Computer Systems

CSE 410 Spring 2012

5 - Instruction Set Architecture

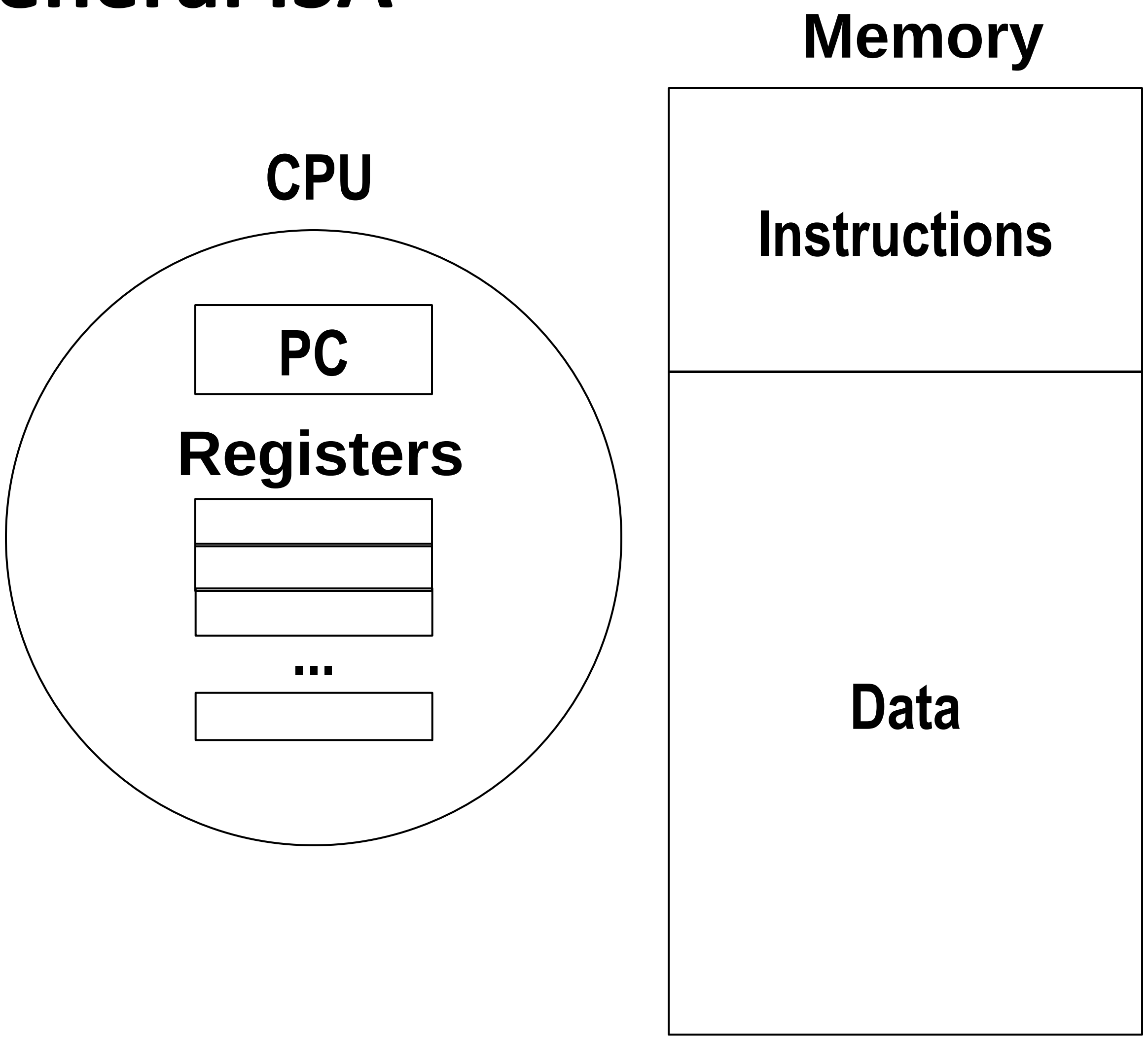
Machine Programming I: Basics

- **What is an ISA (Instruction Set Architecture)**
- **A brief istory of Intel processors and architectures**
  - Intel processors (Wikipedia)
  - Intel microarchitectures
- **C, assembly, machine code**
- **Assembly basics: registers, operands, move instructions**

- **Reading: Bryant/O'Hallaron sec. 3.1-3.2**

What should the HW/SW interface be?

