CS:APP Chapter 4
Computer Architecture
Instruction Set Architecture

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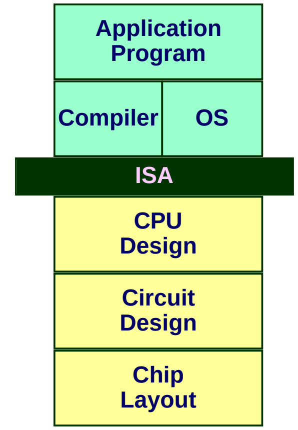
Instruction Set Architecture

Assembly Language View

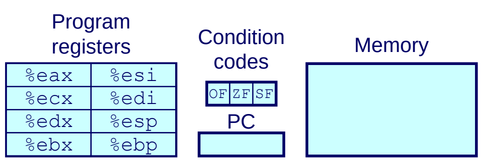
- Processor state
  - Registers, memory, …
- Instructions
  - `addl`, `movl`, `leal`, …
  - How instructions are encoded as bytes

Layer of Abstraction

- Above: how to program machine
  - Processor executes instructions in a sequence
- Below: what needs to be built
  - Use variety of tricks to make it run fast
  - E.g., execute multiple instructions simultaneously



Y86 Processor State



- Program Registers
  - Same 8 as with IA32. Each 32 bits
- Condition Codes
  - Single-bit flags set by arithmetic or logical instructions
    - » OF: Overflow ZF: Zero SF:Negative
- Program Counter
  - Indicates address of instruction
- Memory
  - Byte-addressable storage array
  - Words stored in little-endian byte order

Y86 Instructions

Format

- 1--6 bytes of information read from memory
  - Can determine instruction length from first byte
  - Not as many instruction types, and simpler encoding than with IA32
- Each accesses and modifies some part(s) of the program state

Encoding Registers

Each register has 4-bit ID

%eax	0	%esi	6
%ecx	1	%edi	7
%edx	2	%esp	4
%ebx	3	%ebp	5

- Same encoding as in IA32

Register ID 8 indicates “no register”

- Will use this in our hardware design in multiple places

Instruction Example

Addition Instruction

Generic Form

Encoded Representation

`addl rA, rB` | 6 | 0 | rA | rB |

- Add value in register rA to that in register rB
  - Store result in register rB
  - Note that Y86 only allows addition to be applied to register data
- Set condition codes based on result
- e.g., `addl %eax,%esi` Encoding: `60 06`
- Two-byte encoding
  - First indicates instruction type
  - Second gives source and destination registers

Arithmetic and Logical Operations

Instruction Code / Function Code

Add

`addl rA, rB` | 6 | 0 | rA | rB |

Subtract (rA from rB)

`subl rA, rB` | 6 | 1 | rA | rB |

And

`andl rA, rB` | 6 | 2 | rA | rB |

Exclusive-Or

`xorl rA, rB` | 6 | 3 | rA | rB |

- Refer to generically as “`OPl`”
- Encodings differ only by “function code”
  - Low-order 4 bytes in first instruction word
- Set condition codes as side effect

Move Operations

`rrmovl rA, rB` | 2 | 0 | rA | rB | — Register --> Register

`irmovl V, rB` | 3 | 0 | 8 | rB | V | — Immediate --> Register

`rmmovl rA, D(rB)` | 4 | 0 | rA | rB | D | — Register --> Memory

`mrmovl D(rB), rA` | 5 | 0 | rA | rB | D | — Memory --> Register

- Like the IA32 `movl` instruction
- Simpler format for memory addresses
- Give different names to keep them distinct

Move Instruction Examples

IA32	Y86	Encoding
`movl $0xabcd, %edx`	`irmovl $0xabcd, %edx`	`30 82 cd ab 00 00`
`movl %esp, %ebx`	`rrmovl %esp, %ebx`	`20 43`
`movl -12(%ebp),%ecx`	`mrmovl -12(%ebp),%ecx`	`50 15 f4 ff ff ff`
`movl %esi,0x41c(%esp)`	`rmmovl %esi,0x41c(%esp)`	`40 64 1c 04 00 00`

`movl $0xabcd, (%eax)`	—
`movl %eax, 12(%eax,%edx)`	—
`movl (%ebp,%eax,4),%ecx`	—

Jump Instructions

Jump Unconditionally

`jmp` Dest	7	0	Dest

Jump When Less or Equal

`jle` Dest	7	1	Dest

Jump When Less

`jl` Dest	7	2	Dest

Jump When Equal

`je` Dest	7	3	Dest

Jump When Not Equal

`jne` Dest	7	4	Dest

Jump When Greater or Equal

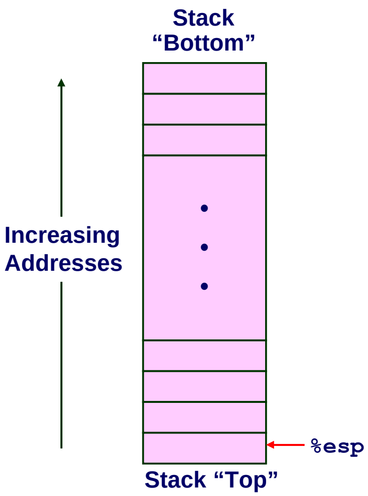
`jge` Dest	7	5	Dest

Jump When Greater

`jg` Dest	7	6	Dest

- Refer to generically as "`jXX`"
- Encodings differ only by "function code"
- Based on values of condition codes
- Same as IA32 counterparts
- Encode full destination address
  - Unlike PC-relative addressing seen in IA32

