CS:APP Chapter 4
Computer Architecture
Instruction Set Architecture

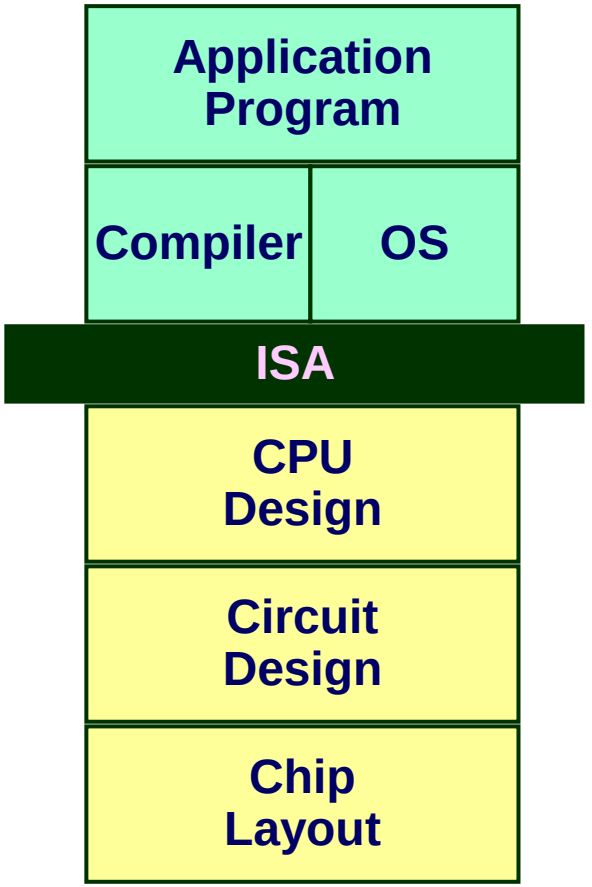
Instruction Set Architecture

Assembly Language View

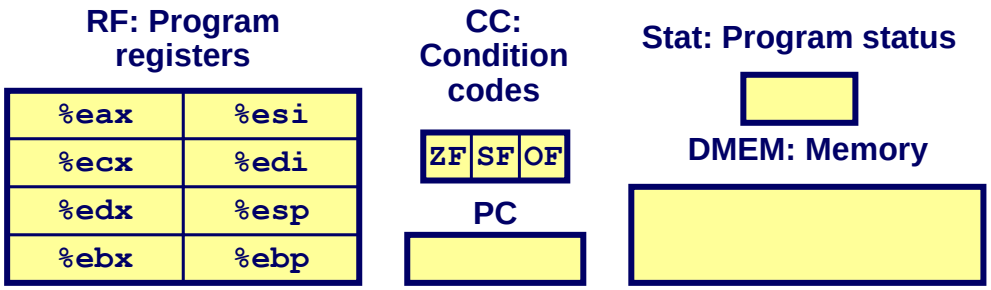
- Processor state
  - Registers, memory, …
- Instructions
  - `addl`, `pushl`, `ret`, …
  - How instructions are encoded as bytes

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



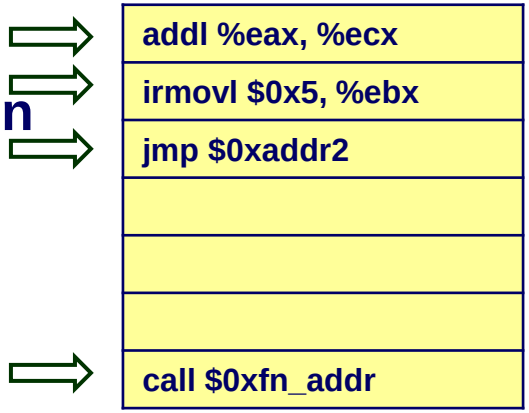
Y86 Processor State

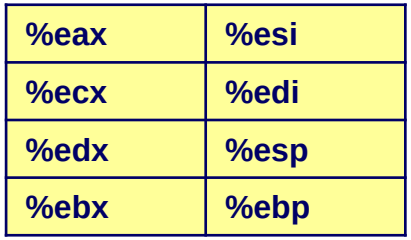


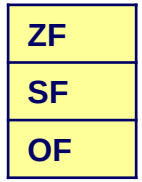
- **Program Registers**
  - **Same 8 as with IA32. Each 32 bits**
- **Condition Codes**
  - **Single-bit flags set by arithmetic or logical instructions**
    - » ZF: Zero SF:Negative OF: Overflow
- **Program Counter**
  - **Indicates address of next instruction**
- **Program Status**
  - **Indicates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

