# Roadmap

- Memory & data
- Integers & floats
- **Machine code & C**
- x86 assembly
- Procedures & stacks
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

**C:**

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

**Java:**

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

**Assembly language:**

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

**Machine code:**

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

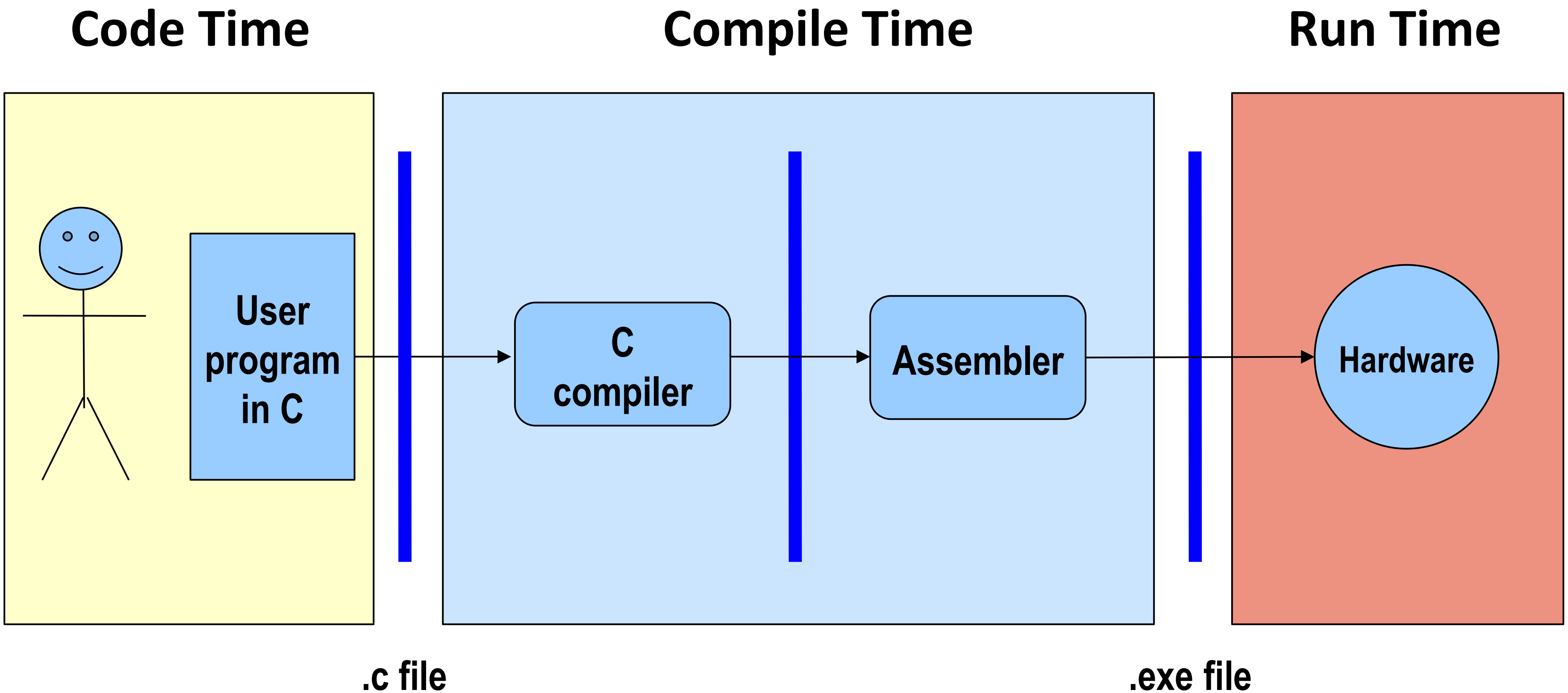
**OS:** Windows 8, Mac, Linux

**Computer system:**


# Basics of Machine Programming and Architecture

- What is an ISA (Instruction Set Architecture)?
- A brief history of Intel processors and architectures
- C, assembly, machine code

