:
  imull %edx,%eax
  decl %edx
  cmpl $1,%edx
  jg .L11

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

Translation?

"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 Translation

C Code

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

Goto Version

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

- Used by GCC for both IA32 & x86-64
- First iteration jumps over body computation within loop straight to test

“While” Loop 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
```

Quick Review

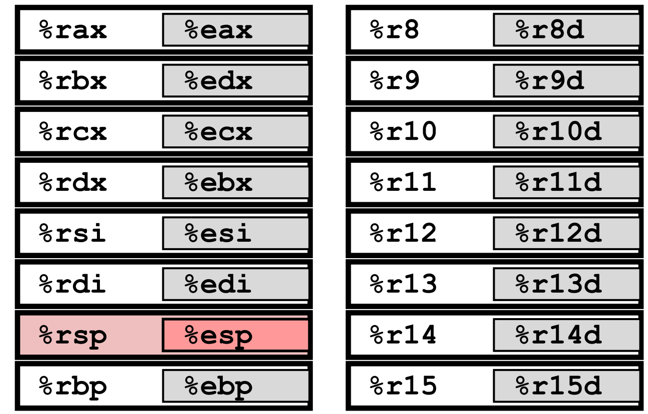
- Complete memory addressing mode
  - `(%eax), 17(%eax), 2(%ebx, %ecx, 8), …`

- Arithmetic operations that do set condition codes
  - `subl %eax, %ecx            # ecx = ecx + eax`
  - `sall $4,%edx               # edx = edx << 4`
  - `addl 16(%ebp),%ecx         # ecx = ecx + Mem[16+ebp]`
  - `imull %ecx,%eax            # eax = eax * ecx`

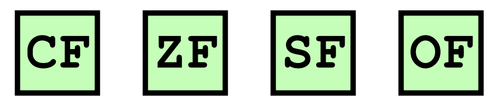
- Arithmetic operations that do NOT set condition codes
  - `leal 4(%edx,%eax),%eax     # eax = 4 + edx + eax`

Quick Review

- **x86-64 vs. IA32**
  - Integer registers: **16 x 64-bit** vs. **8 x 32-bit**
  - **`movq, addq`**, … vs. **`movl, addl`**, …
    - movq -> "move quad word" or 4*16-bits
  - Better support for passing function arguments in registers



- **Control**
  - Condition code registers
  - Set as side effect or by **`cmp, test`**
  - Used:
    - Read out by setx instructions (**`setg, setle`**, …)
    - Or by conditional jumps (**`jle .L4, je .L10,`** …)



Quick Review

- **Do-While loop**

C Code

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

Goto Version

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

- **While-Do loop**

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:
```

or

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

"For" Loop Example: Square-and-Multiply

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p)
{
   int result;
      for (result = 1; p != 0; p = p>>1) {
         if (p & 0x1)
            result *= x;
         x = x*x;
      }
   return result;
}
```

- **Algorithm**
  - Exploit bit representation: $p = p_0 + 2p_1 + 2^2 p_2 + \ldots 2^{n-1} p_{n-1}$
  - Gives: $x^p = z_0 \cdot z_1{}^2 \cdot (z_2{}^2)^2 \cdot \ldots \cdot \underbrace{(\ldots((z_{n-1}{}^2)^2)\ldots)^2}_{n-1 \text{ times}}$

    $z_i = 1$ when $p_i = 0$

    $z_i = x$ when $p_i = 1$

    ***n–1* times**
  - Complexity $O(\log p)$

Example

$3^{10} = 3^2 * 3^8$

$= 3^2 * ((3^2)^2)^2$

ipwr Computation

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned p)
{
  int result;
    for (result = 1; p != 0; p = p>>1) {
      if (p & 0x1)
        result *= x;
      x = x*x;
    }
  return result;
}
```

before iteration	result	x=3	p=10
1	1	3	$10=1010_2$
2	1	9	$5=101_2$
3	9	81	$2=10_2$
4	9	6561	$1=1_2$
5	59049	43046721	0_2

"For" Loop Example

```
int result;
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

General Form

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

Test	*Init*	*Update*	*Body*
`p != 0`	`result = 1`	`p = p >> 1`	`{ if (p & 0x1) result *= x; x = x*x; }`

"For"→ "While"

For Version

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

While Version

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

Goto Version

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

For-Loop: Compilation

For Version