Y86 Program Stack



- Region of memory holding program data
- Used in Y86 (and IA32) for supporting procedure calls
- Stack top indicated by `%esp`
  - Address of top stack element
- Stack grows toward lower addresses
  - Top element is at highest address in the stack
  - When pushing, must first decrement stack pointer
  - When popping, increment stack pointer

Stack Operations

`pushl` rA	a	0	rA	8

- Decrement `%esp` by 4
- Store word from rA to memory at `%esp`
- Like IA32

`popl` rA	b	0	rA	8

- Read word from memory at `%esp`
- Save in rA
- Increment `%esp` by 4
- Like IA32

Subroutine Call and Return

call Dest	8	0	Dest

- Push address of next instruction onto stack
- Start executing instructions at Dest
- Like IA32

ret	9	0

- Pop value from stack
- Use as address for next instruction
- Like IA32

Miscellaneous Instructions

nop	0	0

- Don't do anything

halt	1	0

- Stop executing instructions
- IA32 has comparable instruction, but can't execute it in user mode
- We will use it to stop the simulator

Writing Y86 Code

Try to Use C Compiler as Much as Possible

- Write code in C
- Compile for IA32 with `gcc -S`
- Transliterate into Y86

Coding Example

- Find number of elements in null-terminated list

```
int len1(int a[]);
```

a →
5043
6125
7395
0

⇒ 3

Y86 Code Generation Example

First Try

- Write typical array code

```
/* Find number of elements in
   null-terminated list */
int len1(int a[])
{
  int len;
  for (len = 0; a[len]; len++)
      ;
  return len;
}
```

- Compile with `gcc -O2 -S`

Problem

- Hard to do array indexing on Y86
  - Since don't have scaled addressing modes

```
L18:
   incl %eax
   cmpl $0,(%edx,%eax,4)
   jne L18
```

Y86 Code Generation Example #2

Second Try

- Write with pointer code

```
/* Find number of elements in
   null-terminated list */
int len2(int a[])
{
  int len = 0;
  while (*a++)
       len++;
  return len;
}
```

- Compile with `gcc -O2 -S`

Result

- Don't need to do indexed addressing

```
L24:
   movl (%edx),%eax
   incl %ecx
L26:
   addl $4,%edx
   testl %eax,%eax
   jne L24
```


Y86 Code Generation Example #3

IA32 Code

- Setup

```
len2:
   pushl %ebp
   xorl %ecx,%ecx
   movl %esp,%ebp
   movl 8(%ebp),%edx
   movl (%edx),%eax
   jmp L26
```

Y86 Code

- Setup

```
len2:
   pushl %ebp             # Save %ebp
   xorl %ecx,%ecx         # len = 0
   rrmovl %esp,%ebp       # Set frame
   mrmovl 8(%ebp),%edx    # Get a
   mrmovl (%edx),%eax     # Get *a
   jmp L26                # Goto entry
```


Y86 Code Generation Example #4

IA32 Code

- Loop + Finish

```
L24:
   movl (%edx),%eax
   incl %ecx

L26:
   addl $4,%edx

   testl %eax,%eax
   jne L24
   movl %ebp,%esp
   movl %ecx,%eax
   popl %ebp
   ret
```

Y86 Code

- Loop + Finish

```
L24:
   mrmovl (%edx),%eax  # Get *a
   irmovl $1,%esi
   addl %esi,%ecx      # len++
L26:                   # Entry:
   irmovl $4,%esi
   addl %esi,%edx      # a++
   andl %eax,%eax      # *a == 0?
   jne L24             # No--Loop
   rrmovl %ebp,%esp    # Pop
   rrmovl %ecx,%eax    # Rtn len
   popl %ebp
   ret
```


Y86 Program Structure

```
   irmovl Stack,%esp    # Set up stack
   rrmovl %esp,%ebp     # Set up frame
   irmovl List,%edx
   pushl %edx           # Push argument
   call len2            # Call Function
   halt                 # Halt
.align 4
List:                   # List of elements
   .long 5043
   .long 6125
   .long 7395
   .long 0

# Function
len2:
   . . .

# Allocate space for stack
.pos 0x100
Stack:
```

- Program starts at address 0
- Must set up stack
  - Make sure don't overwrite code!
- Must initialize data
- Can use symbolic names

