# 15-213

# Machine-Level Programming I: Introduction
# Jan. 30, 2001

## 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!

# X86 Evolution: Programmer's View

| Name | Date | Transistors |
|---|---|---|
| 8086 | 1978 | 29K |

- 16-bit processor. Basis for IBM PC & DOS
- Limited to 1MB address space. DOS only gives you 640K

| | | |
|---|---|---|
| 80286 | 1982 | 134K |

- Added elaborate, but not very useful, addressing scheme
- Basis for IBM PC-AT and Windows

| | | |
|---|---|---|
| 386 | 1985 | 275K |

- Extended to 32 bits. Added "flat addressing"
- Capable of running Unix
- Linux/gcc uses no instructions introduced in later models

| | | |
|---|---|---|
| 486 | 1989 | 1.9M |
| Pentium | 1993 | 3.1M |

# X86 Evolution: Programmer's View

| Name | Date | Transistors |
|---|---|---|
| Pentium/MMX | 1997 | 4.5M |

- Added special collection of instructions for operating on 64-bit vectors of 1, 2, or 4 byte integer data

| Name | Date | Transistors |
|---|---|---|
| Pentium II | 1997 | 7M |

- Added conditional move instructions
- Big change in underlying microarchitecture

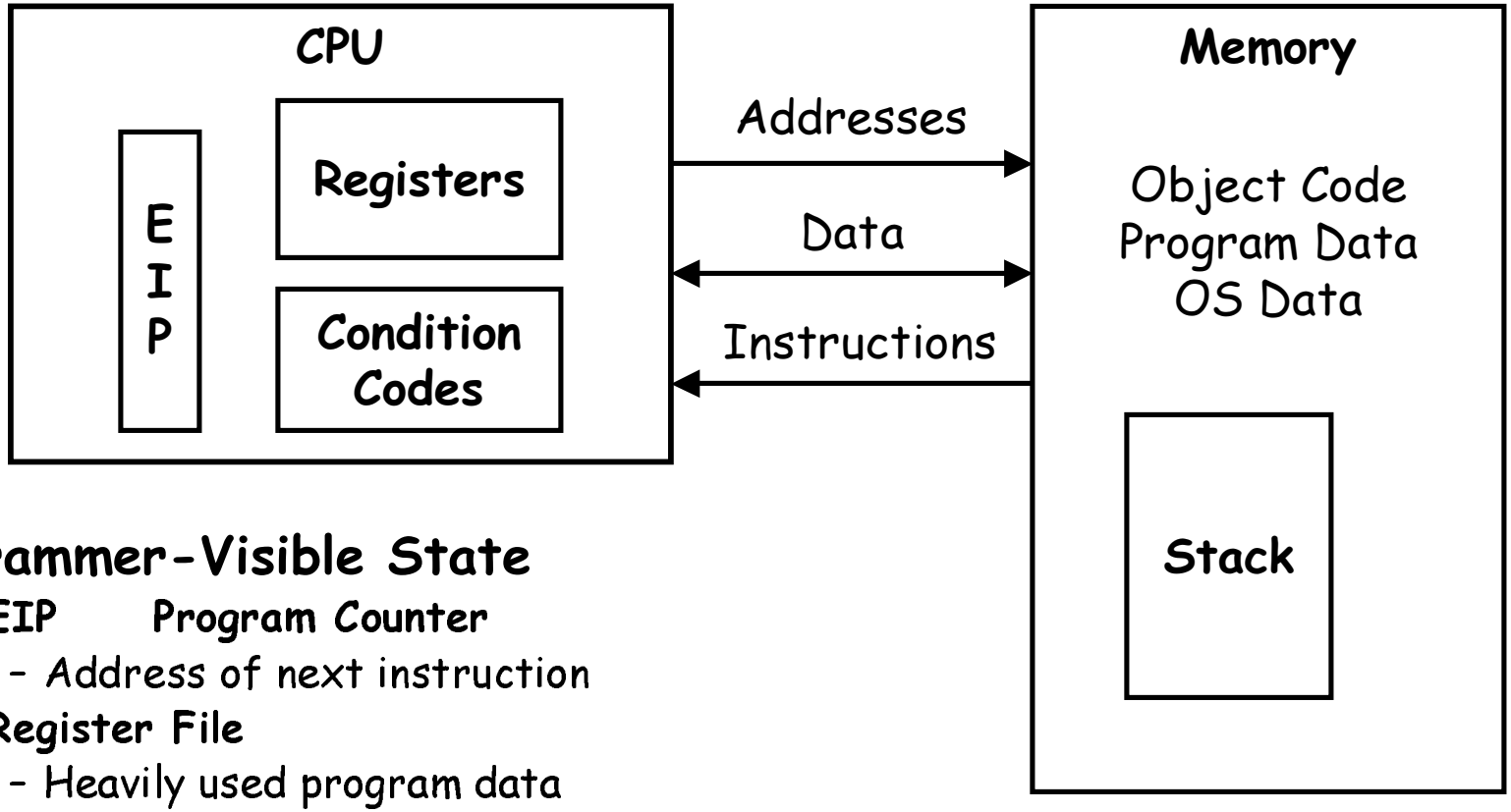
| Name | Date | Transistors |
|---|---|---|
| Pentium III | 1999 | 8.2M |

