Computer Systems

CSE 410 Autumn 2013

6 – x86 Assembly Programming

Roadmap

Memory & data
Integers & floats
Machine code & C
x86 assembly
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

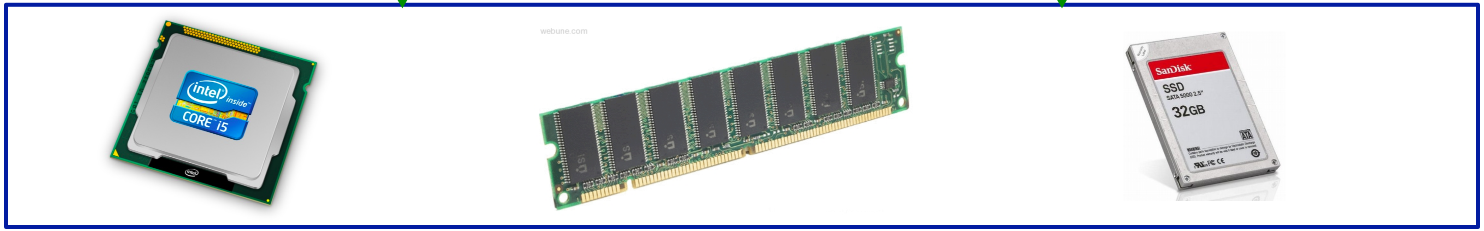
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 8 Mac

Computer system:



x86 Assembly Programming

- Move instructions, registers, and operands
- Memory addressing modes
- `swap` example: 32-bit vs. 64-bit
- Arithmetic operations
- Condition codes
- Conditional and unconditional branches
- Loops
- Switch statements

Three Basic Kinds of Instructions

- **Transfer data between memory and register**
  - *Load* data from memory into register
    - %reg = Mem[address]
  - *Store* register data into memory
    - Mem[address] = %reg

Remember:
memory is indexed
just like an array[]!

- **Perform arithmetic function on register or memory data**
  - c = a + b;

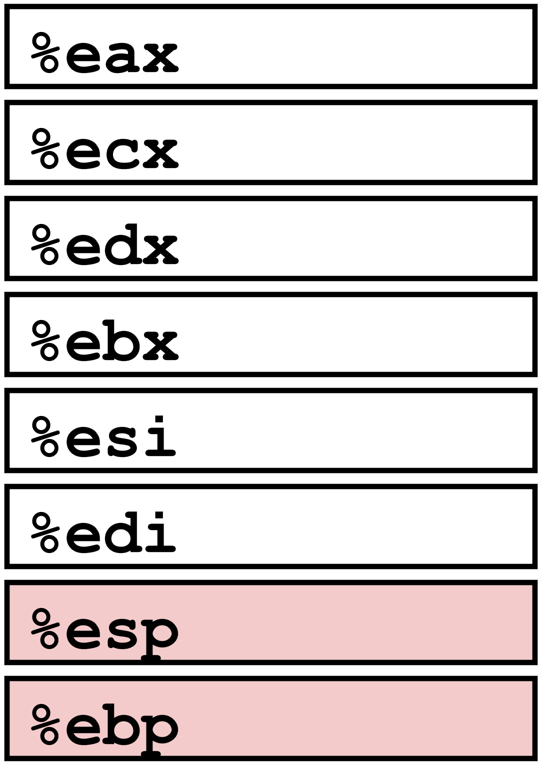
- **Transfer control**
  - Unconditional jumps to/from procedures
  - Conditional branches

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

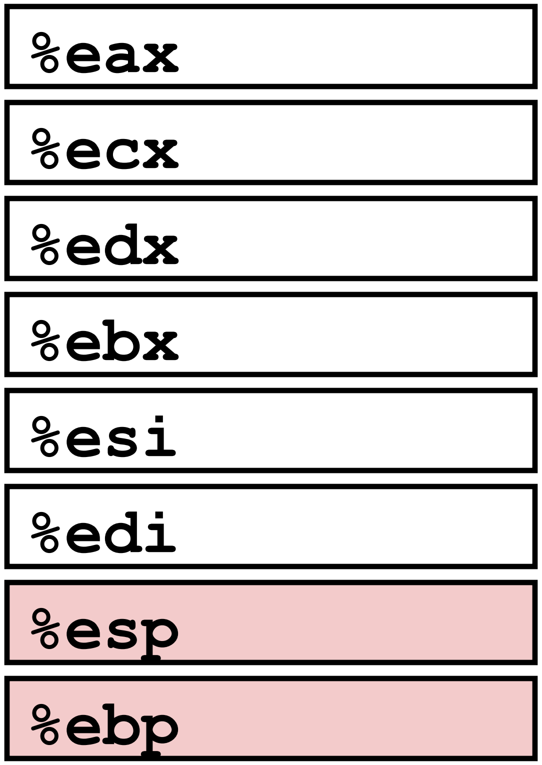
%esi

%edi

%esp

%ebp

Moving Data: IA32



%eax

%ecx

%edx

%ebx

%esi

%edi

%esp

%ebp

- **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`	`var_a = 0x4;`
		Mem	`movl $-147,(%eax)`	`*p_a = -147;`
	Reg	*Reg*	`movl %eax,%edx`	`var_d = var_a;`
		Mem	`movl %eax,(%edx)`	`*p_d = var_a;`
	Mem	*Reg*	`movl (%eax),%edx`	`var_d = *p_a;`

Cannot do memory-memory transfer with a single instruction.

Memory Addressing Modes: Basic

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

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

- **Displacement D(R) Mem[Reg[R]+D]**
  - Register R specifies a memory address
    - (e.g. the start of some memory region)
  - Constant displacement D specifies the offset from that address