Y86 Execution

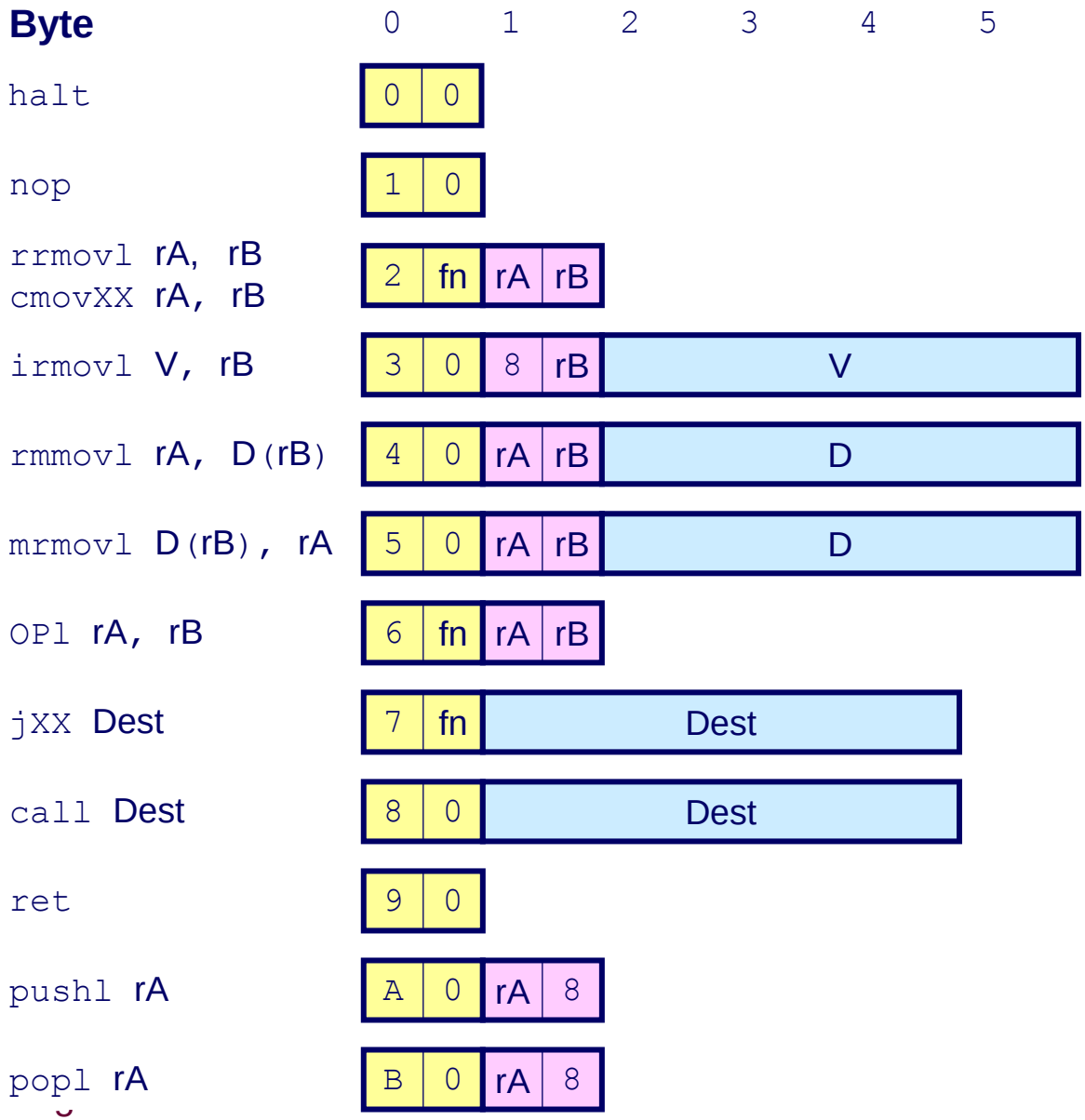
- Sequence of instructions
- PC points to next instruction
- Fetch & decode
  - Read instruction at PC
- Execute
  - Update registers
  - Move values to/from memory
  - Update condition codes
- Update PC
  - Default: next instruction
  - call/jmp instructions set new PC
  - goto considered your only option







