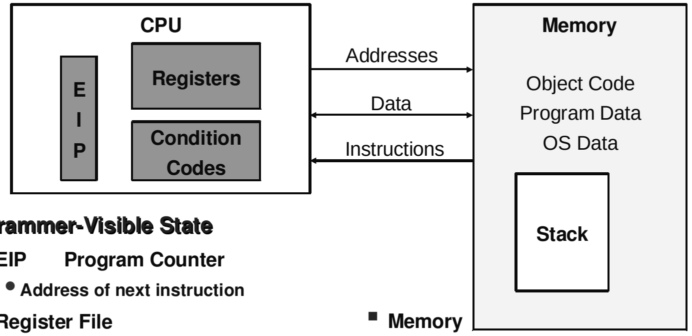
Lecture 4A
Machine-Level Programming I: Introduction

Topics

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

Assembly Programmer's View

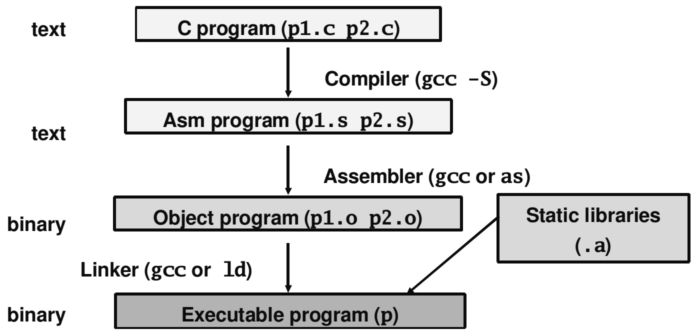


Programmer-Visible State

- 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

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 `y += x`

Assembly

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

`y`:	Register	`%eax`
`x`:	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

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
```

Disassembler

`objdump -d p`

- 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
```

Within gdb Debugger

`gdb p`

`disassemble sum`

- Disassemble procedure

`x/13b sum`

- Examine the 13 bytes starting at `sum`

Moving Data

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”

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

`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;
}
```

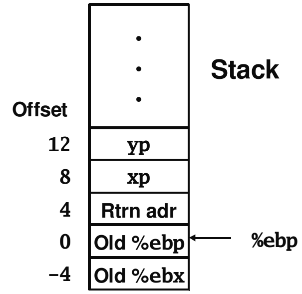
```
swap:
   pushl %ebp
   movl %esp,%ebp
   pushl %ebx
```
Set Up

```
   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

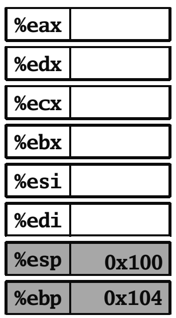
```
void swap(int *xp, int *yp)
{
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

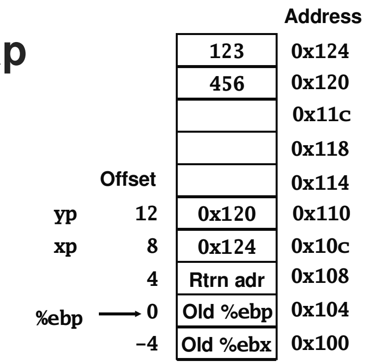


Register	Variable
%ecx	yp
%edx	xp
%eax	t1
%ebx	t0

```
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






```
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". Size of D is 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 + d**
  - 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

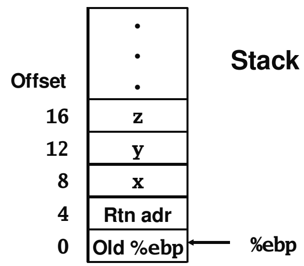
```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```

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

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

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


Understanding `arith`

```
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)
```

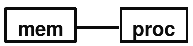
```
int arith
  (int x, int y, int z)
{
  int t1 = x+y;
  int t2 = z+t1;
  int t3 = x+4;
  int t4 = y * 48;
  int t5 = t3 + t4;
  int rval = t2 * t5;
  return rval;
}
```



Summary: Abstract Machines

Machine Models

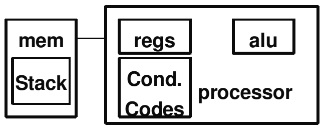
C



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

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

Assembly



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

Control
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)`