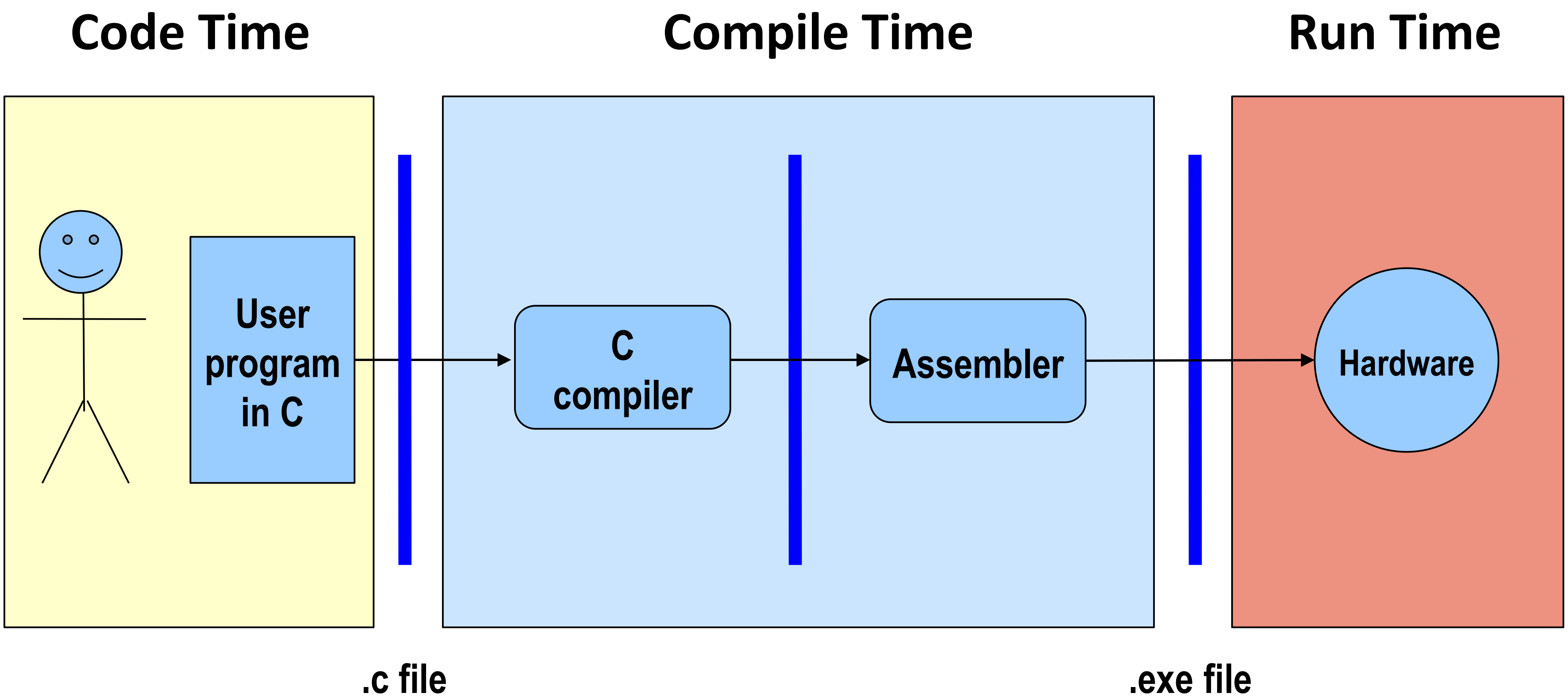
The General ISA



General ISA Design Decisions

- **Instructions**
  - What instructions are available? What do they do?
  - How are they encoded?
- **Registers**
  - How many registers are there?
  - How wide are they?
- **Memory**
  - How do you specify a memory location?