Y86 Instruction Set #1

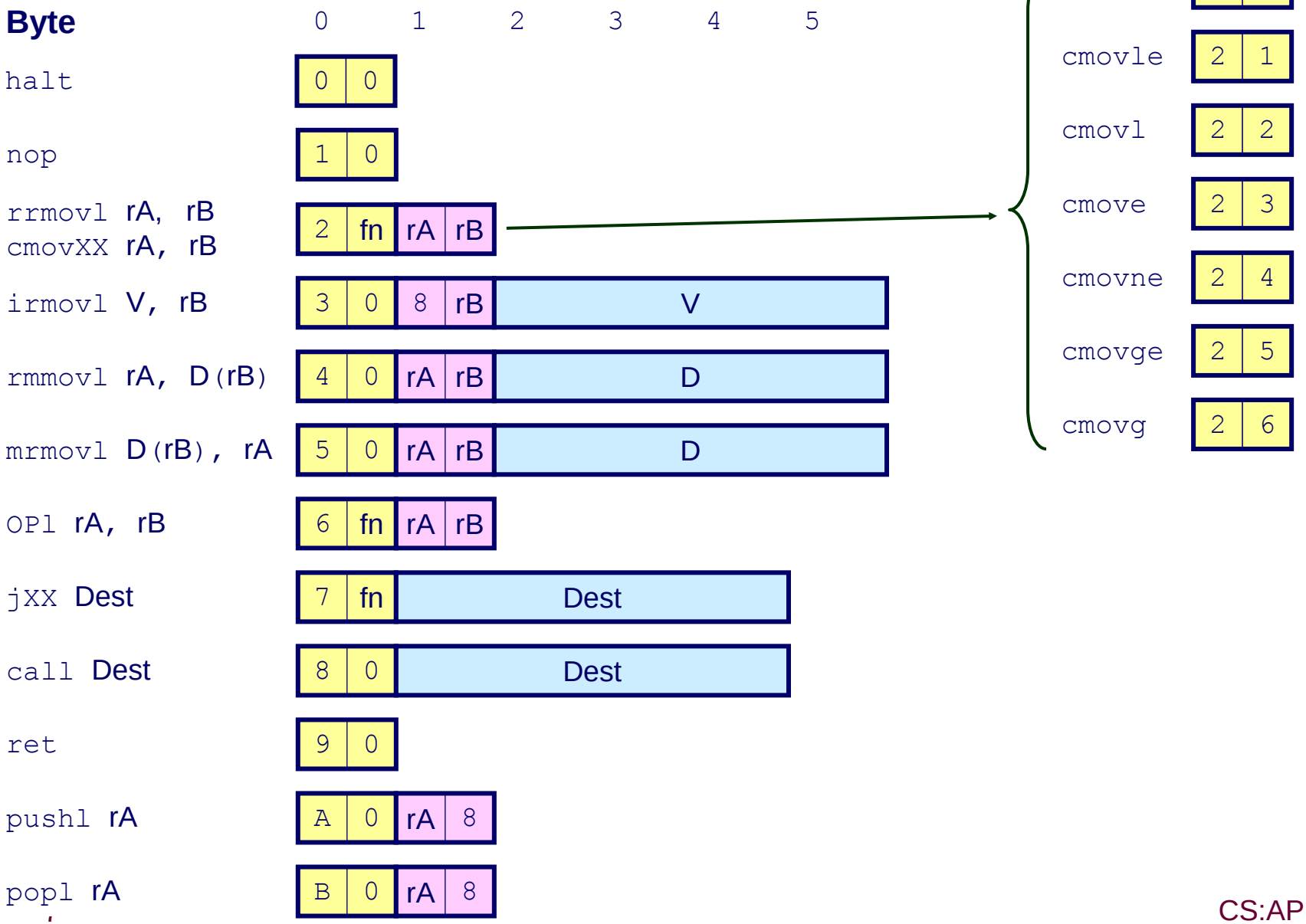


Y86 Instructions

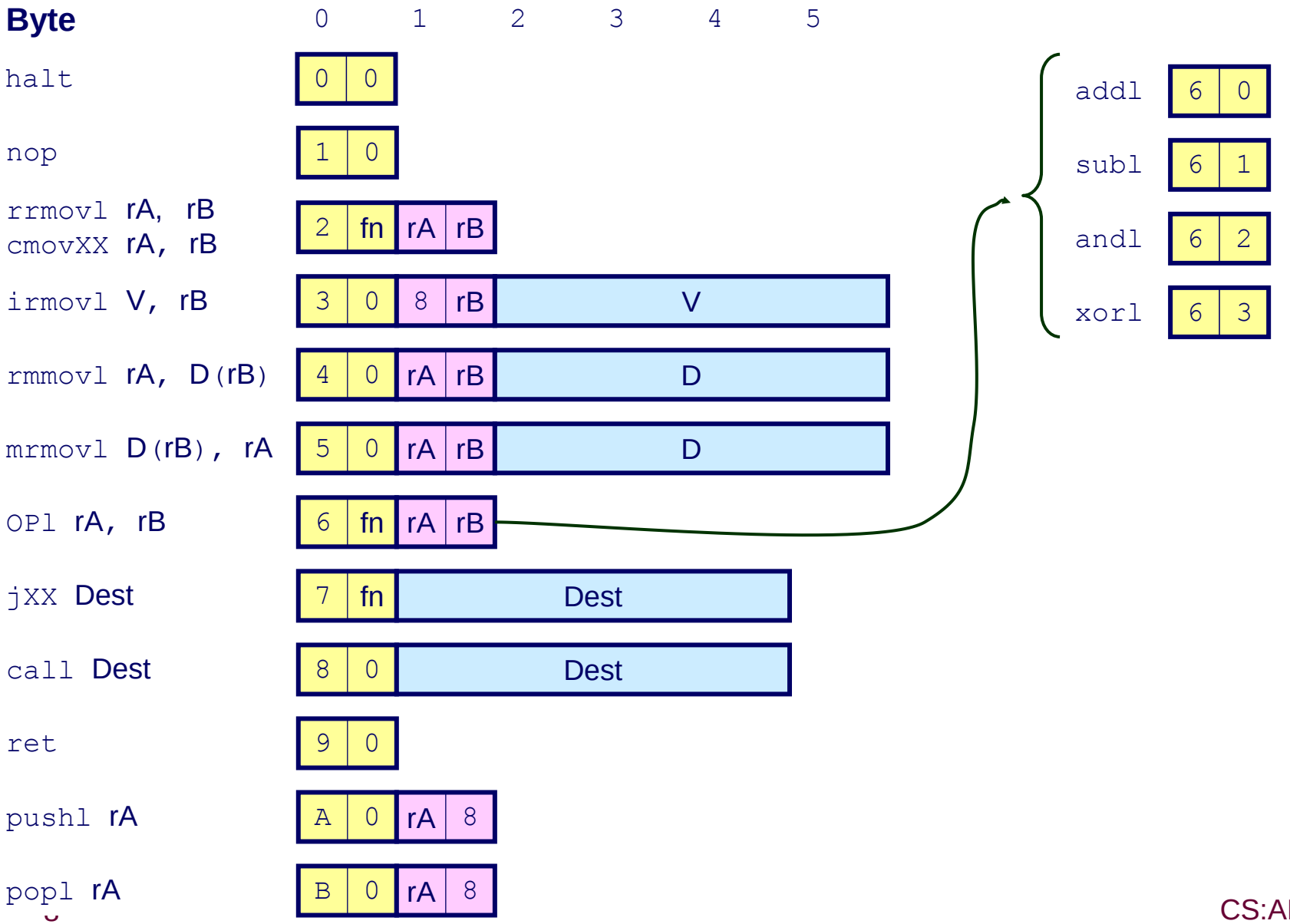
Format

- 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