# Translation




**What makes programs run fast?**

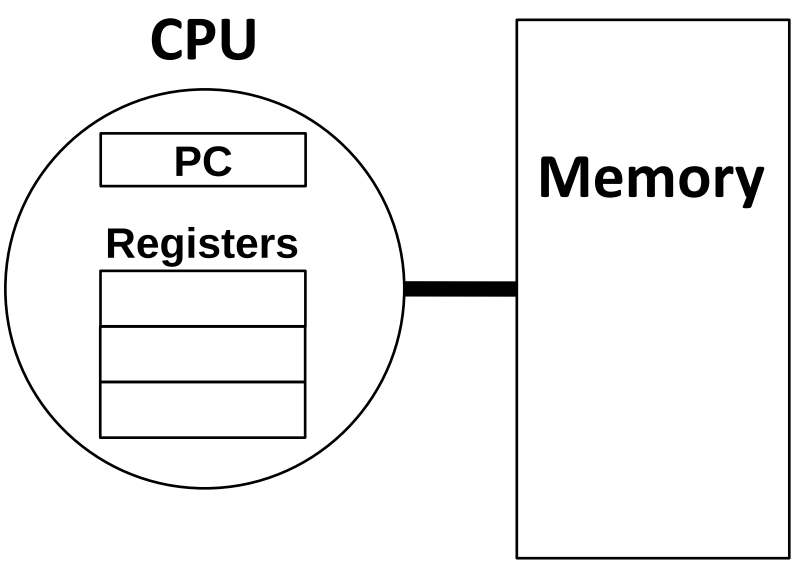
# Translation Impacts Performance

- **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 instruction set architecture* (ISA): what set of instructions it makes available to the compiler
  - *The hardware implementation*: how much time it takes to execute an instruction

## What should the HW/SW interface contain?

# Instruction Set Architectures

- **The ISA defines:**
  - The system's state (e.g. registers, memory, program counter)
  - The instructions the CPU can execute
  - The effect that each of these instructions will have on the system state



# 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?

# X86 ISA

- **Processors that implement the x86 ISA completely dominate the server, desktop and laptop markets**

- **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
  - (as opposed to Reduced Instruction Set Computers (RISC), which use simpler instructions)

# Intel x86 Evolution: Milestones

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

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

| | | | |
|---|---|---|---|
| **386** | **1985** | **275K** | **16-33** |

- First 32 bit Intel processor , referred to as IA32
- Added "flat addressing", capable of running Unix

| | | | |
|---|---|---|---|
| **Pentium 4E** | **2004** | **125M** | **2800-3800** |

- First 64-bit Intel x86 processor, referred to as x86-64

| | | | |
|---|---|---|---|
| **Core 2** | **2006** | **291M** | **1060-3500** |

- First multi-core Intel processor

| | | | |
|---|---|---|---|
| **Core i7** | **2008** | **731M** | **1700-3900** |

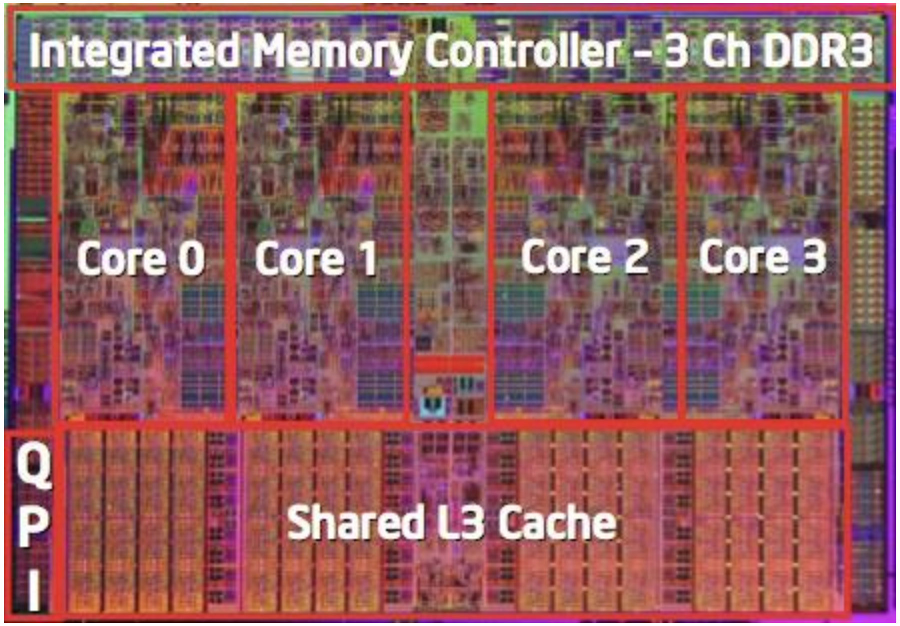
- Four cores

# Intel x86 Processors

## Machine Evolution

| | | |
|---|---|---|
| 486 | 1989 | 1.9M |
| Pentium | 1993 | 3.1M |
| Pentium/MMX | 1997 | 4.5M |
| PentiumPro | 1995 | 6.5M |
| Pentium III | 1999 | 8.2M |
| Pentium 4 | 2001 | 42M |
| Core 2 Duo | 2006 | 291M |
| Core i7 | 2008 | 731M |