- Added "streaming SIMD" instructions for operating on 128-bit vectors of 1, 2, or 4 byte integer or floating point data

| Name | Date | Transistors |
|---|---|---|
| Merced | 2001? | 10M |

- Extends to IA64, a 64-bit architecture
- Radically new instruction set designed for high performance
- Will be able to run existing IA32 programs
  - On-board "x86 engine"

# Assembly Programmer's View



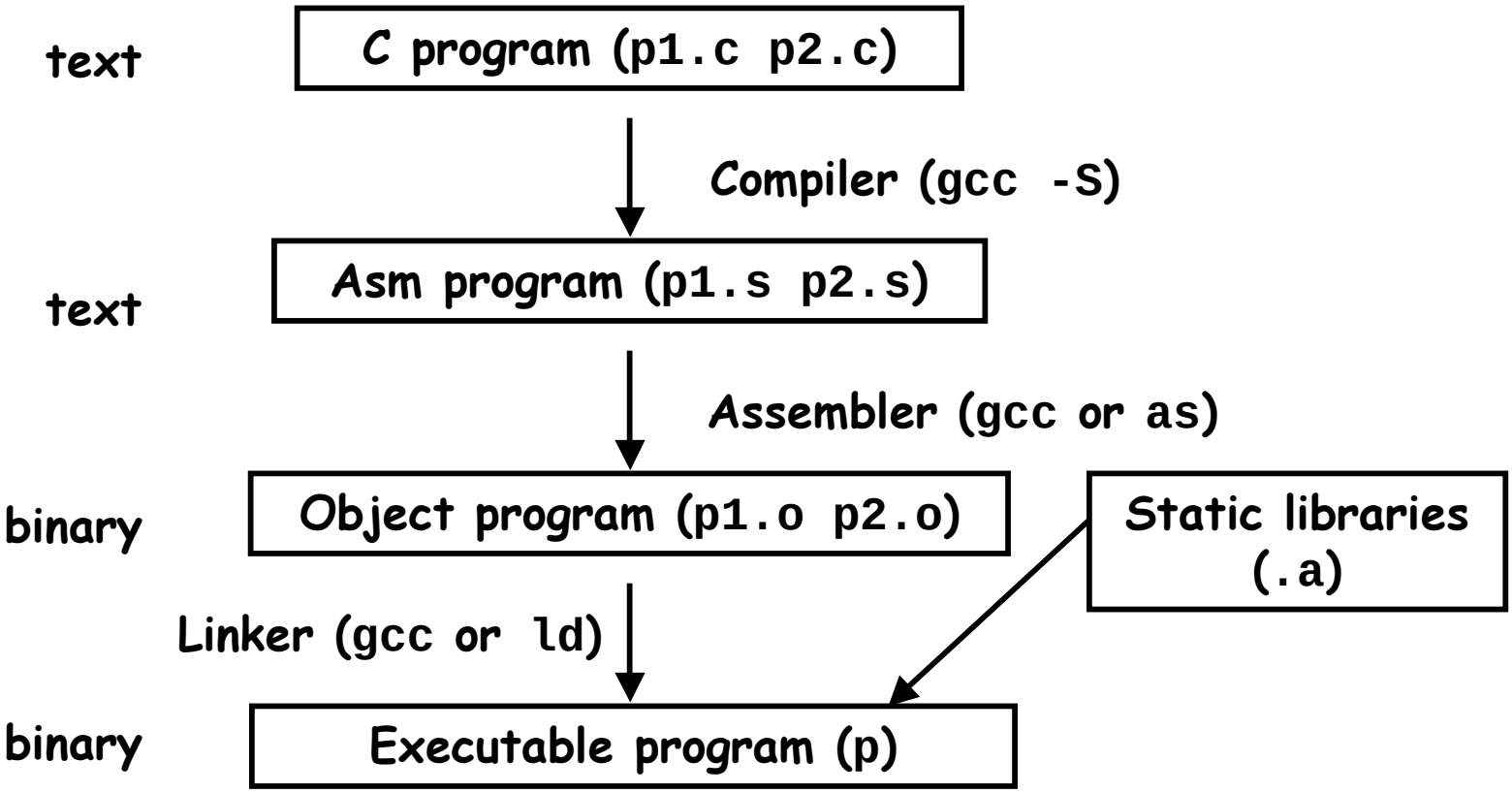

## Programmer-Visible State

- **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 or 8 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;
```

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

**Similar to expression**
**x += y**

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

## C Code

- **Add two signed integers**

## 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**

## 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
   d:      8d 76 00             lea    0x0(%esi),%esi
```