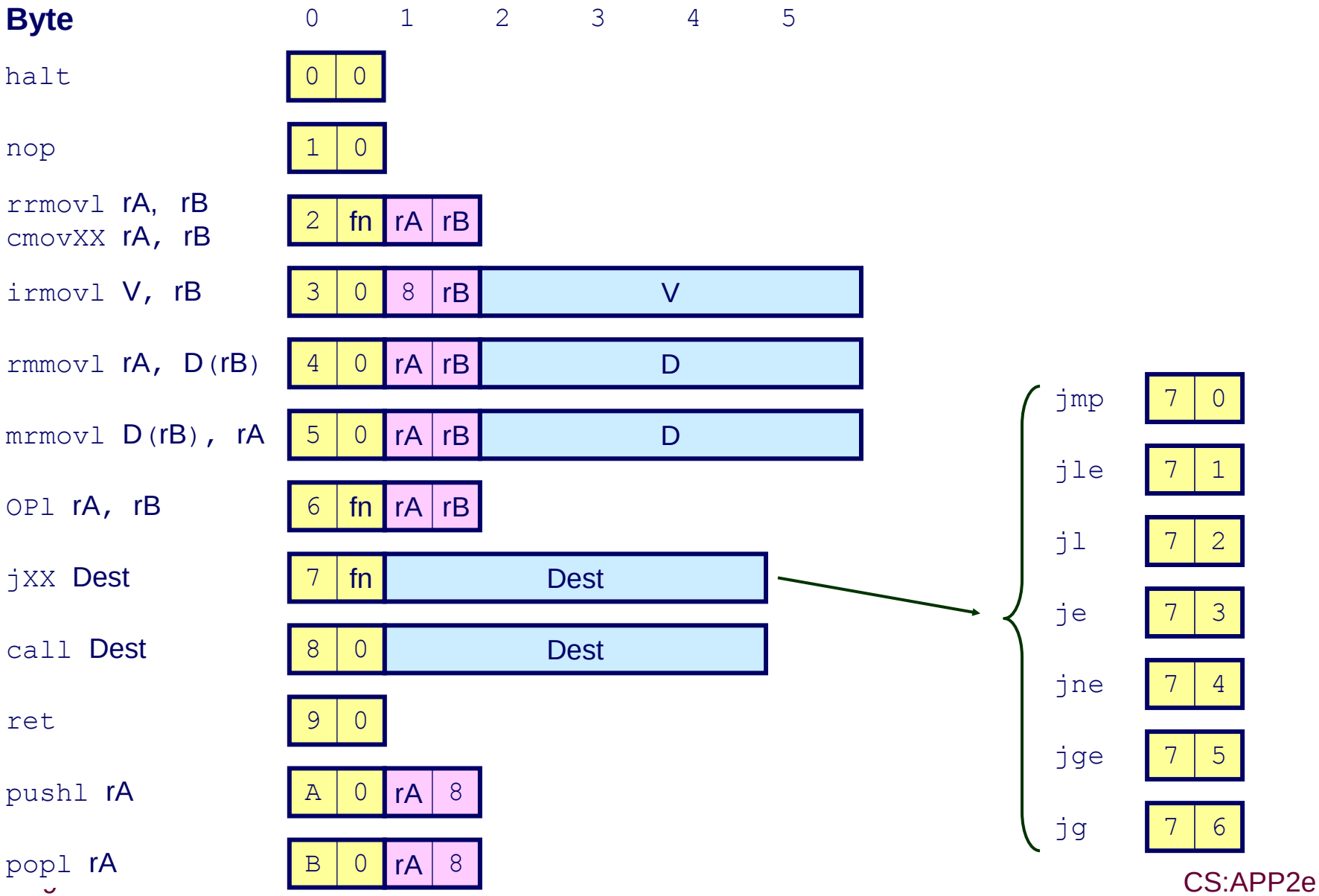
Y86 Instruction Set #2



Y86 Instruction Set #3



Y86 Instruction Set #4



Encoding Registers

Each register has 4-bit ID