**Intel Core i7**




## Added Features

- Instructions to support multimedia operations
  - Parallel operations on 1, 2, and 4-byte data
- Instructions to enable more efficient conditional operations
- More cores!

# More information

- **References for Intel processor specifications:**
  - Intel's "automated relational knowledgebase":
    - http://ark.intel.com/
  - Wikipedia:
    - http://en.wikipedia.org/wiki/List_of_Intel_microprocessors

# x86 Clones: Advanced Micro Devices (AMD)

- **Same ISA, different implementation**
- **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 of x86 to 64 bits

# Intel's Transition to 64-Bit

- **Intel attempted radical shift from IA32 to IA64 (2001)**
  - Totally different architecture (Itanium) and ISA than x86
  - Executes IA32 code only as legacy
  - Performance disappointing
- **AMD stepped in with *evolutionary* solution (2003)**
  - x86-64 (also called "AMD64")
- **Intel felt obligated to focus on IA64**
  - Hard to admit mistake or that AMD is better
- **Intel announces "EM64T" extension to IA32 (2004)**
  - Extended Memory 64-bit Technology
  - Almost identical to AMD64!
- **Today: all but low-end x86 processors support x86-64**
  - But, lots of code out there is still just IA32

# Our Coverage in 351

- **x86-64**
  - The new 64-bit x86 ISA – all lab assignments use x86-64!
  - Book covers x86-64

- **Previous versions of CSE 351 and 2nd edition of textbook covered IA32 (traditional 32-bit x86 ISA) and x86-64**

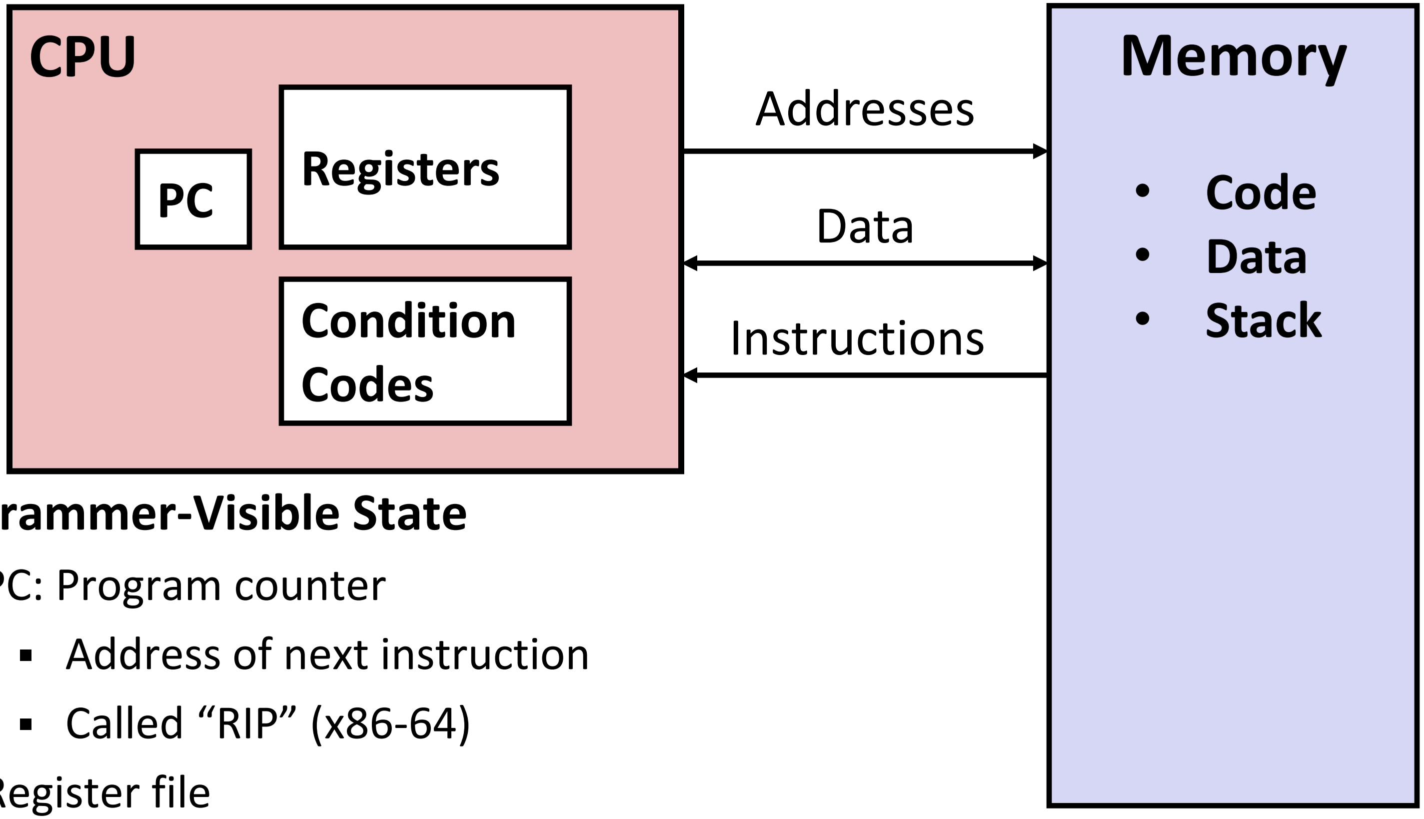
- **We will only cover x86-64 this quarter**