## 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
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

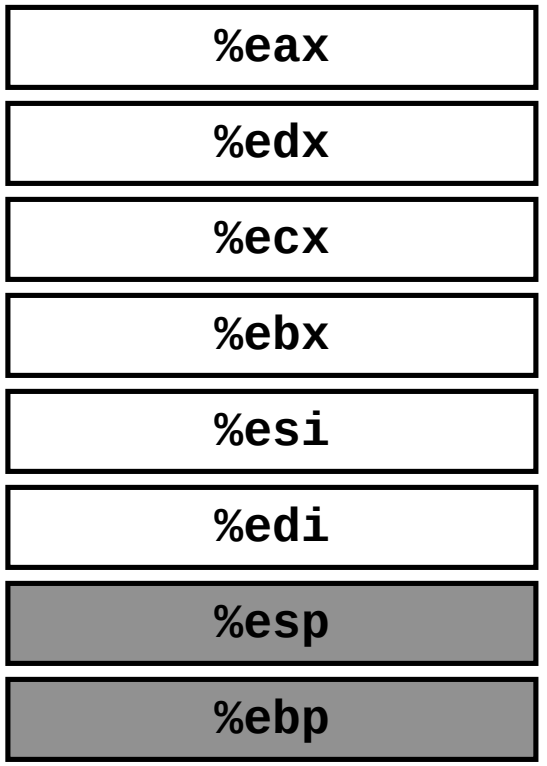
## Moving Data

**`movl` *Source,Dest*: Move 4-byte ("long") word**

- **Accounts for 31% of all instructions in sample**

## 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

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

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

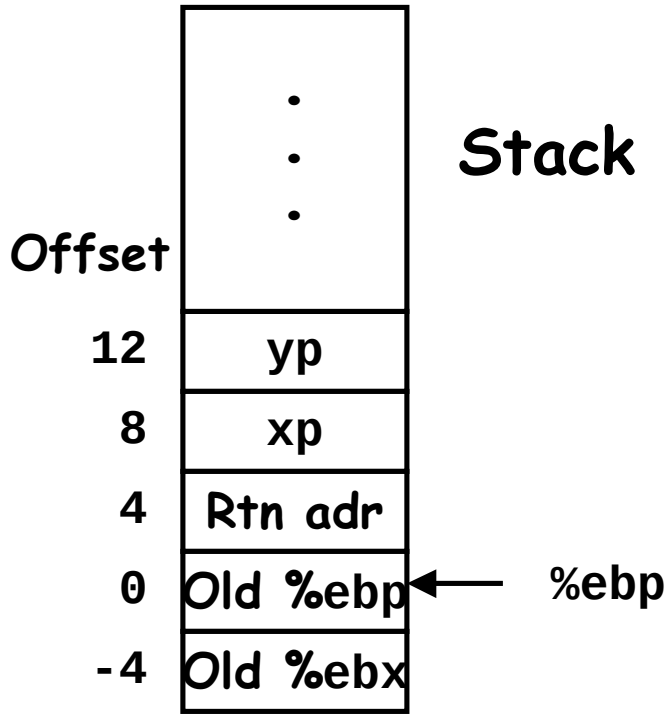
Set Up

Body

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
```

# 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 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* | |
| **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
    movl %esp,%ebp

    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

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

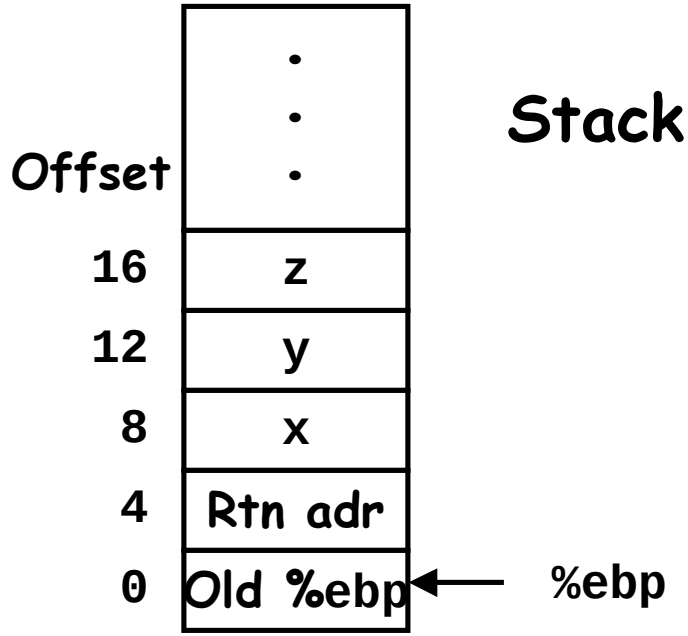
Set Up

Body

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 = 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
    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

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