%eax	0
%ecx	1
%edx	2
%ebx	3

%esi	6
%edi	7
%esp	4
%ebp	5

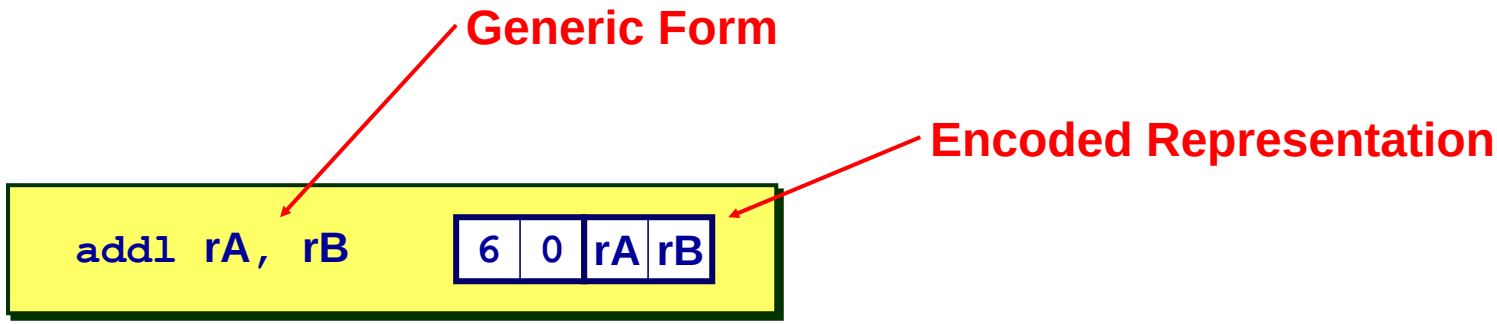
- Same encoding as in IA32

Register ID 15 (0xF) indicates “no register”