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

Using Basic 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
```

Set Up

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

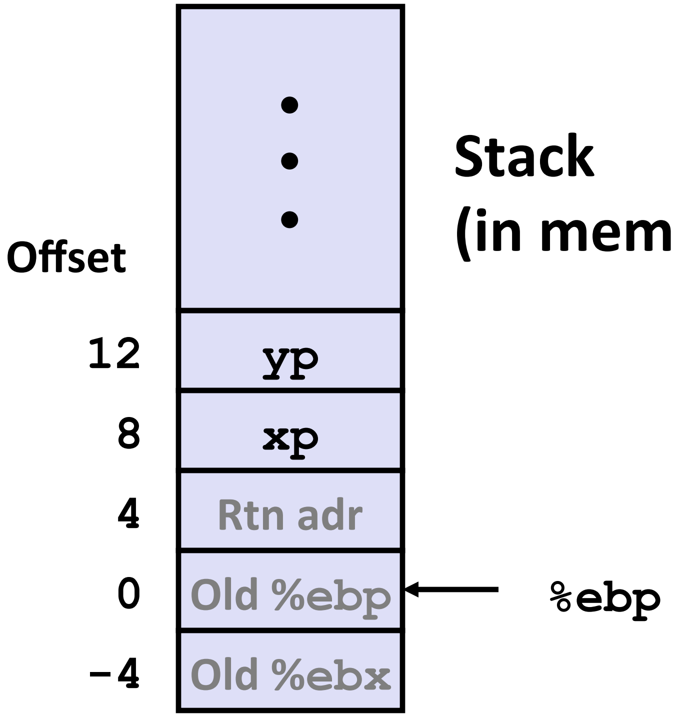
Body

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

Finish

Understanding Swap

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

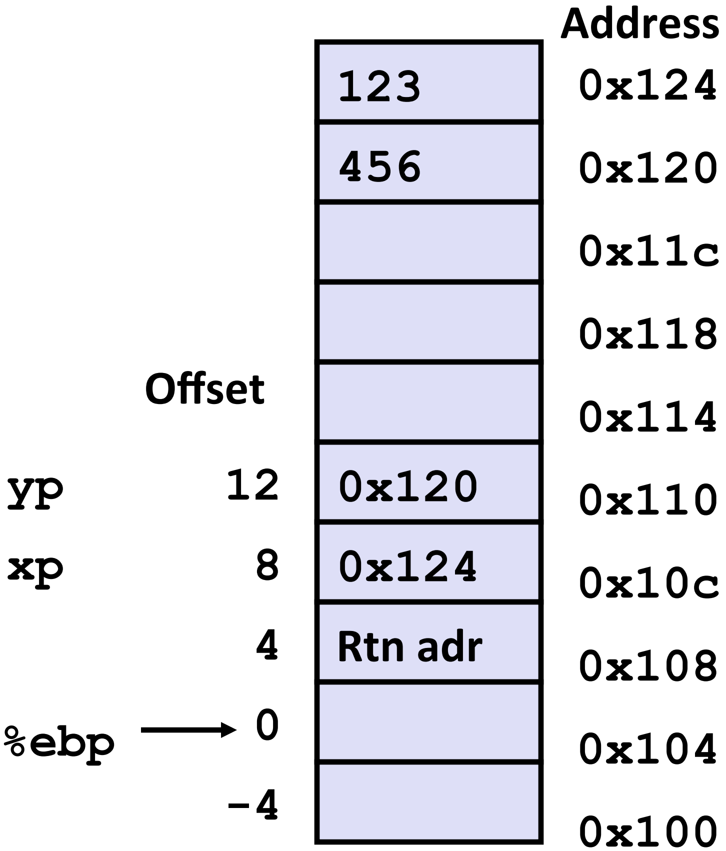


Register	Value
%ecx	yp
%edx	xp
%eax	t1
%ebx	t0

```
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

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



	Offset		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
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```
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	0x124
%ecx	0x120
%ebx	
%esi	
%edi	
%esp	
%ebp	0x104

	Offset		Address
		123	0x124
		456	0x120
			0x11c
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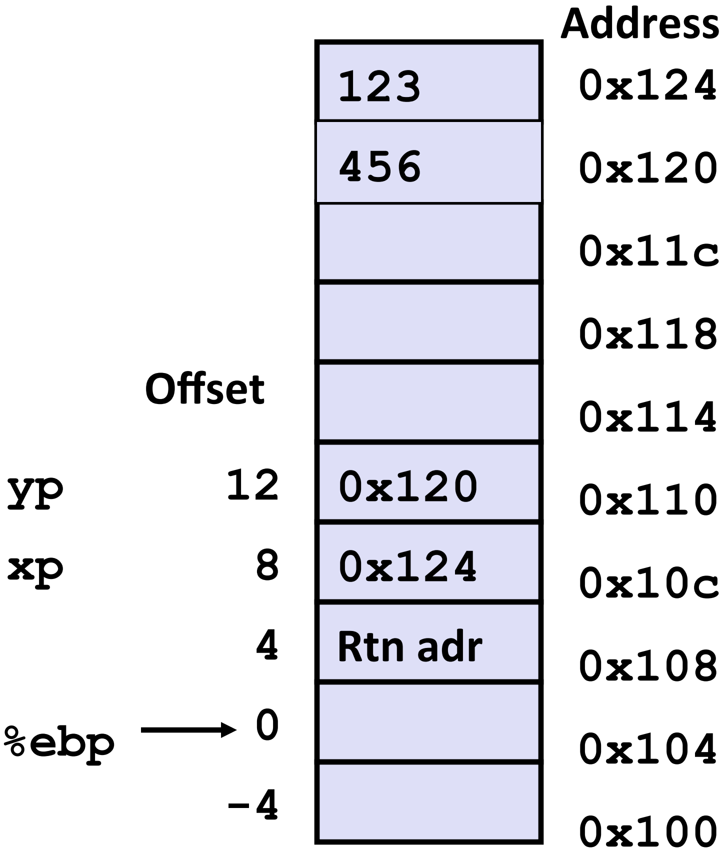
	-4		0x100