Assembling Y86 Program

```
unix> yas eg.ys
```

- Generates "object code" file `eg.yo`
  - Actually looks like disassembler output

```
0x000: 308400010000 | irmovl Stack,%esp     # Set up stack
0x006: 2045         | rrmovl %esp,%ebp      # Set up frame
0x008: 308218000000 | irmovl List,%edx
0x00e: a028         | pushl %edx            # Push argument
0x010: 8028000000   | call len2             # Call Function
0x015: 10           | halt                  # Halt
0x018:              | .align 4
0x018:              | List:                 # List of elements
0x018: b3130000     | .long 5043
0x01c: ed170000     | .long 6125
0x020: e31c0000     | .long 7395
0x024: 00000000     | .long 0
```


Simulating Y86 Program

```
unix> yis eg.yo
```

- Instruction set simulator
  - Computes effect of each instruction on processor state
  - Prints changes in state from original

```
Stopped in 41 steps at PC = 0x16.  Exception 'HLT', CC Z=1 S=0 O=0
Changes to registers:
%eax:                   0x00000000      0x00000003
%ecx:                   0x00000000      0x00000003
%edx:                   0x00000000      0x00000028
%esp:                   0x00000000      0x000000fc
%ebp:                   0x00000000      0x00000100
%esi:                   0x00000000      0x00000004

Changes to memory:
0x00f4:                 0x00000000      0x00000100
0x00f8:                 0x00000000      0x00000015
0x00fc:                 0x00000000      0x00000018
```


CISC Instruction Sets

- Complex Instruction Set Computer
- Dominant style through mid-80's

Stack-oriented instruction set

- Use stack to pass arguments, save program counter
- Explicit push and pop instructions

Arithmetic instructions can access memory

- `addl %eax, 12(%ebx,%ecx,4)`
  - requires memory read and write
  - Complex address calculation

Condition codes

- Set as side effect of arithmetic and logical instructions

Philosophy

- Add instructions to perform "typical" programming tasks

RISC Instruction Sets

- Reduced Instruction Set Computer
- Internal project at IBM, later popularized by Hennessy (Stanford) and Patterson (Berkeley)

Fewer, simpler instructions

- Might take more to get given task done
- Can execute them with small and fast hardware

Register-oriented instruction set

- Many more (typically 32) registers
- Use for arguments, return pointer, temporaries

Only load and store instructions can access memory

- Similar to Y86 `mrmovl` and `rmmovl`

No Condition codes

- Test instructions return 0/1 in register

MIPS Registers

$0	$0	Constant 0
$1	$at	Reserved Temp.
$2	$v0	Return Values
$3	$v1	
$4	$a0	Procedure arguments
$5	$a1	
$6	$a2	
$7	$a3	
$8	$t0	Caller Save Temporaries: May be overwritten by called procedures
$9	$t1	
$10	$t2	
$11	$t3	
$12	$t4	
$13	$t5	
$14	$t6	
$15	$t7	
$16	$s0	Callee Save Temporaries: May not be overwritten by called procedures
$17	$s1	
$18	$s2	
$19	$s3	
$20	$s4	
$21	$s5	
$22	$s6	
$23	$s7	
$24	$t8	Caller Save Temp
$25	$t9	
$26	$k0	Reserved for Operating Sys
$27	$k1	
$28	$gp	Global Pointer
$29	$sp	Stack Pointer
$30	$s8	Callee Save Temp
$31	$ra	Return Address

MIPS Instruction Examples

R-R

Op	Ra	Rb	Rd	00000	Fn

```
addu $3,$2,$1       # Register add: $3 = $2+$1
```

R-I

Op	Ra	Rb	Immediate

```
addu $3,$2, 3145    # Immediate add: $3 = $2+3145
sll $3,$2,2         # Shift left: $3 = $2 << 2
```

Branch

Op	Ra	Rb	Offset

```
beq $3,$2,dest      # Branch when $3 = $2
```

Load/Store

Op	Ra	Rb	Offset

```
lw $3,16($2)        # Load Word: $3 = M[$2+16]
sw $3,16($2)        # Store Word: M[$2+16] = $3
```


CISC vs. RISC

Original Debate

- Strong opinions!
- CISC proponents---easy for compiler, fewer code bytes
- RISC proponents---better for optimizing compilers, can make run fast with simple chip design

Current Status

- For desktop processors, choice of ISA not a technical issue
  - With enough hardware, can make anything run fast
  - Code compatibility more important
- For embedded processors, RISC makes sense
  - Smaller, cheaper, less power

Summary

Y86 Instruction Set Architecture

- Similar state and instructions as IA32
- Simpler encodings
- Somewhere between CISC and RISC

How Important is ISA Design?

- Less now than before
  - With enough hardware, can make almost anything go fast
- Intel is moving away from IA32
  - Does not allow enough parallel execution
  - Introduced IA64
    - » 64-bit word sizes (overcome address space limitations)
    - » Radically different style of instruction set with explicit parallelism
    - » Requires sophisticated compilers