- Will use this in our hardware design in multiple places

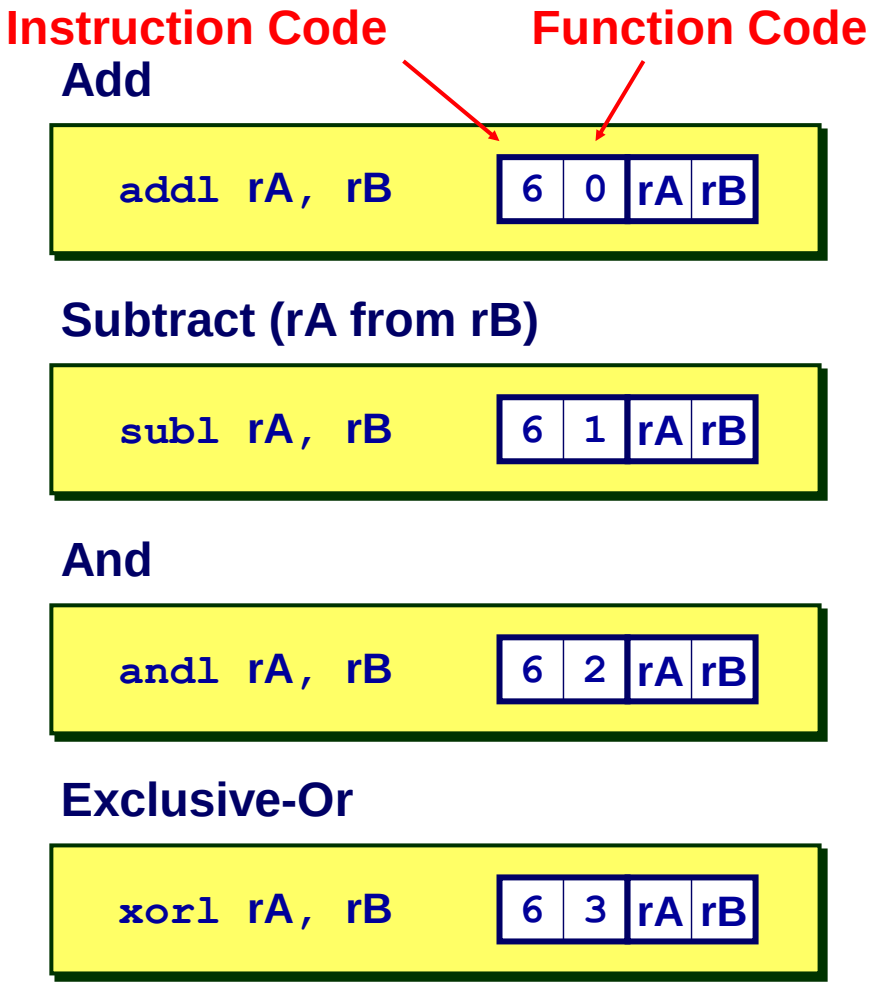
Instruction Example

Addition Instruction



- 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



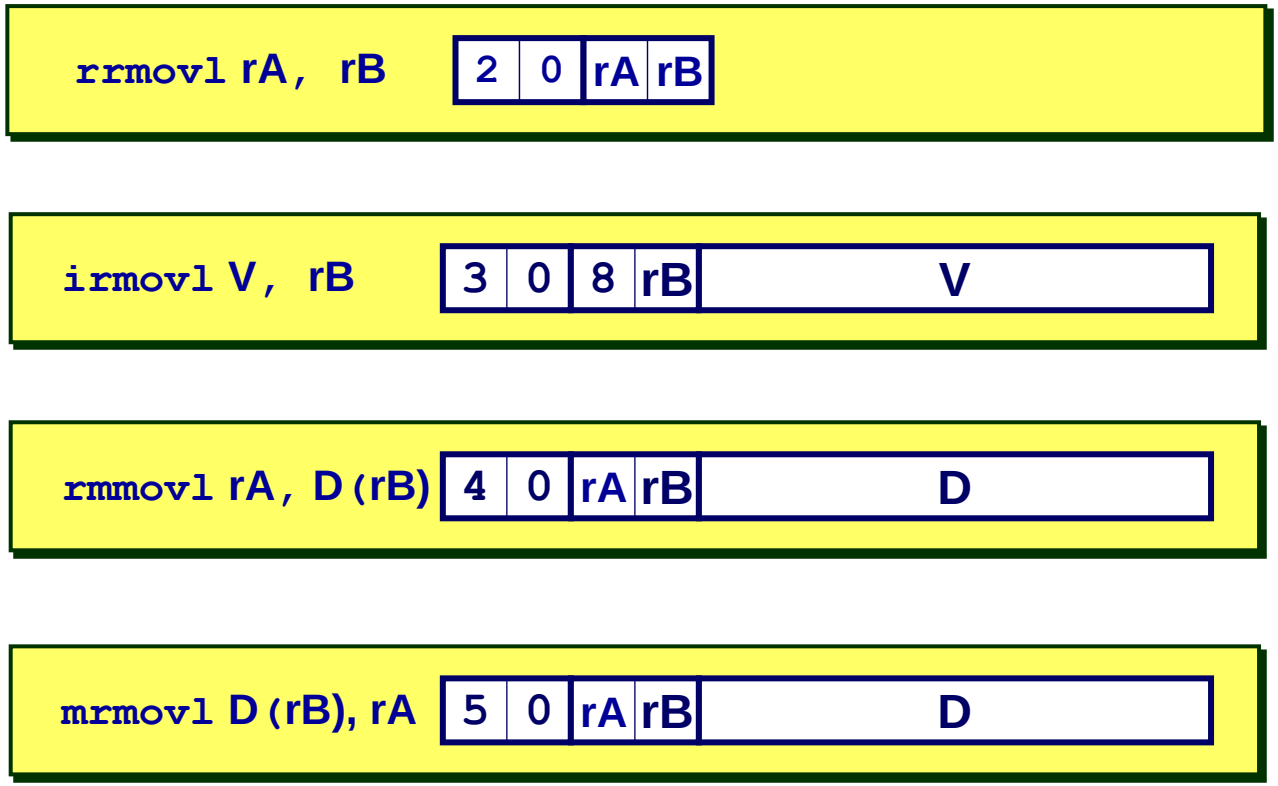
- Refer to generically as "`OPl`"
- Encodings differ only by "function code"
  - Low-order 4 bytes in first instruction word
- Set condition codes as side effect

Condition codes

- Set with each arithmetic/logical op.
- ZF: was the result 0?
- SF: was the result <0?
- OF: did the result overflow? (two's complement)

instruction	values	ZF,SF,OF
`addl rA, rB`	`0x1,0x2`	`0,0,0`
`addl rA, rB`	`TMIN,-1`	`0,0,1`
`addl rA, rB`	`1,-2`	`0,1,0`
`addl rA, rB`	`5,-5`	`1,0,0`
`addl rA, rB`	`TMIN,TMIN`	`1,0,1`

Move Operations



- 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`	—

Conditional Move Instructions

Move Unconditionally

`rrmovl` rA, rB | 2 | 0 | rA | rB

Move When Less or Equal

`cmovle` rA, rB | 2 | 1 | rA | rB

Move When Less

`cmovl` rA, rB | 2 | 2 | rA | rB

Move When Equal

`cmove` rA, rB | 2 | 3 | rA | rB

Move When Not Equal

`cmovne` rA, rB | 2 | 4 | rA | rB

Move When Greater or Equal

`cmovge` rA, rB | 2 | 5 | rA | rB

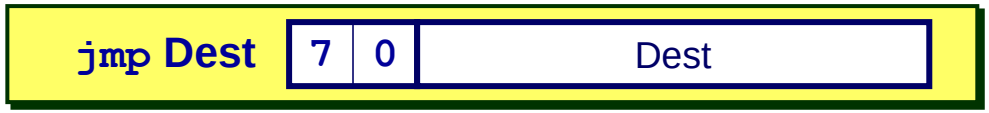
Move When Greater

`cmovg` rA, rB | 2 | 6 | rA | rB

- Refer to generically as "`cmovXX`"
- Encodings differ only by "function code"
- Based on values of condition codes
- Variants of `rrmovl` instruction
  - (Conditionally) copy value from source to destination register