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



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

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

	Offset		Address
		456	0x124
		456	0x120
			0x11c
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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
```

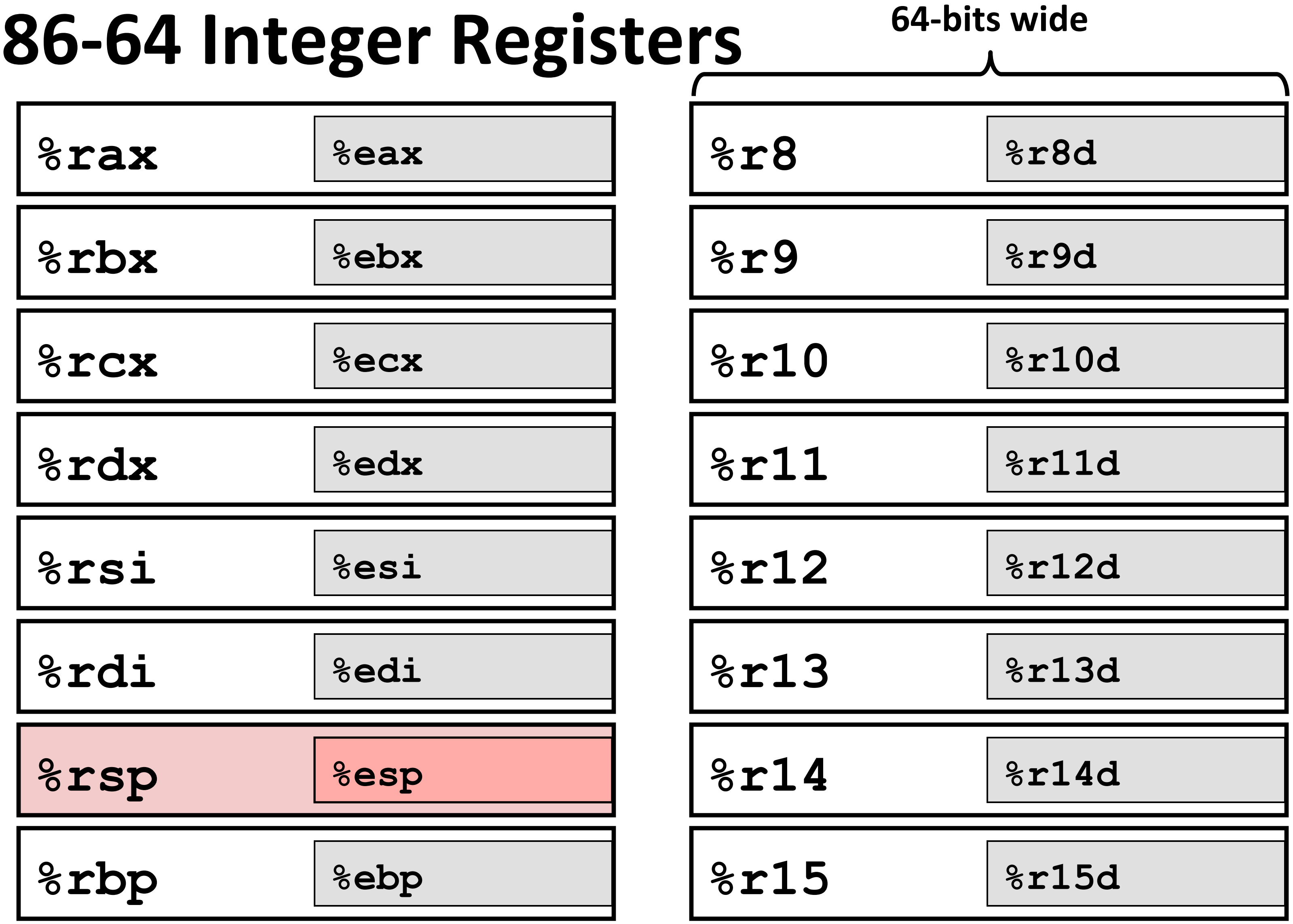
Understanding Swap

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

	Offset		Address
		456	0x124
		123	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
```

x86-64 Integer Registers



64-bits wide

%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, and add 8 new ones; *all* accessible as 8, 16, 32, 64 bits.

32-bit vs. 64-bit operands

- **Long word `l` (4 Bytes) ↔ Quad word `q` (8 Bytes)**

- **New instruction forms:**
  - **`movl`** → **`movq`**
  - **`addl`** → **`addq`**
  - **`sall`** → **`salq`**
  - etc.

- **x86-64 can still use 32-bit instructions that generate 32-bit results**
  - Higher-order bits of destination register are just set to 0
  - Example: **`addl`**

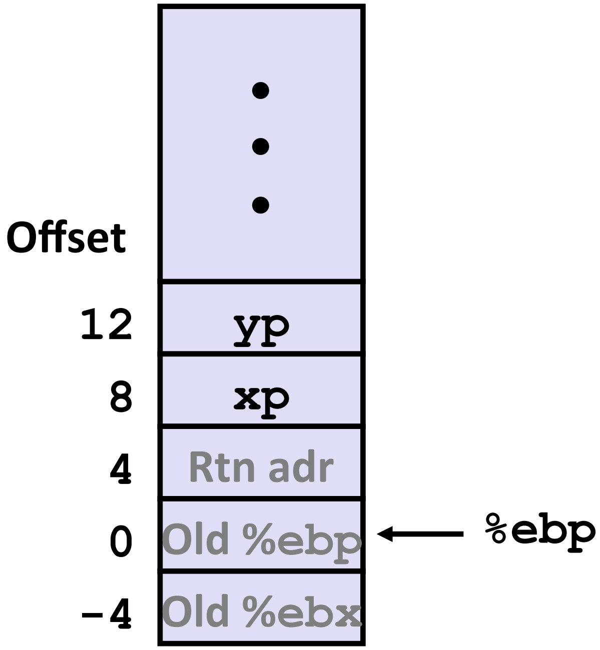
Swap Ints in 32-bit Mode

```
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
```



Offset		
	⋮	
12	yp	
8	xp	
4	Rtn adr	
0	Old %ebp	← %ebp
-4	Old %ebx	

Swap Ints 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
```

- **Arguments 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 (the **`l`** refers to data width, not address width)

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

Complete Memory Addressing Modes

- **Remember, the addresses used for accessing memory in `mov` (and other) instructions can be computed in several different ways**
- **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 the 8/16 integer registers
  - Ri: Index register: Any, except for `%esp` or `%rsp`
    - Unlikely you'd use `%ebp`, either
  - S: Scale: 1, 2, 4, or 8 (*why these numbers?*)
- **Special Cases: can use any combination of D, Rb, Ri and S**

  (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(,Ri,S)	Mem[S*Reg[Ri]+D]
(Rb,Ri,S)	Mem[Reg[Rb]+S*Reg[Ri]]
D(Rb)	Mem[Reg[Rb] +D]

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 computed by expression
    - (lea stands for *load effective address)*
  - Example: **`leal (%edx,%ecx,4), %eax`**

- **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 (Binary) 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*	

- Watch out for argument order! (especially `subl`)
- No distinction between signed and unsigned int (why?)

Some Arithmetic Operations

- **One Operand (Unary) Instructions**

`incl`	*Dest*	*Dest* = *Dest* + 1
`decl`	*Dest*	*Dest* = *Dest* - 1
`negl`	*Dest*	*Dest* = −*Dest*
`notl`	*Dest*	*Dest* = ~*Dest*

- **See textbook section 3.5.5 for more instructions: `mull`, `cltd`, `idivl`, `divl`**

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
   movl %esp,%ebp
```