# 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 software"
- **Microarchitecture: Implementation of the architecture**
  - CSE 352

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

# Assembly Programmer's View

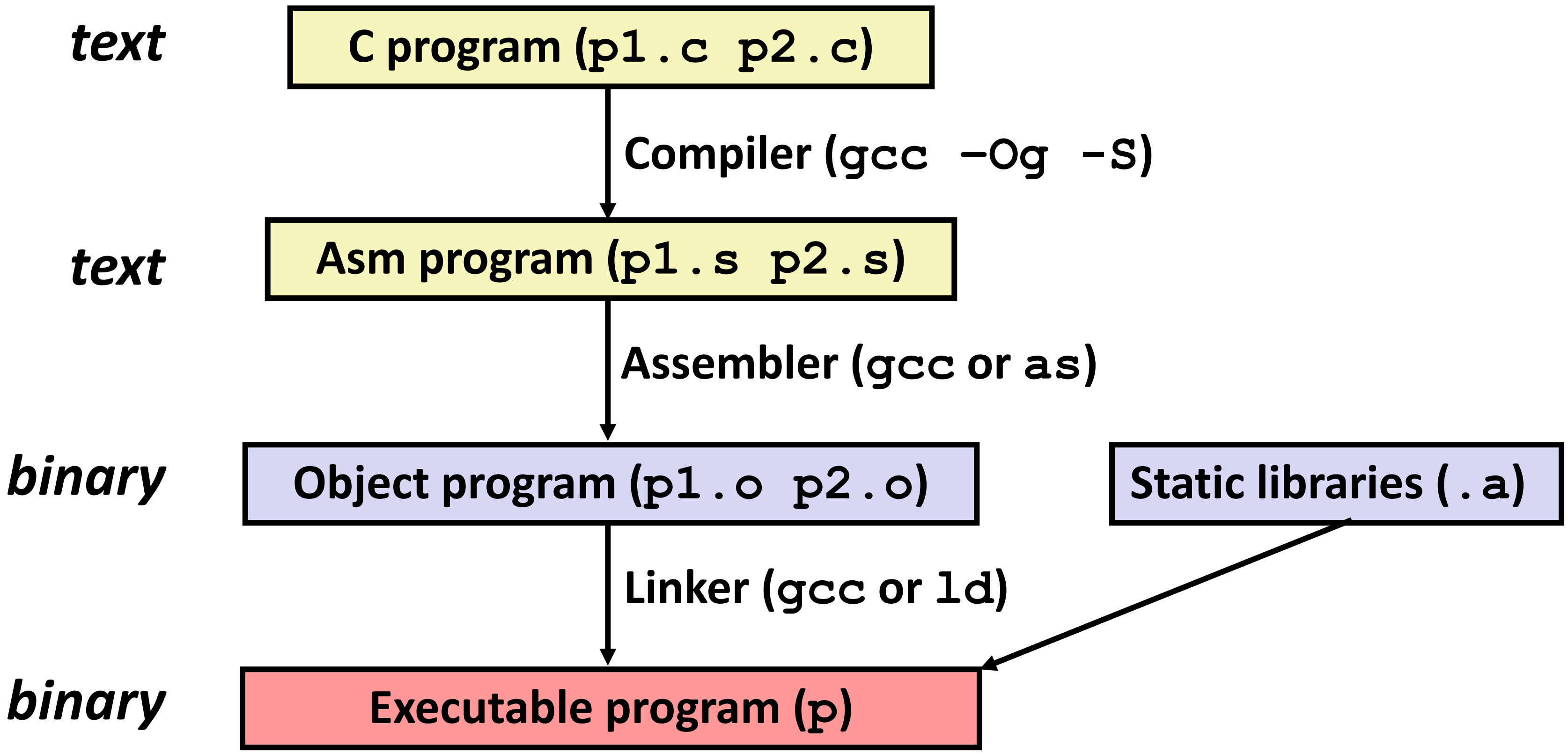



- **Programmer-Visible State**
  - PC: Program counter
    - Address of next instruction
    - Called "RIP" (x86-64)
  - Register file
    - Heavily used program data
  - Condition codes
    - Store status information about most recent arithmetic operation
    - Used for conditional branching

- **Memory**
  - Byte addressable array
  - Code and user data
  - Includes stack used to support procedures (we'll come back to that)

# Turning C into Object Code

- **Code in files `p1.c p2.c`**
- **Compile with command: `gcc -Og p1.c p2.c -o p`**
  - Use basic optimizations (`-Og`) ) [New to recent versions of GCC]
  - Put resulting machine code in file `p`



# Compiling Into Assembly

## C Code (sum.c)

```
long plus(long x, long y);

void sumstore(long x, long y,
              long *dest)
{
    long t = plus(x, y);
    *dest = t;
}
```

## Generated x86-64 Assembly

```
sumstore:
   pushq   %rbx
   movq    %rdx, %rbx
   call    plus
   movq    %rax, (%rbx)
   popq    %rbx
   ret
```

**Obtain with command:**

```
gcc -Og -S sum.c
```

**Produces file `sum.s`**

***Warning*: You may get different results with other versions of gcc and different compiler settings.**

# Machine Instruction Example

```
*dest = t;
```