Jump Instructions

Jump Unconditionally



Jump When Less or Equal

Jump When Less

Jump When Equal

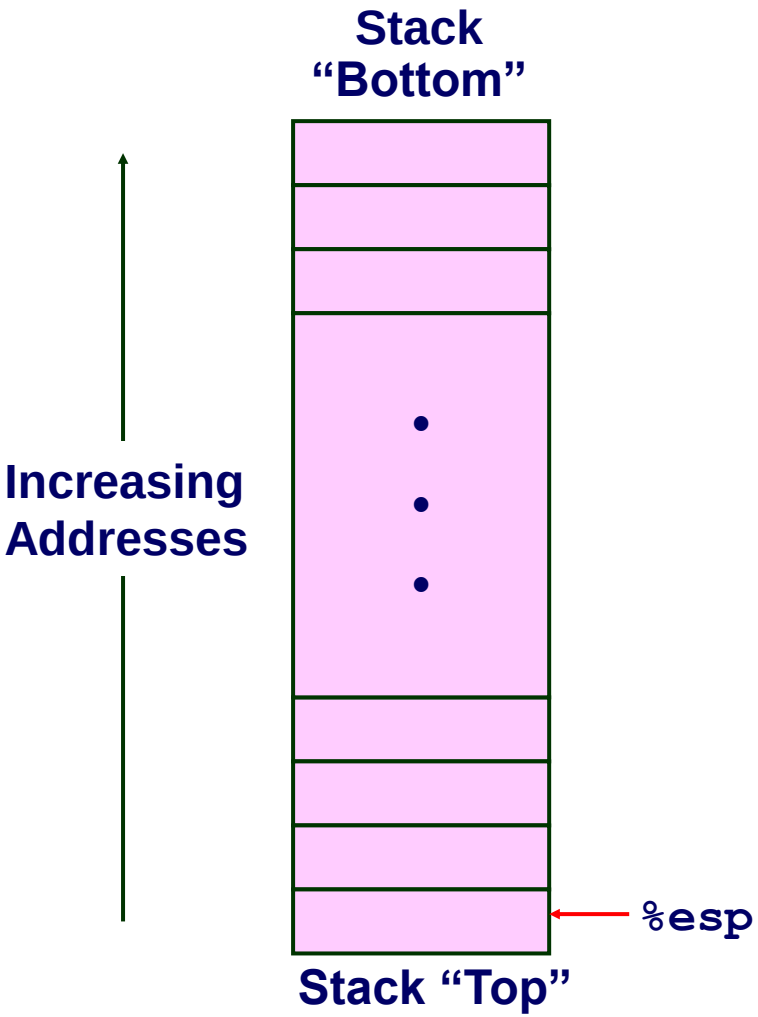
Jump When Not Equal

Jump When Greater or Equal

Jump When Greater

- 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
  - Bottom element is at highest address in the stack
  - When pushing, must first decrement stack pointer
  - After popping, increment stack pointer

Stack Operations

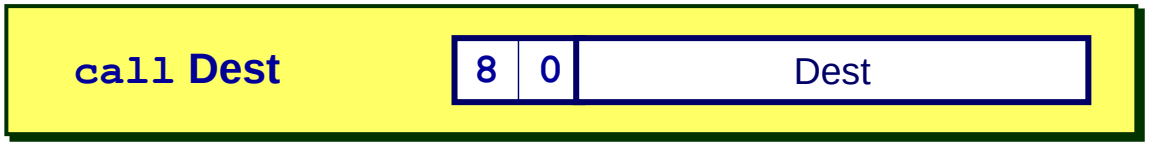
`pushl rA`

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

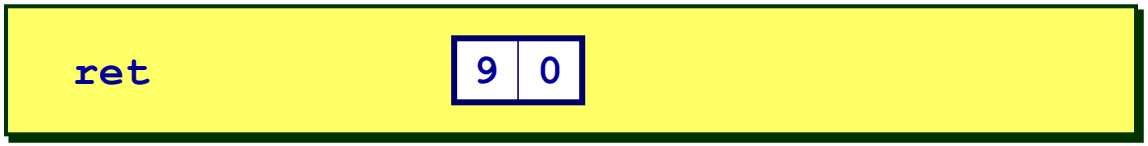
`popl rA`

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

Subroutine Call and Return



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



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

Miscellaneous Instructions

- Don’t do anything

- Stop executing instructions
- IA32 has comparable instruction, but can’t execute it in user mode
- We will use it to stop the simulator
- Encoding ensures that program hitting memory initialized to zero will halt

Status Conditions

Mnemonic	Code
AOK	1

- Normal operation

Mnemonic	Code
HLT	2

- Halt instruction encountered

Mnemonic	Code
ADR	3

- Bad address (either instruction or data) encountered

Mnemonic	Code
INS	4

- Invalid instruction encountered

Desired Behavior

- If AOK, keep going
- Otherwise, stop program execution

Writing Y86 Code

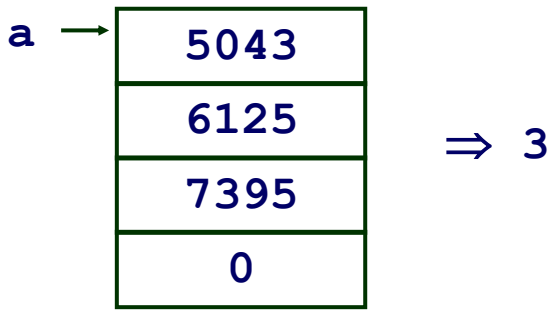
Try to Use C Compiler as Much as Possible

- Write code in C
- Compile for IA32 with `gcc34 -O1 -S`
  - Newer versions of GCC do too much optimization
  - Use `ls /usr/bin/gcc*` to find what versions are available
- Transliterate into Y86