Set Up

```
   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
```

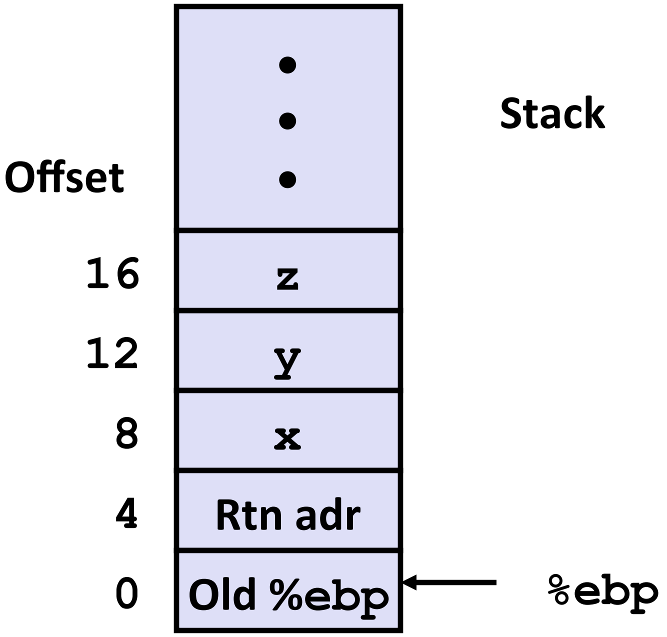
Body

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

Finish

Understanding `arith`

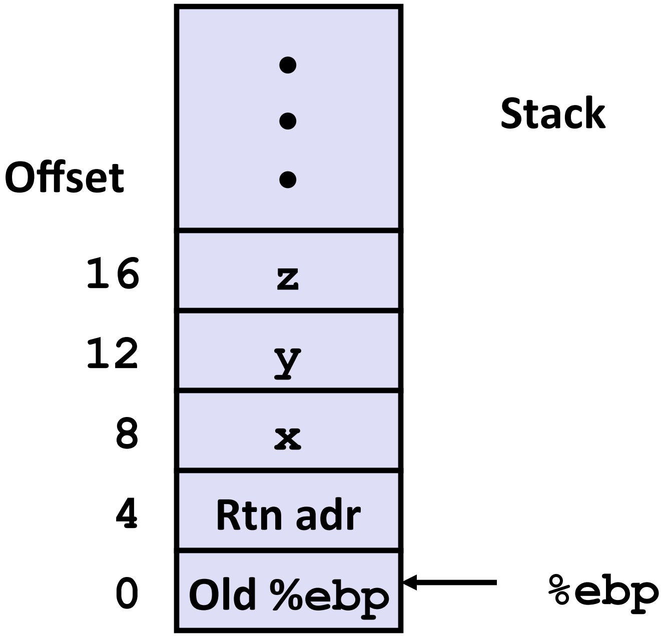
```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```



```
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 = y + 2*y = 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

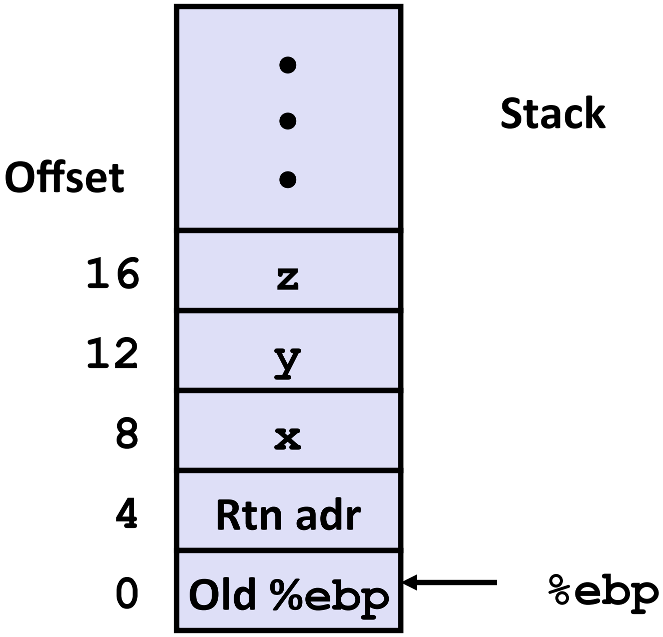
```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```



```
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 = y + 2*y = 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;
   int t4 = y * 48;
   int t5 = t3 + t4;
   int rval = t2 * t5;
   return rval;
}
```



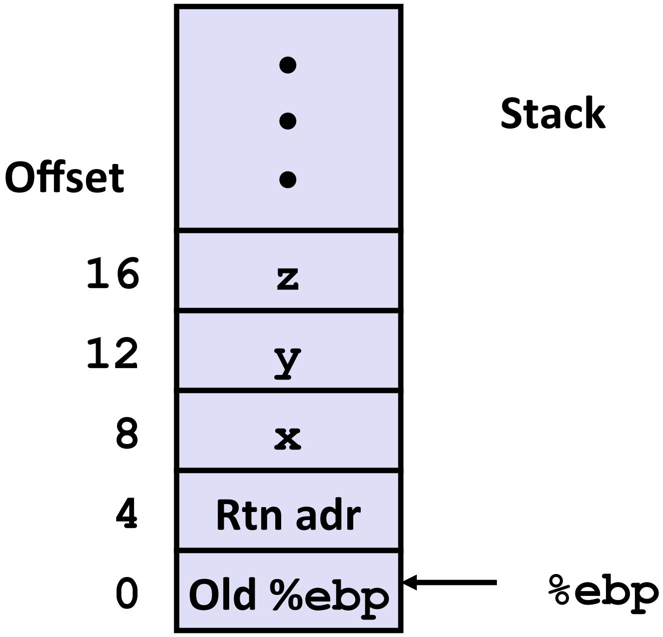
Stack

Offset	
	• • •
16	z
12	y
8	x
4	Rtn adr
0	Old %ebp ← %ebp

```
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 = y + 2*y = 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;
   int t4 = y * 48;
   int t5 = t3 + t4;
   int rval = t2 * t5;
   return rval;
}
```



Offset	Stack	
	• • •	
16	z	
12	y	
8	x	
4	Rtn adr	
0	Old %ebp	%ebp

```
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 = y + 2*y = 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)
```

Observations about `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;
}
```

- Instructions in different order from C code
- Some expressions require multiple instructions
- Some instructions cover multiple expressions
- Get exact same code if we compile

  `(x+y+z)*(x+4+48*y)`

```
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 = y + 2*y = 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)
```

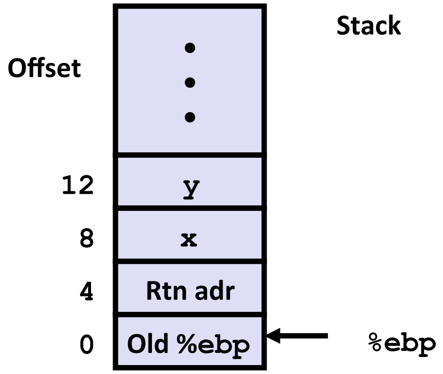
Another Example

```
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
```



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
    movl %esp,%ebp

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

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

Set Up

Body

Finish

```
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

```c
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     (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;
}
```

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

…0010000000000000, …0001111111111001

```
logical:
    pushl %ebp
    movl %esp,%ebp
```

Set Up

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

Body

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

Finish