```
for (Init; Test; Update )

      Body
```

```
for (result = 1; p != 0; p = p>>1)
{
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

Goto Version

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

```
  result = 1;
goto middle;
loop:
  if (p & 0x1)
    result *= x;
  x = x*x;
  p = p >> 1;
middle:
  if (p != 0)
    goto loop;
done:
```

```
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

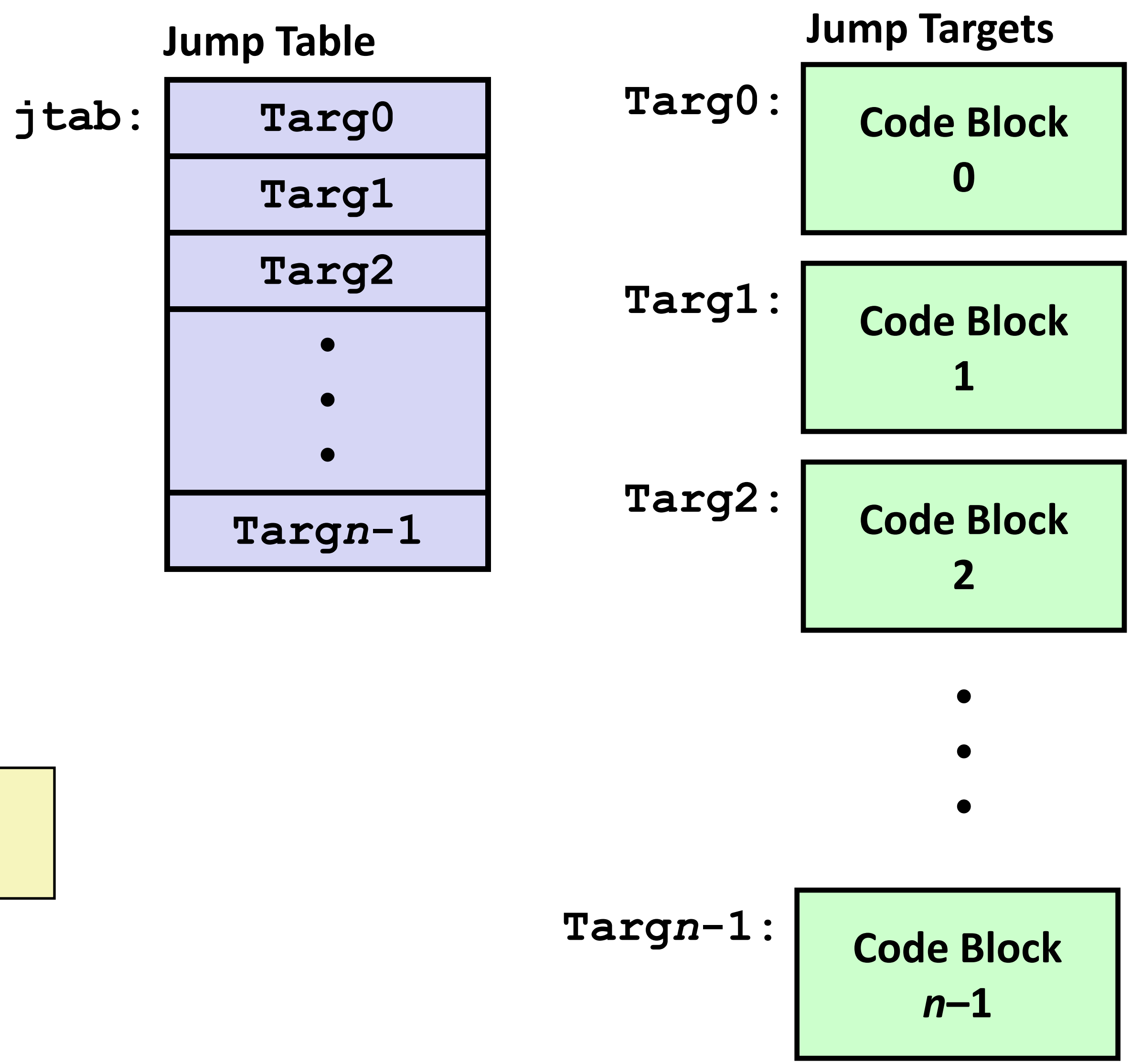
- **Multiple case labels**
  - Here: 5, 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

- **Lots to manage, we need a “jump table”**

Jump Table Structure

Switch Form

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



Approximate Translation

