Machine-Level Programming I: Introduction
Sept. 16, 2009

Topics

- Assembly Programmer’s Execution Model
- Accessing Information
  - Registers
  - Memory
- Arithmetic operations

IA32 Processors

Totally Dominate Computer Market

Evolutionary Design

- Starting in 1978 with 8086
- Added more features as time goes on
- Still support old features, although obsolete

Complex Instruction Set Computer (CISC)

- Many different instructions with many different formats
  - But, only small subset encountered with Linux programs
- Hard to match performance of Reduced Instruction Set Computers (RISC)
- But, Intel has done just that!

CISC Properties

Instruction can reference different operand types

- Immediate, register, memory

Arithmetic operations can read/write memory

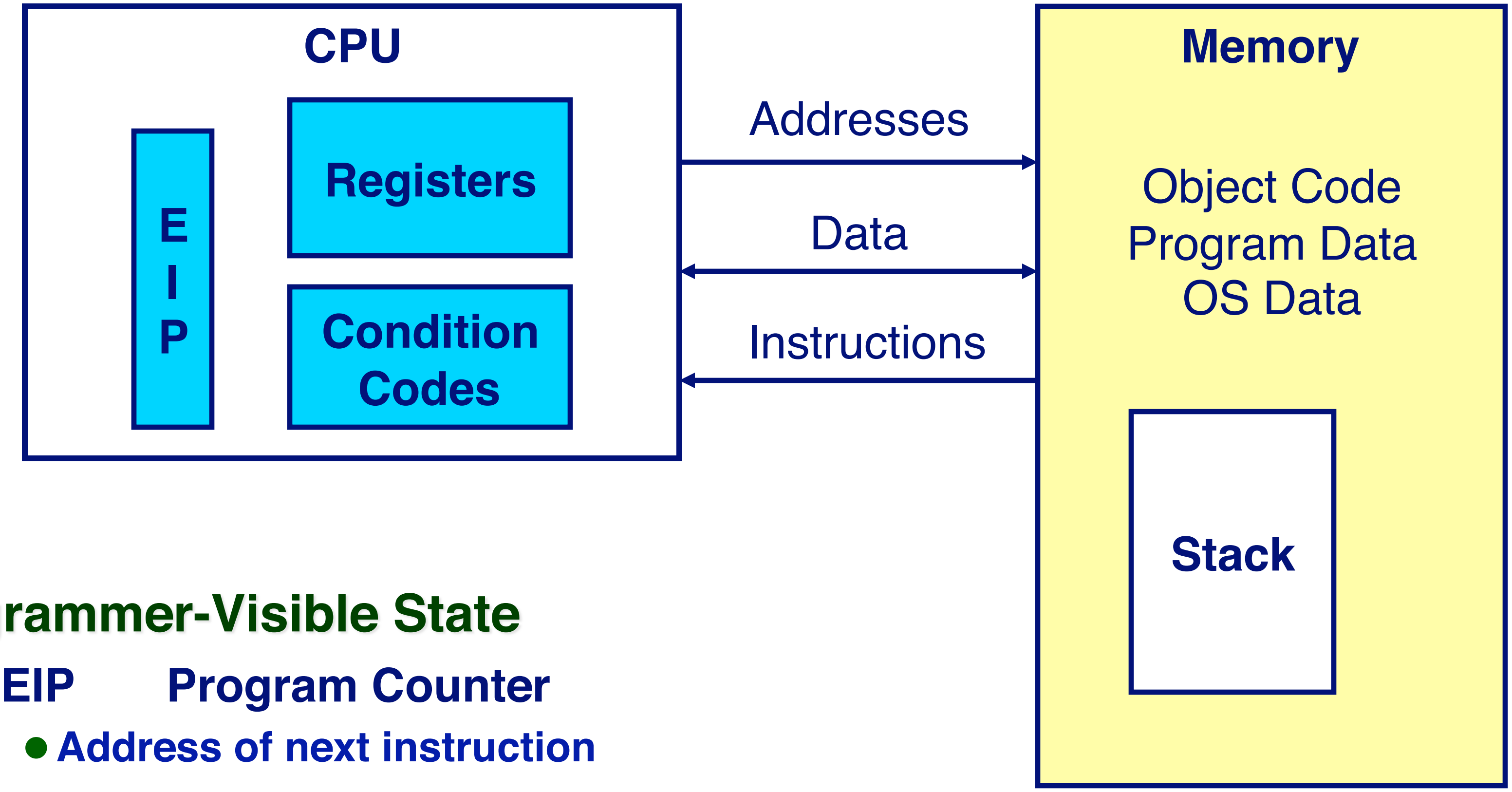
Memory reference can involve complex computation