```
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
```

Conditionals and Control Flow

- **A 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 implement some related control flow constructs**
  - break, continue

- **In x86, we'll refer to branches as "jumps" (either conditional or unconditional)**

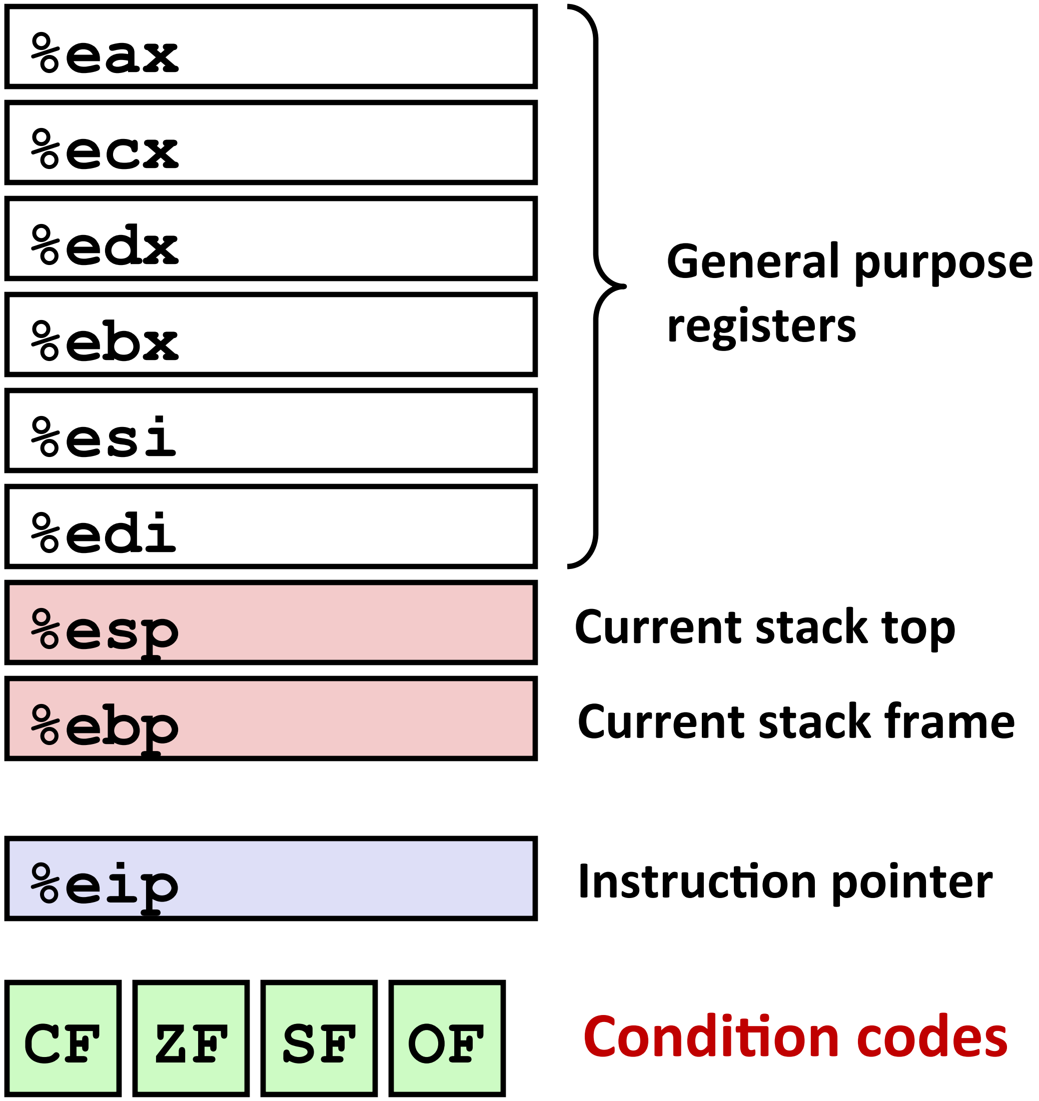
Jumping

- **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`)



%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 (beware!)**

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

Condition Codes (Explicit Setting: Compare)

- **Single-bit registers**

`CF`	Carry Flag (for unsigned)	`SF`	Sign Flag (for signed)
`ZF`	Zero Flag	`OF`	Overflow Flag (for signed)

- **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)

- **Single-bit registers**

`CF`	Carry Flag (for unsigned)	`SF`	Sign Flag (for signed)
`ZF`	Zero Flag	`OF`	Overflow Flag (for signed)

- **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** if **`a&b == 0`**
- **SF set** if **`a&b < 0`**

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

Reading Condition Codes

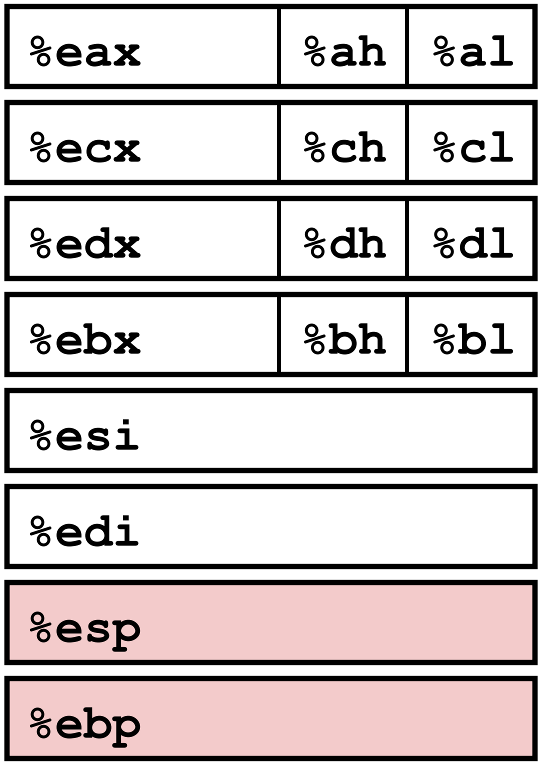
- **SetX Instructions**
  - Set a single byte to 0 or 1 based on combinations of condition codes

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 to 0 or 1 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: y at 12(%ebp), x at 8(%ebp)

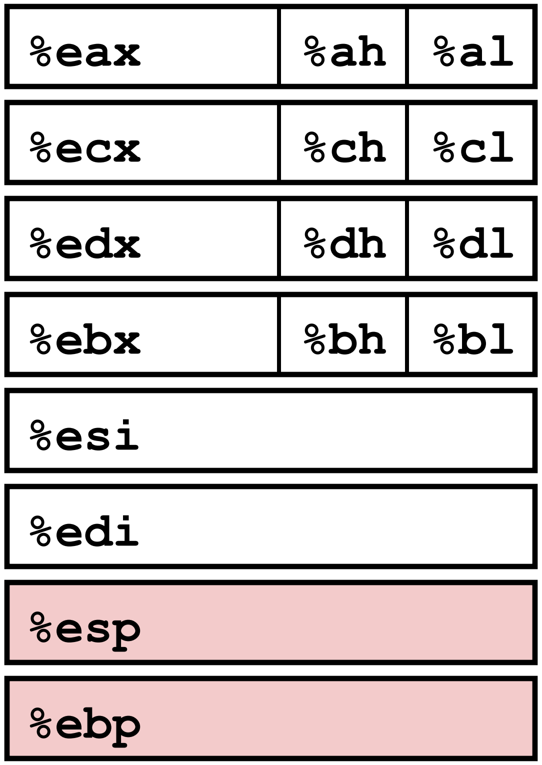
```
movl  12(%ebp),%eax
cmpl  %eax,8(%ebp)
setg  %al
movzbl %al,%eax
```

What does each of these instructions do?

Reading Condition Codes (Cont.)

- **SetX Instructions:**
  Set single byte to 0 or 1 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: **y at 12(%ebp), x at 8(%ebp)**