HW/SW Interface: Code / Compile / Run Times



What makes programs run fast?

(deja-vu? ☺)

Executing Programs Fast!

- **The time required to execute a program depends on:**
  - The program (as written in C, for instance)
  - The compiler: what set of assembler instructions it translates the C program into
  - The ISA: what set of instructions it made available to the compiler
  - The hardware implementation: how much time it takes to execute an instruction

- **There is a complex interaction among these**

Intel x86 Processors

- **Totally dominate the server/laptop market**

- **Evolutionary design**
  - Backwards compatible up until 8086, introduced in 1978
  - Added more features as time goes on

- **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!

Intel x86 Evolution: Milestones

	Name	*Date*	*Transistors*	*MHz*
■	**8086**	**1978**	**29K**	**5-10**

- First 16-bit processor. Basis for IBM PC & DOS
- 1MB address space

■	**386**	**1985**	**275K**	**16-33**

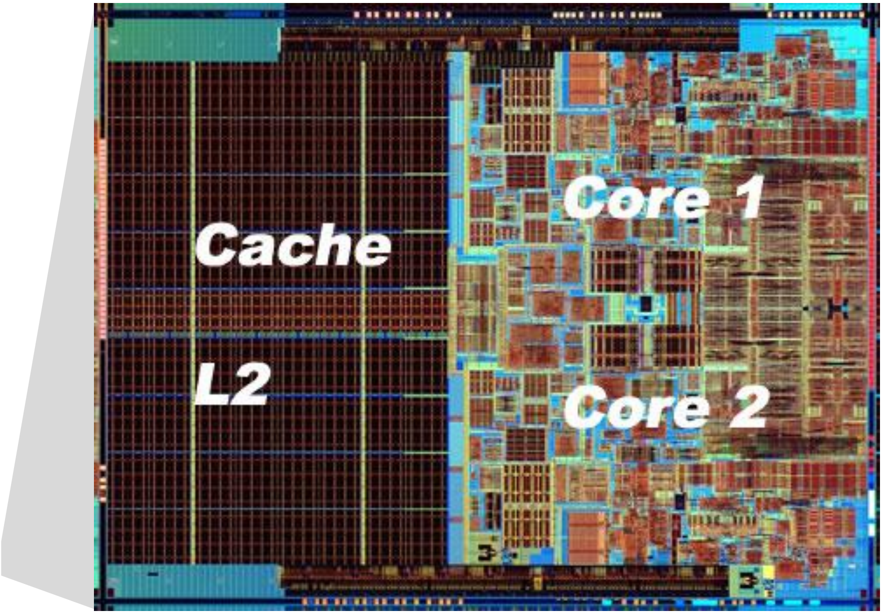
- First 32 bit processor , referred to as IA32
- Added "flat addressing"
- Capable of running Unix
- 32-bit Linux/gcc uses no instructions introduced in later models

■	**Pentium 4F**	**2005**	**230M**	**2800-3800**

- First 64-bit processor
- Meanwhile, Pentium 4s (Netburst arch.) phased out in favor of "Core" line

Intel x86 Processors

- **Machine Evolution**
  - 486 1989
  - Pentium 1993
  - Pentium/MMX 1997
  - PentiumPro 1995
  - Pentium III 1999
  - Pentium 4 2001
  - Core 2 Duo 2006



- **Added Features**
  - Instructions to support multimedia operations
    - Parallel operations on 1, 2, and 4-byte data, both integer & FP
  - Instructions to enable more efficient conditional operations
- **Linux/GCC Evolution**
  - Very limited impact on performance --- mostly came from HW.