- Rb + S*Ri + D
- Useful for arithmetic expressions, too

Instructions can have varying lengths

- IA32 instructions can range from 1 to 15 bytes

Assembly Programmer's View



Programmer-Visible State

- EIP Program Counter
  - Address of next instruction
- Register File
  - Heavily used program data
- Condition Codes
  - Store status information about most recent arithmetic operation
  - Used for conditional branching

- Memory
  - Byte addressable array
  - Code, user data, (some) OS data
  - Includes stack used to support procedures

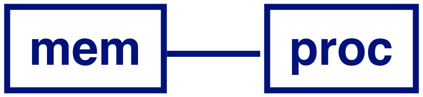
Abstract Machines

Machine Models

Data

Control

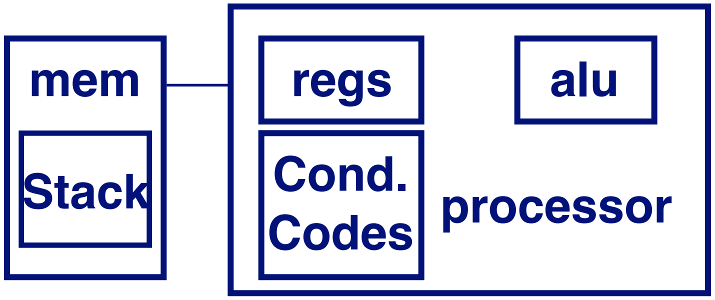
C



1) `char`
2) `int`, `float`
3) `double`
4) `struct`, array
5) pointer

1) loops
2) conditionals
3) `switch`
4) Proc. call
5) Proc. return

Assembly



1) byte
2) 2-byte word
3) 4-byte long word
4) contiguous byte allocation
5) address of initial byte

3) branch/jump
4) `call`
5) `ret`

Whose Assembler?

Intel/Microsoft Format

```
lea   eax,[ecx+ecx*2]
sub   esp,8
cmp   dword ptr [ebp-8],0
mov   eax,dword ptr [eax*4+100h]
```

GAS/Gnu Format

```
leal         (%ecx,%ecx,2),%eax
subl         $8,%esp
cmpl         $0,-8(%ebp)
movl         $0x100(,%eax,4),%eax
```