```
target = JTab[x];
goto *target;
```

Switch Statement Example (IA32)

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

Jump table

```
.section .rodata
  .align 4
.L62:
  .long    .L61  # x = 0
  .long    .L56  # x = 1
  .long    .L57  # x = 2
  .long    .L58  # x = 3
  .long    .L61  # x = 4
  .long    .L60  # x = 5
  .long    .L60  # x = 6
```

Setup:

```
switch_eg:
    pushl %ebp          # Setup
    movl  %esp, %ebp    # Setup
    pushl %ebx          # Setup
    movl  $1, %ebx
    movl  8(%ebp), %edx
    movl  16(%ebp), %ecx
    cmpl  $6, %edx
    ja    .L61
    jmp   *.L62(,%edx,4)
```

Translation?

Switch Statement Example (IA32)

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

Jump table

```
.section .rodata
   .align 4
.L62:
  .long    .L61   # x = 0
  .long    .L56   # x = 1
  .long    .L57   # x = 2
  .long    .L58   # x = 3
  .long    .L61   # x = 4
  .long    .L60   # x = 5
  .long    .L60   # x = 6
```

Setup:

```
switch_eg:
    pushl  %ebp             # Setup
    movl   %esp, %ebp       # Setup
    pushl  %ebx             # Setup
    movl   $1, %ebx         # w = 1
    movl   8(%ebp), %edx    # edx = x
    movl   16(%ebp), %ecx   # ecx = z
    cmpl   $6, %edx         # x:6
    ja     .L61             # if > goto default
    jmp    *.L62(,%edx,4)   # goto JTab[x]
```

Indirect jump → (points to `jmp *.L62(,%edx,4)`)

Assembly Setup Explanation

- **Table Structure**
  - Each target requires 4 bytes
  - Base address at `.L62`

- **Jumping**

  Direct: `jmp .L61`
  - Jump target is denoted by label `.L61`

  Indirect: `jmp *.L62(,%edx,4)`
  - Start of jump table: `.L62`
  - Must scale by factor of 4 (labels have 32-bit = 4 Bytes on IA32)
  - Fetch target from effective Address `.L62 + edx*4`
    - Only for $0 \leq \mathbf{x} \leq 6$

Jump table

```
.section .rodata
   .align 4
.L62:
  .long    .L61   # x = 0
  .long    .L56   # x = 1
  .long    .L57   # x = 2
  .long    .L58   # x = 3
  .long    .L61   # x = 4
  .long    .L60   # x = 5
  .long    .L60   # x = 6
```

Jump Table

Jump table

```
.section .rodata
   .align 4
.L62:
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  .long    .L57  # x = 2
  .long    .L58  # x = 3
  .long    .L61  # x = 4
  .long    .L60  # x = 5
  .long    .L60  # x = 6
```

```
switch(x) {
case 1:         // .L56
    w = y*z;
    break;
case 2:         // .L57
    w = y/z;
    /* Fall Through */
case 3:         // .L58
    w += z;
    break;
case 5:
case 6:         // .L60
    w -= z;
    break;
default:        // .L61
    w = 2;
}
```

Code Blocks (Partial)

```
switch(x) {
  . . .
case 2:        // .L57
    w = y/z;
    /* Fall Through */
case 3:        // .L58
    w += z;
    break;
  . . .
default:       // .L61
    w = 2;
}
```

```
.L61:  // Default case
  movl  $2, %ebx      # w = 2
  movl  %ebx, %eax    # Return w
  popl  %ebx
  leave
  ret
.L57:  // Case 2:
  movl  12(%ebp), %eax   # y
  cltd                 # Div prep
  idivl %ecx           # y/z
  movl  %eax, %ebx # w = y/z
# Fall through
.L58:  // Case 3:
  addl  %ecx, %ebx # w+= z
  movl  %ebx, %eax # Return w
  popl  %ebx
  leave
  ret
```

Code Blocks (Rest)