```
    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
```

# 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**

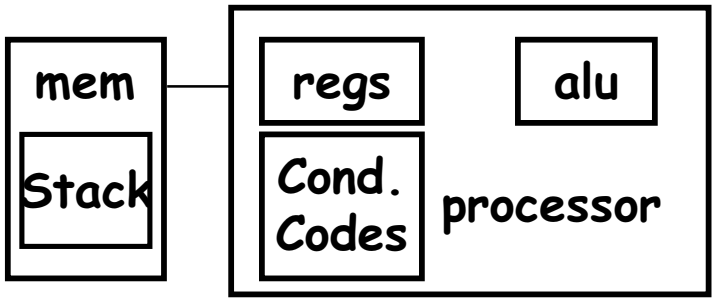
- IA32 instructions can range from 1 to 15 bytes

# Summary: Abstract Machines

## Machine Models

### C

### Assembly




## Data

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

1) byte
2) 4-byte long word
3) 8-byte quad word
4) contiguous byte allocation
5) address of initial byte

## Control

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

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

# Pentium Pro (P6)

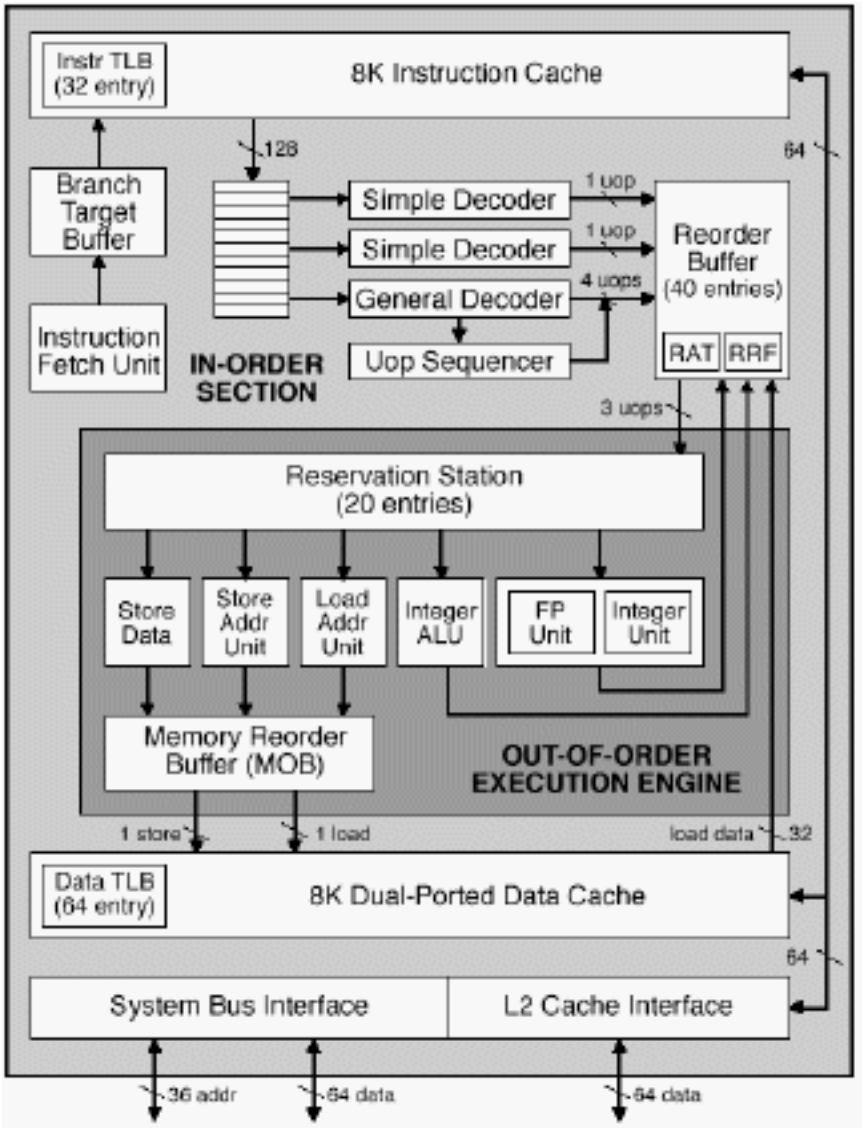
## History

- **Announced in Feb. '95**
- **Basis for Pentium II & Pentium III**

## Features

- **Dynamically translates instructions to more regular format**
  - Very wide, but simple instructions
- **Executes operations in parallel**
  - Up to 5 at once
- **Very deep pipeline**
  - 12–18 cycle latency

# PentiumPro Block Diagram




Microprocessor Report
2/16/95

# PentiumPro Operation

## Translates instructions dynamically into "Uops"

- **118 bits wide**
- **Holds operation, two sources, and destination**

## Executes Uops with "Out of Order" engine

- **Uop executed when**
  - Operands available
  - Functional unit available
- **Execution controlled by "Reservation Stations"**
  - Keeps track of data dependencies between uops
  - Allocates resources

## Consequences

- **Indirect relationship between IA32 code & what actually gets executed**
- **Difficult to predict / optimize performance at assembly level**

# 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 hexadecimal 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)`