Coding Example

- Find number of elements in null-terminated list

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



⇒ 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 `gcc34 –O1 -S`

Problem

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

```
L5:
   incl   %eax
   cmpl   $0, (%edx,%eax,4)
   jne L5
```

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 `gcc34 –O1 -S`

Result

- Don't need to do indexed addressing

```
.L11:
   incl        %ecx
   movl        (%edx), %eax
   addl        $4, %edx
   testl       %eax, %eax
   jne .L11
```

Y86 Code Generation Example #3

IA32 Code

- Setup

```
len2:
   pushl %ebp
   movl %esp, %ebp




   movl 8(%ebp), %edx
   movl $0, %ecx
   movl (%edx), %eax
   addl $4, %edx
   testl %eax, %eax
   je   .L13
```

Y86 Code

- Setup

```
len2:
   pushl %ebp           # Save %ebp
   rrmovl %esp, %ebp    # New FP
   pushl %esi           # Save
   irmovl $4, %esi      # Constant 4
   pushl %edi           # Save
   irmovl $1, %edi      # Constant 1
   mrmovl 8(%ebp), %edx     # Get a
   irmovl $0, %ecx          # len = 0
   mrmovl (%edx), %eax      # Get *a
   addl %esi, %edx          # a++
   andl %eax, %eax          # Test *a
   je Done      # If zero, goto Done
```

- Need constants 1 & 4
- Store in callee-save registers
- Use `andl` to test register

Y86 Code Generation Example #4

IA32 Code

- Loop

```
.L11:
   incl %ecx
   movl (%edx), %eax
   addl $4, %edx
   testl %eax, %eax
   jne .L11
```

Y86 Code

- Loop

```
Loop:
   addl %edi, %ecx          # len++
   mrmovl (%edx), %eax      # Get *a
   addl %esi, %edx          # a++
   andl %eax, %eax          # Test *a
   jne Loop      # If !0, goto Loop
```

Y86 Code Generation Example #5

IA32 Code

- Finish

```
.L13:
  movl %ecx, %eax


  leave

  ret
```

Y86 Code

- Finish

```
Done:
   rrmovl %ecx, %eax  # return len
   popl %edi     # Restore %edi
   popl %esi     # Restore %esi
   rrmovl %ebp, %esp # Restore SP
   popl %ebp          # Restore FP
   ret
```

Y86 Sample Program Structure #1

```
init:                   # Initialization
    . . .
    call Main
    halt

    .align 4            # Program data
array:
    . . .

Main:                   # Main function
    . . .
    call len2
    . . .

len2:                   # Length function
    . . .

    .pos 0x100          # Placement of stack
Stack:
```

- Program starts at address 0
- Must set up stack
  - Where located
  - Pointer values
  - Make sure don't overwrite code!
- Must initialize data

Y86 Program Structure #2

```
init:
   irmovl Stack, %esp  # Set up SP
   irmovl Stack, %ebp  # Set up FP
   call Main           # Execute main
   halt                # Terminate

# Array of 4 elements + terminating 0
   .align 4
array:
   .long 0x000d
   .long 0x00c0
   .long 0x0b00
   .long 0xa000
   .long 0
```

- Program starts at address 0
- Must set up stack
- Must initialize data
- Can use symbolic names

Y86 Program Structure #3

```
Main:
   pushl %ebp
   rrmovl %esp,%ebp
   irmovl array,%edx
   pushl %edx           # Push array
   call len2            # Call len2(array)
   rrmovl %ebp,%esp
   popl %ebp
   ret
```

Set up call to len2

- Follow IA32 procedure conventions
- Push array address as argument

Assembling Y86 Program

```
unix> yas len.ys
```

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

```
0x000:                  |    .pos 0
0x000: 30f400010000     | init:   irmovl Stack, %esp  # Set up stack pointer
0x006: 30f500010000     |    irmovl Stack, %ebp      # Set up base pointer
0x00c: 8028000000       |    call Main               # Execute main program
0x011: 00               |    halt                    # Terminate program
                        |
                        | # Array of 4 elements + terminating 0
0x014:                  |    .align 4
0x014:                  | array:
0x014: 0d000000         |    .long 0x000d
0x018: c0000000         |    .long 0x00c0
0x01c: 000b0000         |    .long 0x0b00
0x020: 00a00000         |    .long 0xa000
0x024: 00000000         |    .long 0
```

Simulating Y86 Program

```
unix> yis len.yo
```

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

```
Stopped in 50 steps at PC = 0x11.  Status 'HLT', CC Z=1 S=0 O=0
Changes to registers:
%eax:                   0x00000000    0x00000004
%ecx:                   0x00000000    0x00000004
%edx:                   0x00000000    0x00000028
%esp:                   0x00000000    0x00000100
%ebp:                   0x00000000    0x00000100

Changes to memory:
0x00ec:                 0x00000000    0x000000f8
0x00f0:                 0x00000000    0x00000039
0x00f4:                 0x00000000    0x00000014
0x00f8:                 0x00000000    0x00000100
0x00fc:                 0x00000000    0x00000011
```

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

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
  - Most cell phones use ARM processor

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 has evolved from IA32 to x86-64
  - Uses 64-bit words (including addresses)
  - Adopted some features found in RISC
    - » More registers (16)
    - » Less reliance on stack