Intel/Microsoft Differs from GAS

- Operands listed in opposite order

  `mov` Dest, Src   `movl` Src, Dest

- Constants not preceded by '$', Denote hex with 'h' at end

  `100h`   `$0x100`

- Operand size indicated by operands rather than operator suffix

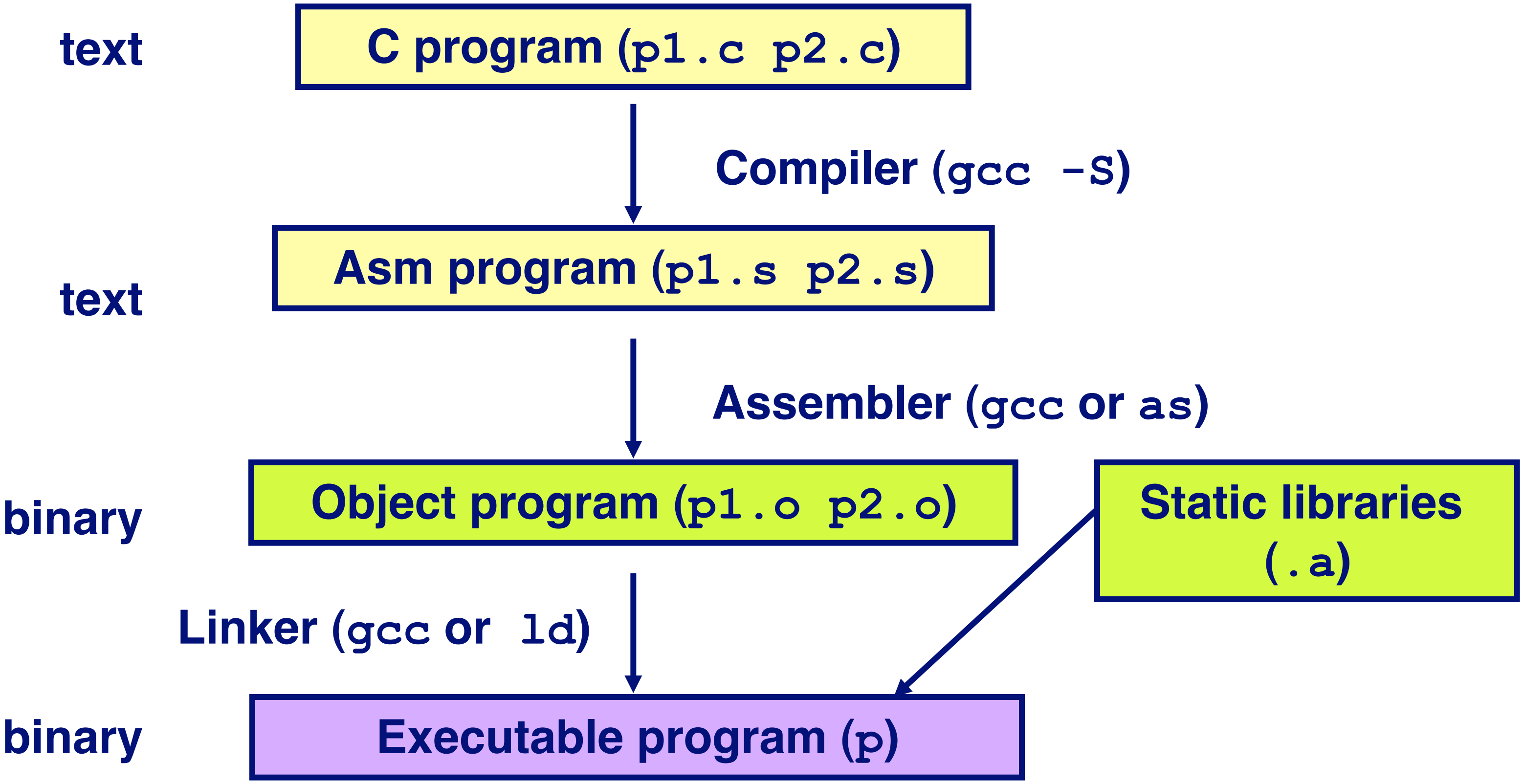
  `sub`   `subl`

- Addressing format shows effective address computation

  `[eax*4+100h]`   `$0x100(,%eax,4)`

Turning C into Object Code

- Code in files `p1.c p2.c`
- Compile with command: `gcc -O p1.c p2.c -o p`
  - Use optimizations (`-O`)
  - Put resulting binary in file `p`



Compiling Into Assembly

C Code

```
int sum(int x, int y)
{
  int t = x+y;
  return t;
}
```

Generated Assembly

```
_sum:
    pushl %ebp
    movl %esp,%ebp
    movl 12(%ebp),%eax
    addl 8(%ebp),%eax
    movl %ebp,%esp
    popl %ebp
    ret
```

Obtain with command

```
gcc -O -S code.c
```

Produces file `code.s`

Assembly Characteristics

Minimal Data Types

- “Integer” data of 1, 2, or 4 bytes
  - Data values
  - Addresses (untyped pointers)
- Floating point data of 4, 8, or 10 bytes
- No aggregate types such as arrays or structures
  - Just contiguously allocated bytes in memory