```
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
```

(x – y)

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

Conditional Branch Example (Cont.)

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

```
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;
}
```

- 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;
}
```

int x	%edx
int y	%eax

```
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;
}
```

int x	%edx
int y	%eax

```
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;
}
```

int x	%edx
int y	%eax

```
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;
}
```

int x	%edx
int y	%eax

```
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;
}
```

```
int x          %edx
int y          %eax
```

```
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;
```

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

```
if (Test)
  val = Then-Expr;
else
  val = Else-Expr;
```

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 might you make this more efficient?

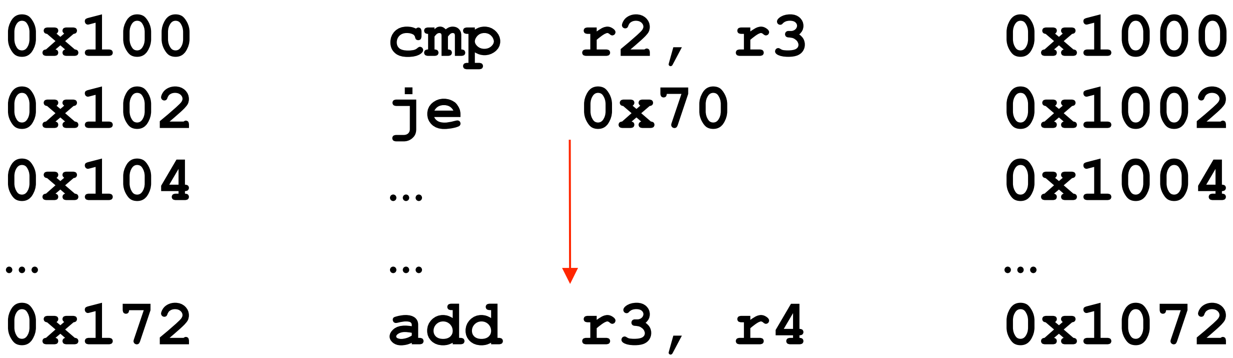
Conditionals: x86-64

```
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**
  - **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

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>**

  (same code works no matter where code is stored in memory)

- **Absolute branches are not**

  (actual branch address encoded in instruction)

Compiling Loops

C/Java code:

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

Machine code:

```
loopTop:    cmpl   $0, %eax
            je     loopDone
              <loop body code>
            jmp    loopTop
loopDone:
```

- **How to compile other loops should be straightforward**
  - The only slightly tricky part is to be sure where the conditional branch occurs: top or bottom of the loop
- **How would for(i=0; i<100; i++) be implemented?**

“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 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
```

“For” Loop Example: Square-and-Multiply

```
/* Compute x raised to nonnegative power p */
int ipwr_for(int x, unsigned int 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: $x^p = z_0 \cdot z_1^{\ 2} \cdot (z_2^{\ 2})^{\ 2} \cdot\ \ldots\ \cdot \underbrace{(\ldots((z_{n-1}^{\ 2})^{\ 2})\ldots)^{\ 2}}_{n\text{–}1\ \text{times}}$

    $z_i = 1$ when $p_i = 0$

    $z_i = x$ when $p_i = 1$
  - Complexity $\mathrm{O}(\log p)$

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 int 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
```

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
{
   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:
```

Switch Statement Example

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

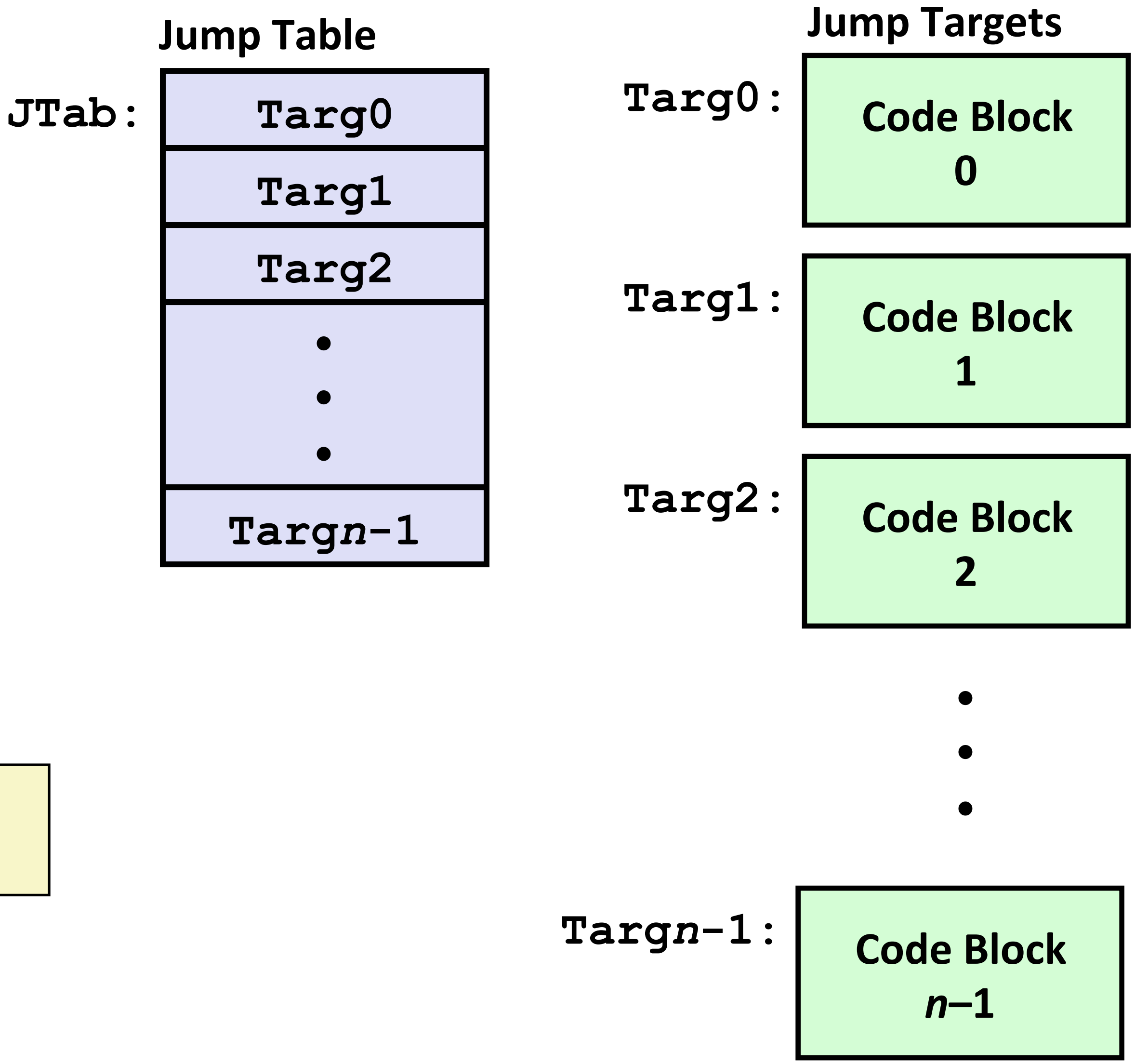
- **Multiple case labels**
  - Here: 5, 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

- **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
}
```