x86 Clones: Advanced Micro Devices (AMD)

- **Historically**
  - AMD has followed just behind Intel
  - A little bit slower, a lot cheaper
- **Then**
  - Recruited top circuit designers from Digital Equipment and other downward trending companies
  - Built Opteron: tough competitor to Pentium 4
  - Developed x86-64, their own extension to 64 bits

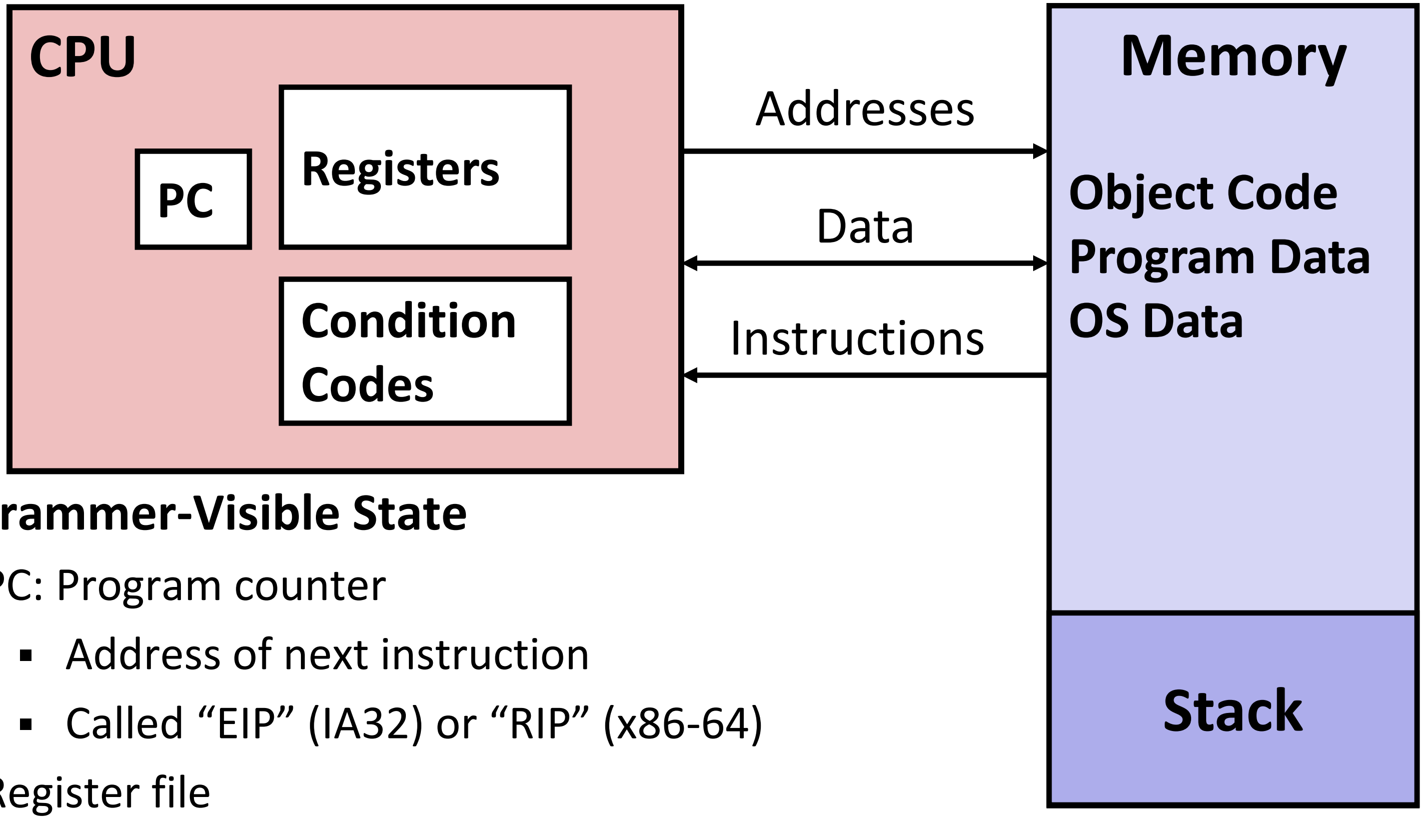
Intel's 64-Bit

- **Intel Attempted Radical Shift from IA32 to IA64**
  - Totally different architecture (Itanium) and ISA
  - Executes IA32 code only as legacy
  - Performance disappointing
- **AMD Stepped in with Evolutionary Solution**
  - x86-64 (now called "AMD64")
- **Intel Felt Obligated to Focus on IA64**
  - Hard to admit mistake or that AMD is better
- **2004: Intel Announces EM64T extension to IA32**
  - Extended Memory 64-bit Technology
  - Almost identical to x86-64!
- **Meanwhile: EM64T well introduced, however, still often not used by OS, programs**

Our Coverage in 410

- **IA32**
  - The traditional x86
- **x86-64/EM64T**
  - The emerging standard – all Labs in 64 bits!

Assembly Programmer's View



- **Programmer-Visible State**
  - PC: Program counter
    - Address of next instruction
    - Called "EIP" (IA32) or "RIP" (x86-64)
  - 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 (we'll come back to that)