Primitive Operations

- Perform arithmetic function on register or memory data
- Transfer data between memory and register
  - Load data from memory into register
  - Store register data into memory
- Transfer control
  - Unconditional jumps to/from procedures
  - Conditional branches

Object Code

Code for `sum`

```
0x401040 <sum>:
    0x55
    0x89
    0xe5
    0x8b
    0x45
    0x0c
    0x03
    0x45
    0x08
    0x89
    0xec
    0x5d
    0xc3
```

- Total of 13 bytes
- Each instruction 1, 2, or 3 bytes
- Starts at address `0x401040`

Assembler

- Translates `.s` into `.o`
- Binary encoding of each instruction
- Nearly-complete image of executable code
- Missing linkages between code in different files

Linker

- Resolves references between files
- Combines with static run-time libraries
  - E.g., code for `malloc`, `printf`
- Some libraries are *dynamically linked*
  - Linking occurs when program begins execution

Machine Instruction Example

```
int t = x+y;
```

C Code

- Add two signed integers

```
    addl 8(%ebp),%eax
```

Similar to expression
`x += y`

Assembly

- Add 2 4-byte integers
  - “Long” words in GCC parlance
  - Same instruction whether signed or unsigned
- Operands:

`x`:	Register	`%eax`
`y`:	Memory	M[`%ebp+8`]
`t`:	Register	`%eax`

» Return function value in `%eax`

```
0x401046:     03 45 08
```

Object Code

- 3-byte instruction
- Stored at address `0x401046`

Disassembling Object Code

Sum Disassembled

```
00401040 <_sum>:
   0:      55                     push    %ebp
   1:      89 e5                  mov     %esp,%ebp
   3:      8b 45 0c               mov     0xc(%ebp),
%eax
   6:      03 45 08               add     0x8(%ebp),
%eax
   9:      89 ec                  mov     %ebp,%esp
   b:      5d                     pop     %ebp
   c:      c3                     ret
   d:      8d 76 00               lea   0x0(%esi),%esi
```

Disassembler

`objdump -d`

- Useful tool for examining object code
- Analyzes bit pattern of series of instructions
- Produces approximate rendition of assembly code
- Can be run on either `a.out` (complete executable) or `.o` file

Alternate Disassembly

Object

```
0x401040:
    0x55
    0x89
    0xe5
    0x8b
    0x45
    0x0c
    0x03
    0x45
    0x08
    0x89
    0xec
    0x5d
    0xc3
```

Disassembled

```
0x401040 <sum>:     push   %ebp
0x401041 <sum+1>:   mov    %esp,%ebp
0x401043 <sum+3>:   mov    0xc(%ebp),%eax
0x401046 <sum+6>:   add    0x8(%ebp),%eax
0x401049 <sum+9>:   mov    %ebp,%esp
0x40104b <sum+11>:  pop    %ebp
0x40104c <sum+12>:  ret
0x40104d <sum+13>:  lea    0x0(%esi),%esi
```