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

Approximate Translation

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

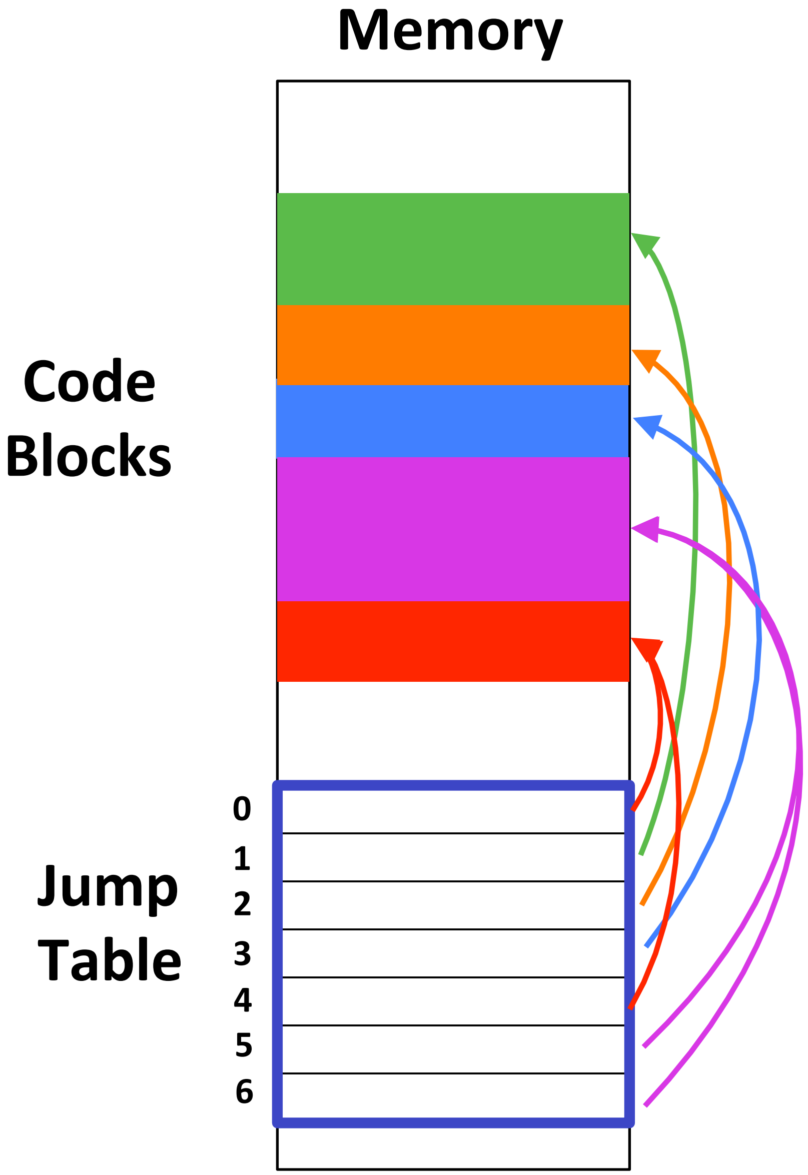
Jump Table Structure

C code:

```
switch(x) {
  case 1: <some code>
          break;
  case 2: <some code>
  case 3: <some code>
          break;
  case 5:
  case 6: <some code>
          break;
  default: <some code>
}
```

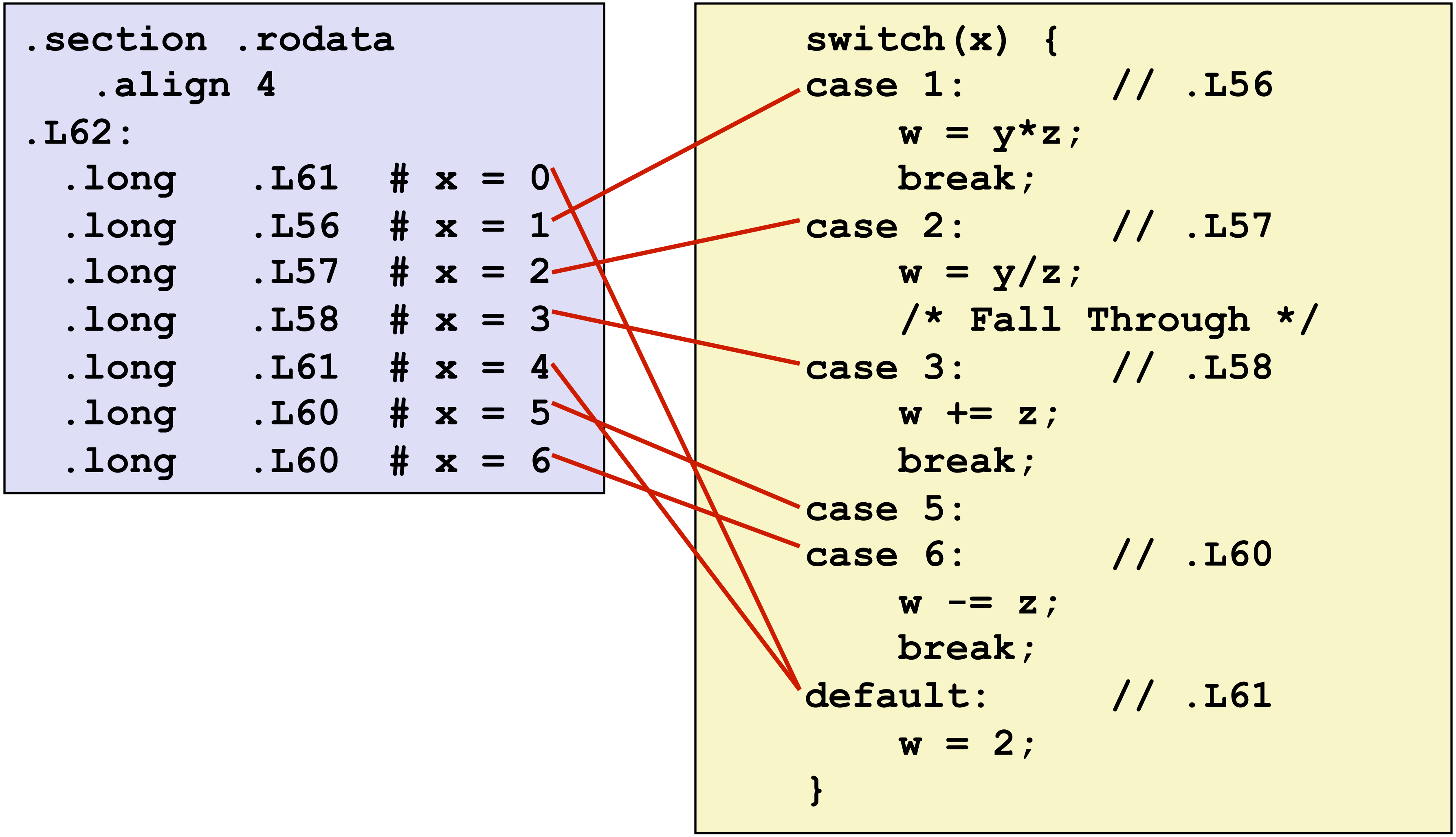
We can use the jump table when x <= 6:

```
if (x <= 6)
  target = JTab[x];
  goto *target;
else
  goto default;
```