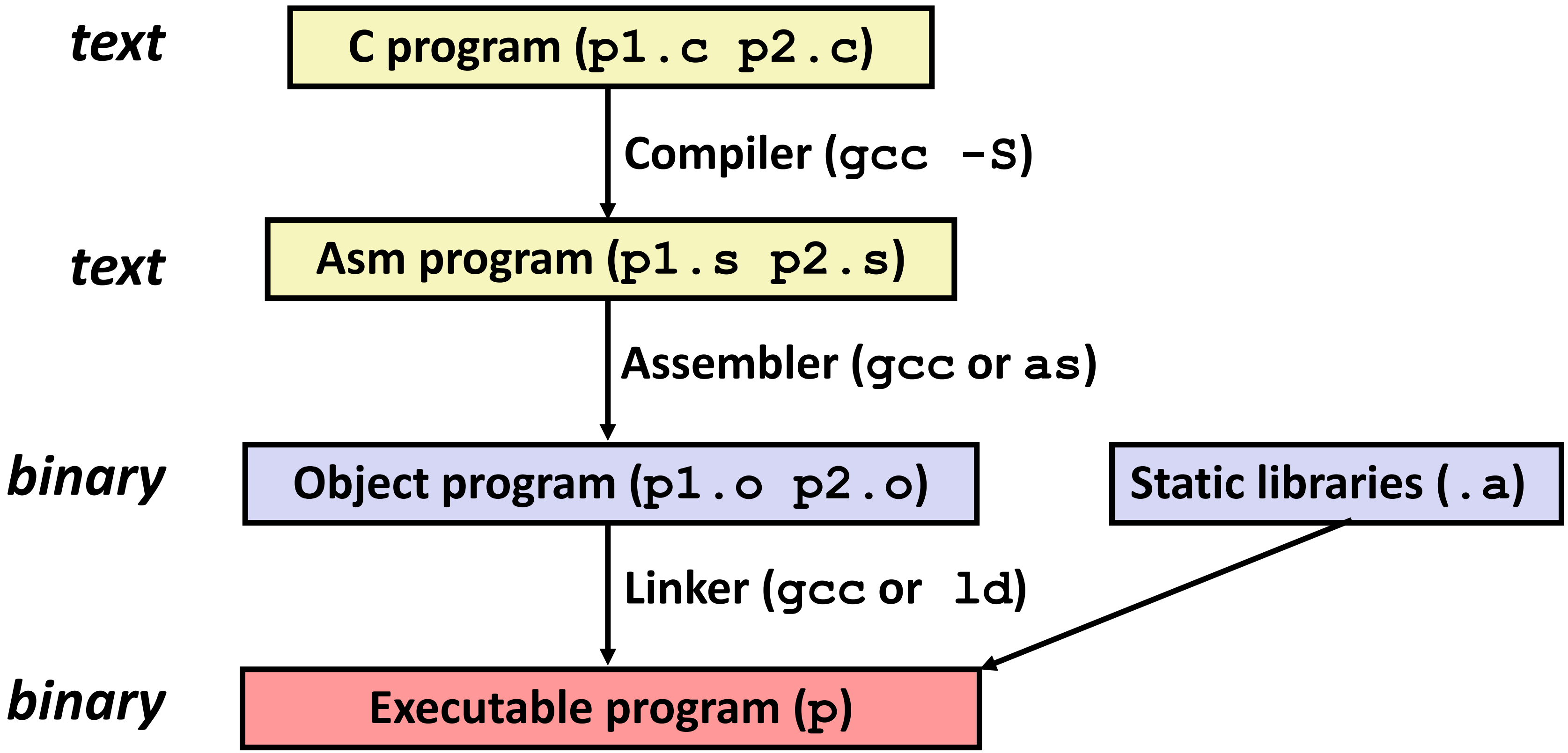
Definitions

- **Architecture**: (also instruction set architecture or ISA) The parts of a processor design that one needs to understand to write assembly code ("what is directly visible to SW")
- **Microarchitecture**: Implementation of the architecture

- How about CPU frequency?
- The number of registers?
- Is the cache size "architecture"?

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 IA32 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`

Three Basic Kinds of Instructions

- **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 (control flow)**
  - Unconditional jumps to/from procedures
  - Conditional branches

Assembly Characteristics: Data Types

- **"Integer" data of 1, 2, or 4, 8 (x86-64) bytes**
  - Data values
  - Addresses

- **Floating point data of 4, 8, or 10 bytes**

- **What about aggregate types such as arrays or structures?**

Assembly Characteristics: Data Types

- **"Integer" data of 1, 2, or 4, 8 (x86-64) 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

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

Example

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

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

Similar to expression:

```
x += y
```

More precisely:

```
int eax;
int *ebp;
eax += ebp[2]
```

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

- **C Code**
  - Add two signed integers
- **Assembly**
  - Add 2 4-byte integers
    - "Long" words in GCC speak
    - 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`