Within gdb Debugger

```
gdb p
disassemble sum
```

- Disassemble procedure

```
x/13b sum
```

- Examine the 13 bytes starting at `sum`

What Can be Disassembled?

```
% objdump -d WINWORD.EXE

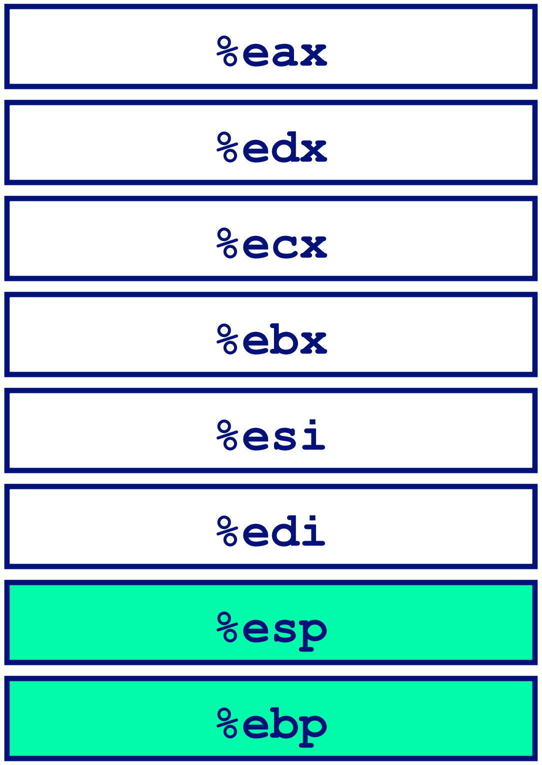
WINWORD.EXE:     file format pei-i386

No symbols in "WINWORD.EXE".
Disassembly of section .text:

30001000 <.text>:
30001000:  55                 push   %ebp
30001001:  8b ec              mov    %esp,%ebp
30001003:  6a ff              push   $0xffffffff
30001005:  68 90 10 00 30     push   $0x30001090
3000100a:  68 91 dc 4c 30     push   $0x304cdc91
```

- **Anything that can be interpreted as executable code**
- **Disassembler examines bytes and reconstructs assembly source**

Moving Data


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

Moving Data

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

- Move 4-byte ("long") word
- Lots of these in typical code

Operand Types

- Immediate: Constant integer data
  - Like C constant, but prefixed with '`$`'
  - E.g., `$0x400`, `$-533`
  - Encoded with 1, 2, or 4 bytes
- Register: One of 8 integer registers
  - But `%esp` and `%ebp` reserved for special use
  - Others have special uses for particular instructions
- Memory: 4 consecutive bytes of memory
  - Various "address modes"

`movl` Operand Combinations

	Source	Destination		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;`

- Cannot do memory-memory transfers with single instruction

Simple 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
```

Set Up

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

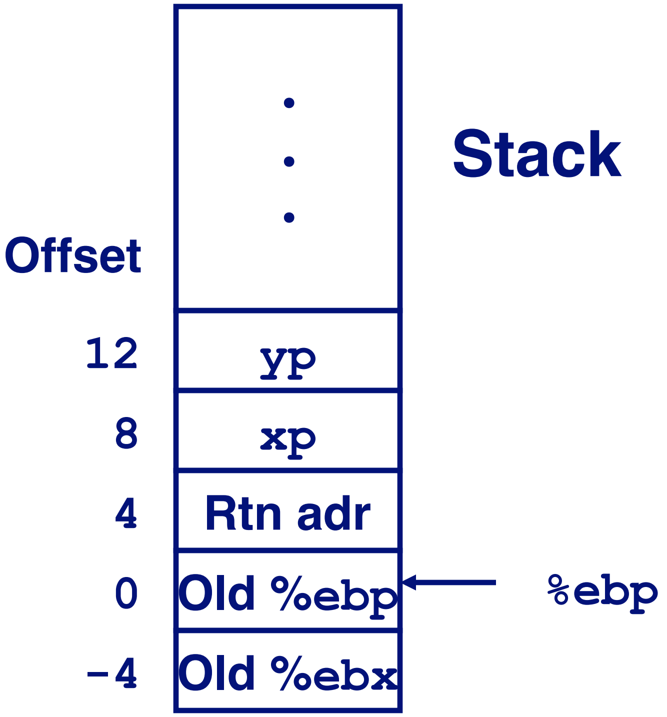
Body