```
switch(x) {
case 1:         // .L56
    w = y*z;
    break;
  . . .
case 5:
case 6:         // .L60
    w -= z;
    break;
  . . .
}
```

```
.L60: // Cases 5&6:
   subl   %ecx, %ebx   # w -= z
   movl   %ebx, %eax   # Return w
   popl   %ebx
   leave
   ret
.L56: // Case 1:
   movl   12(%ebp), %ebx # w = y
   imull  %ecx, %ebx      # w*= z
   movl   %ebx, %eax   # Return w
   popl   %ebx
   leave
   ret
```

IA32 Object Code

- **Setup**
  - Label **`.L61`** becomes address **`0x08048630`**
  - Label **`.L62`** becomes address **`0x080488dc`**

Assembly Code

```
switch_eg:
   . . .
   ja     .L61              # if > goto default
   jmp    *.L62(,%edx,4)    # goto JTab[x]
```

Disassembled Object Code

```
08048610 <switch_eg>:
  . . .
08048622:   77 0c                   ja     8048630
08048624:   ff 24 95 dc 88 04 08    jmp    *0x80488dc(,%edx,4)
```

IA32 Object Code (cont.)

- **Jump Table**
  - Doesn't show up in disassembled code
  - Can inspect using GDB

```
gdb asm-cntl
(gdb) x/7xw 0x080488dc
```

    - Examine 7 hexadecimal format "words" (4-bytes each)
    - Use command "`help x`" to get format documentation

```
0x080488dc:
  0x08048630
  0x08048650
  0x0804863a
  0x08048642
  0x08048630
  0x08048649
  0x08048649
```

Disassembled Targets

```
8048630:    bb 02 00 00 00    mov    $0x2,%ebx
8048635:    89 d8             mov    %ebx,%eax
8048637:    5b                pop    %ebx
8048638:    c9                leave
8048639:    c3                ret
804863a:    8b 45 0c          mov    0xc(%ebp),%eax
804863d:    99                cltd
804863e:    f7 f9             idiv   %ecx
8048640:    89 c3             mov    %eax,%ebx
8048642:    01 cb             add    %ecx,%ebx
8048644:    89 d8             mov    %ebx,%eax
8048646:    5b                pop    %ebx
8048647:    c9                leave
8048648:    c3                ret
8048649:    29 cb             sub    %ecx,%ebx
804864b:    89 d8             mov    %ebx,%eax
804864d:    5b                pop    %ebx
804864e:    c9                leave
804864f:    c3                ret
8048650:    8b 5d 0c          mov    0xc(%ebp),%ebx
8048653:    0f af d9          imul   %ecx,%ebx
8048656:    89 d8             mov    %ebx,%eax
8048658:    5b                pop    %ebx
8048659:    c9                leave
804865a:    c3                ret
```

Matching Disassembled Targets

```
0x08048630
0x08048650
0x0804863a
0x08048642
0x08048630
0x08048649
0x08048649
```

```
8048630:   bb 02 00 00 00    mov
8048635:   89 d8             mov
8048637:   5b                pop
8048638:   c9                leave
8048639:   c3                ret
804863a:   8b 45 0c          mov
804863d:   99                cltd
804863e:   f7 f9             idiv
8048640:   89 c3             mov
8048642:   01 cb             add
8048644:   89 d8             mov
8048646:   5b                pop
8048647:   c9                leave
8048648:   c3                ret
8048649:   29 cb             sub
804864b:   89 d8             mov
804864d:   5b                pop
804864e:   c9                leave
804864f:   c3                ret
8048650:   8b 5d 0c          mov
8048653:   0f af d9          imul
8048656:   89 d8             mov
8048658:   5b                pop
8048659:   c9                leave
804865a:   c3                ret
```

Summarizing

- **C Control**
  - if-then-else
  - do-while
  - while, for
  - switch

- **Assembler Control**
  - Conditional jump
  - Conditional move
  - Indirect jump
  - Compiler
  - Must generate assembly code
    to implement more complex control

- **Standard Techniques**
  - Loops converted to do-while form
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees (see text)

- **Conditions in CISC**
  - CISC machines generally have condition code registers