Jump Table

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
```

```
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;
}
```

Switch Statement Example (IA32)

```
long switch_eg(unsigned 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
  ja    .L61
  jmp   *.L62(,%edx,4)
```

Translation?

Switch Statement Example (IA32)

```
long switch_eg(unsigned 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

Assembly Setup Explanation

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

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
```

- **Jumping: different address modes for target**

  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 are 32-bits = 4 bytes on IA32)
  - Fetch target from effective address `.L62 + edx*4`
    - `target = JTab[x]; goto *target;` (only for 0 ≤ **x** ≤ 6)

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
```

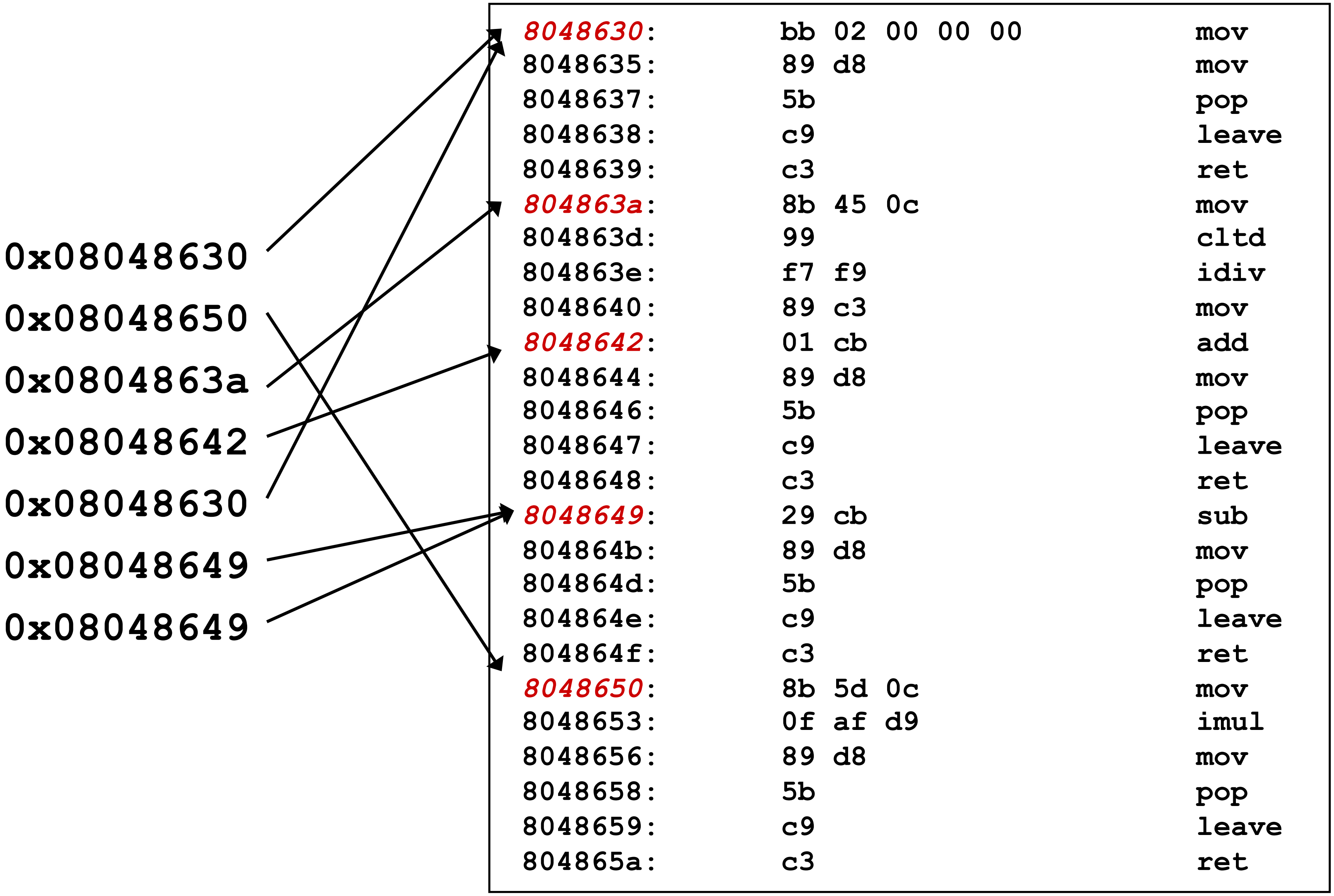
    - Examine 7 hexadecimal format “words” (4-bytes each)
    - Use command “**`help x`**” to get format documentation

```
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
```

Question

- **Would you implement this with a jump table?**

```
switch(x) {
   case 0:       <some code>
                 break;
   case 10:      <some code>
                 break;
   case 52000:   <some code>
                 break;
   default:      <some code>
                 break;
}
```

- **Probably not:**
  - Don’t want a jump table with 52001 entries (too big)