```
    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;
}
```



Stack

Offset

12 yp

8 xp

4 Rtn adr

0 Old %ebp ← %ebp

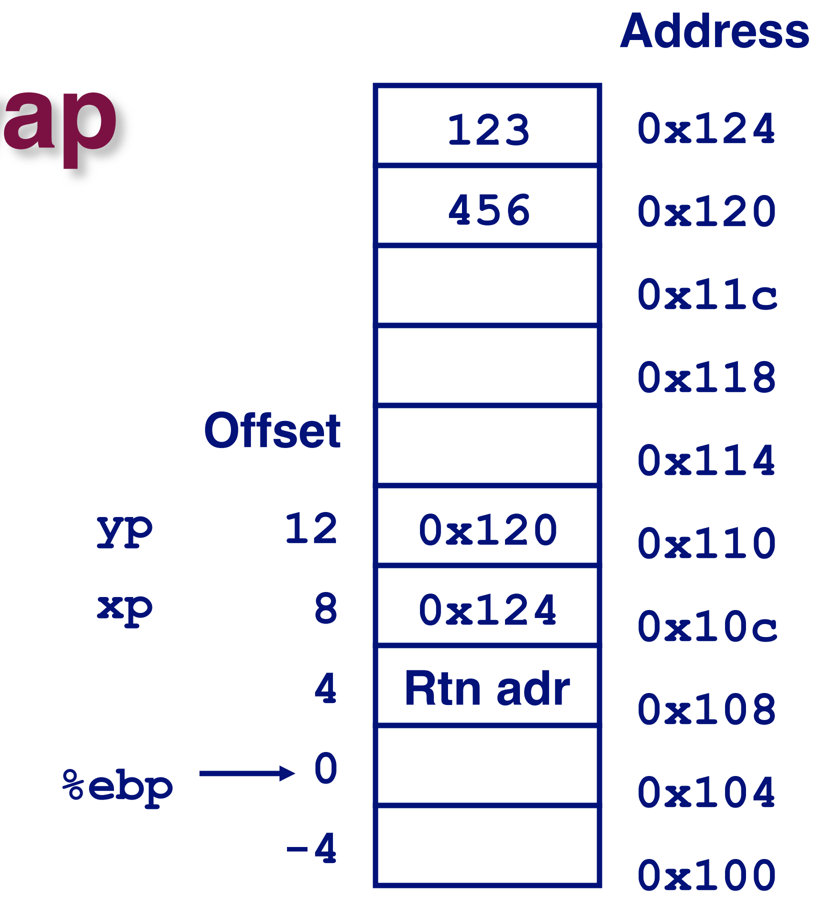
-4 Old %ebx

Register	Variable
%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	
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movl %eax,(%edx)        # *xp = eax
movl %ebx,(%ecx)        # *yp = ebx
```

Understanding Swap

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

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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

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Understanding Swap

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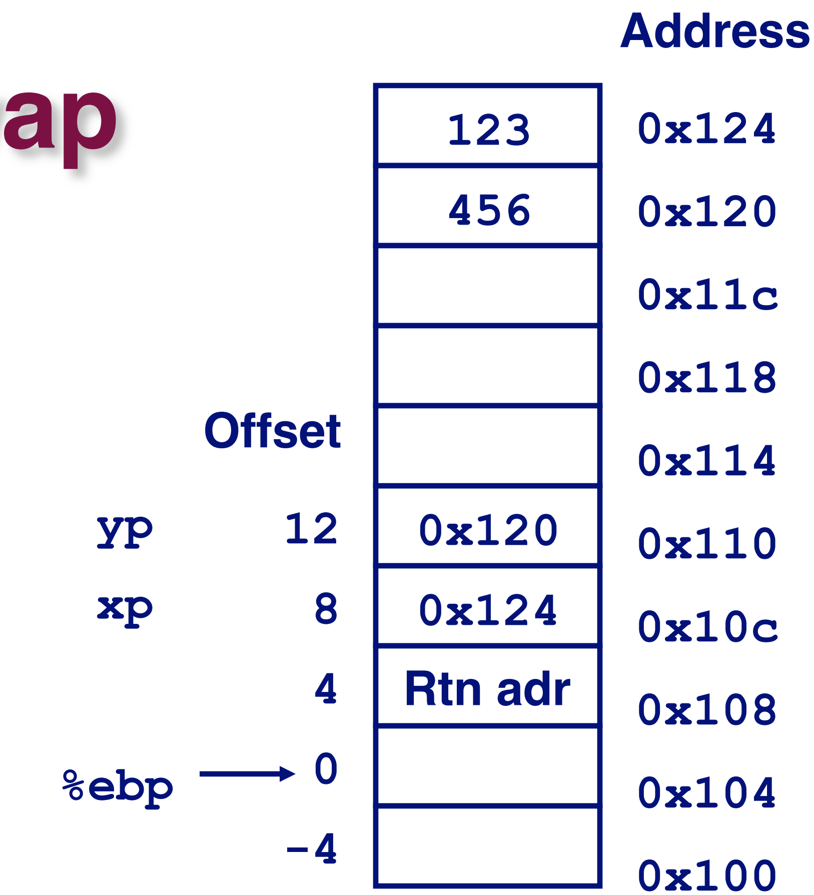
%edx	0x124
%ecx	0x120
%ebx	123
%esi	
%edi	
%esp	
%ebp	0x104