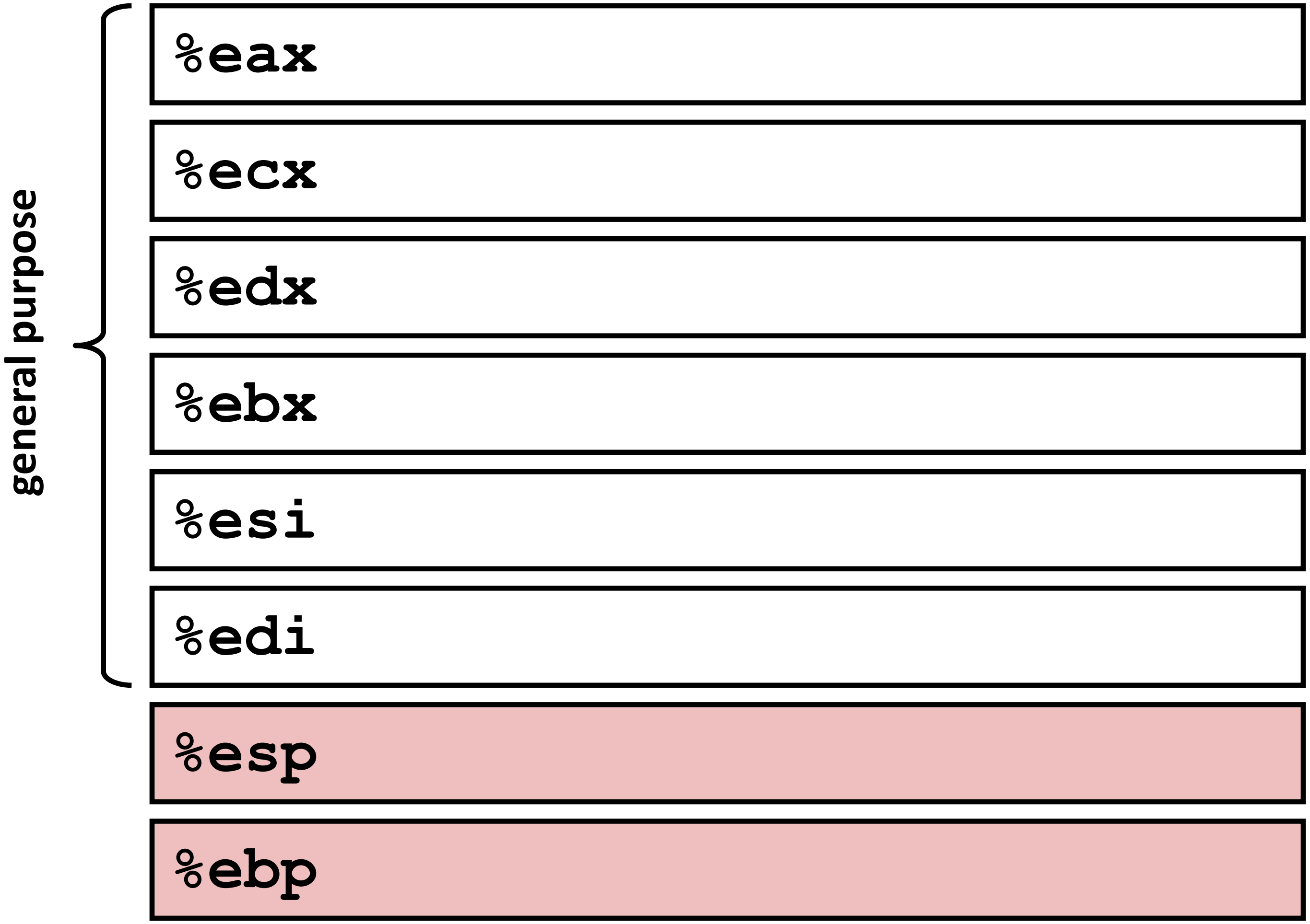
  - Examine the 13 bytes starting at `sum`

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**

Integer Registers (IA32)



Integer Registers (IA32)

general purpose: %eax, %ecx, %edx, %ebx, %esi, %edi

32-bit	16-bit	High byte	Low byte	Origin (mostly obsolete)
%eax	%ax	%ah	%al	*accumulate*
%ecx	%cx	%ch	%cl	*counter*
%edx	%dx	%dh	%dl	*data*
%ebx	%bx	%bh	%bl	*base*
%esi	%si			*source index*
%edi	%di			*destination index*
%esp	%sp			***stack pointer***
%ebp	%bp			***base pointer***

16-bit virtual registers (backwards compatibility)

x86-64 Integer Registers

%rax	%eax	%r8	%r8d
%rbx	%ebx	%r9	%r9d
%rcx	%ecx	%r10	%r10d
%rdx	%edx	%r11	%r11d
%rsi	%esi	%r12	%r12d
%rdi	%edi	%r13	%r13d
%rsp	%esp	%r14	%r14d
%rbp	%ebp	%r15	%r15d

- Twice the number of registers
- Accessible as 8, 16, 32, 64 bits

x86-64 Integer Registers: Usage Conventions

`%rax`	Return value	`%r8`	Argument #5
`%rbx`	Callee saved	`%r9`	Argument #6
`%rcx`	Argument #4	`%r10`	Caller saved
`%rdx`	Argument #3	`%r11`	Caller Saved
`%rsi`	Argument #2	`%r12`	Callee saved
`%rdi`	Argument #1	`%r13`	Callee saved
`%rsp`	Stack pointer	`%r14`	Callee saved
`%rbp`	Callee saved	`%r15`	Callee saved