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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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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
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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
```

Indexed 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

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

Some Arithmetic Operations

Format		Computation	
Two Operand Instructions			
`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

Format	Computation
One Operand Instructions	
`incl` ***Dest***	***Dest*** `=` ***Dest*** `+ 1`
`decl` ***Dest***	***Dest*** `=` ***Dest*** `- 1`
`negl` ***Dest***	***Dest*** `= -` ***Dest***
`notl` ***Dest***	***Dest*** `= ~` ***Dest***

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;
}
```

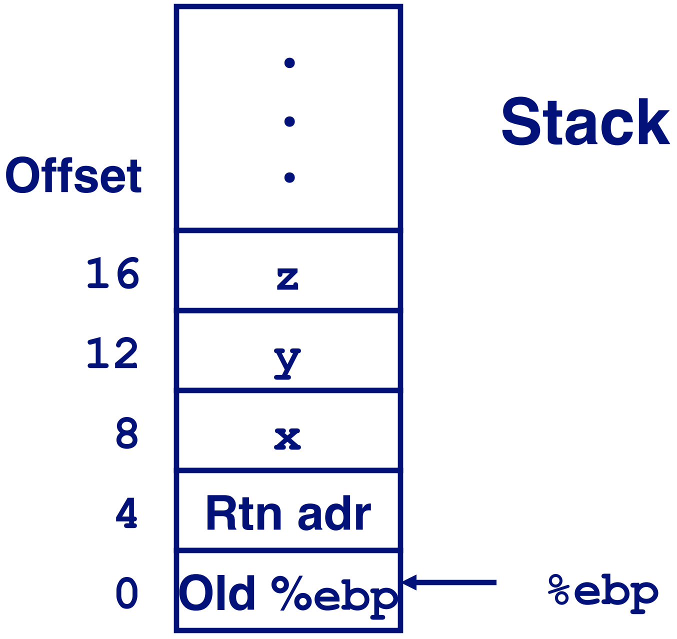
```
arith:
    pushl %ebp                        Set
    movl %esp,%ebp                    Up

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

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

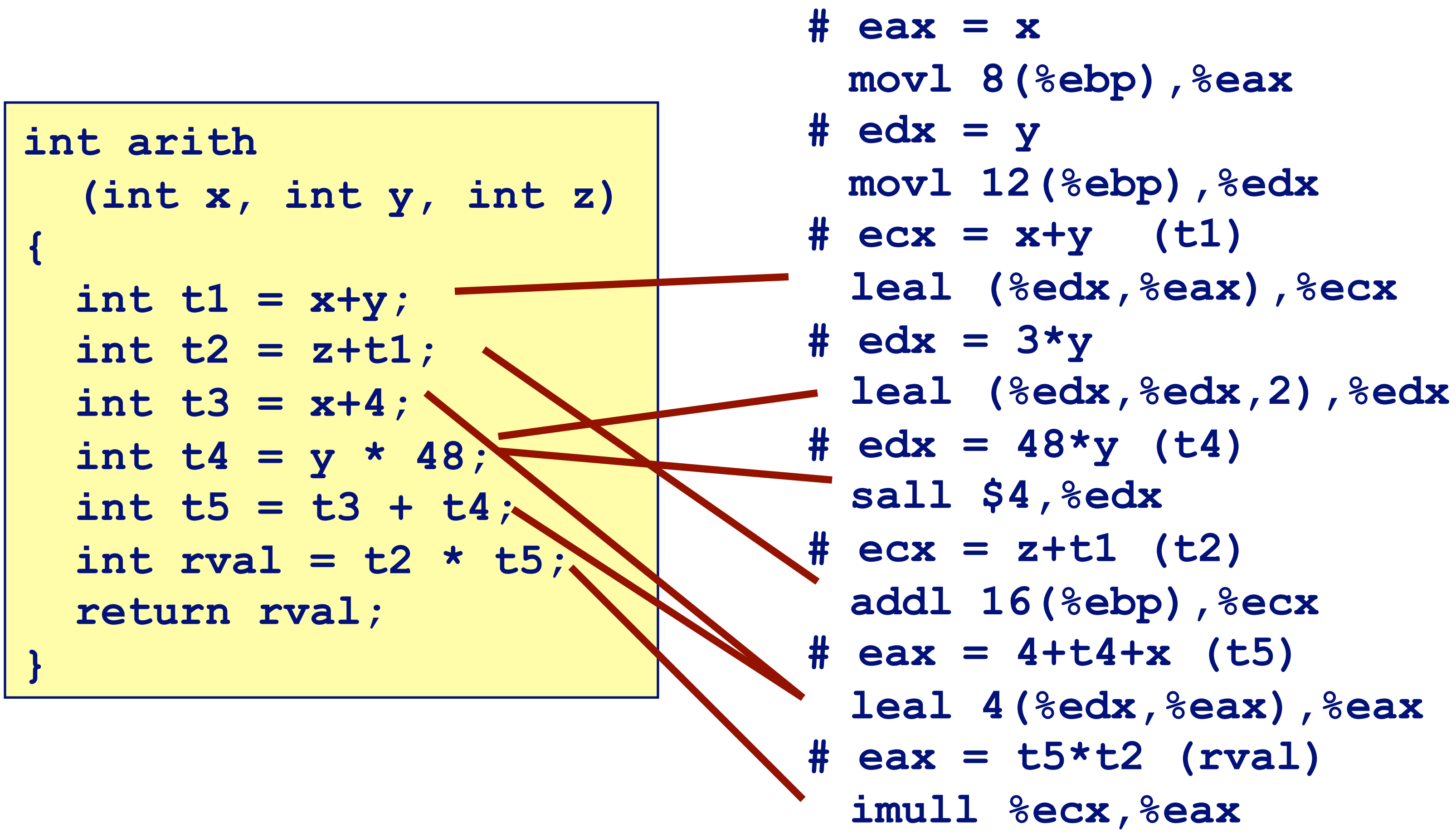


Stack

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 = 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;
}
```

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

Another Example

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

$2^{13} = 8192$, $2^{13} – 7 = 8185$

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

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

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

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

Another Example

```
for (i=0; i<n; i++)
    v += 1;
```

gcc -c -O -S foo.c

```
 .text
.globl _foo
_foo:
        pushl   %ebp
        movl    %esp, %ebp
        testl   %eax, %eax
        jle     L2
        movl    $0, %edx
L4:
        addl    %edx, %eax
        incl    %edx
        cmpl    %edx, %eax
        jne     L4
L2:
        leave
        ret
```

gcc –c -S foo.c

```
 .text
.globl _foo
_foo:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        movl    $0, -20(%ebp)
        jmp     L2
L3:
        movl    -20(%ebp), %eax
        leal    -12(%ebp), %edx
        addl    %eax, (%edx)
        leal    -20(%ebp), %eax
        incl    (%eax)
L2:
        movl    -20(%ebp), %eax
        cmpl    -16(%ebp), %eax
        jl      L3
        movl    -12(%ebp), %eax
        leave
        ret
```

Additional Help

Intel Instruction set online

- http://faydoc.tripod.com/cpu/index.htm

Useful GDB command if you’ve worked with Intel format

- set assembly-flavor intel
- set assembly-flavor att