```
movq %rax, (%rbx)
```

```
0x40059e:   48 89 03
```

- **C Code**
  - Store value `t` where designated by `dest`
- **Assembly**
  - Move 8-byte value to memory
    - Quad words in x86-64 parlance
  - Operands:

    `t:` Register `%rax`

    `dest:` Register `%rbx`

    `*dest:` Memory `M[%rbx]`
- **Object Code**
  - 3-byte instruction
  - Stored at address `0x40059e`

# Object Code

## Code for `sumstore`

```
0x0400595:
    0x53
    0x48
    0x89
    0xd3
    0xe8
    0xf2
    0xff
    0xff
    0xff
    0x48
    0x89
    0x03
    0x5b
    0xc3
```

- Total of 14 bytes
- Each instruction 1, 3, or 5 bytes
- Starts at address `0x0400595`

- **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

# Disassembling Object Code

## Disassembled

```
0000000000400595 <sumstore>:
  400595:  53                 push   %rbx
  400596:  48 89 d3           mov    %rdx,%rbx
  400599:  e8 f2 ff ff ff     callq  400590 <plus>
  40059e:  48 89 03           mov    %rax,(%rbx)
  4005a1:  5b                 pop    %rbx
  4005a2:  c3                 retq
```

- **Disassembler**

  **`objdump -d sum`**

  - Useful tool for examining object code (Try `man 1 objdump`)
  - 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**

```
0x0400595:
    0x53
    0x48
    0x89
    0xd3
    0xe8
    0xf2
    0xff
    0xff
    0xff
    0x48
    0x89
    0x03
    0x5b
    0xc3
```

**Disassembled**

```
Dump of assembler code for function sumstore:
 0x0000000000400595 <+0>: push   %rbx
 0x0000000000400596 <+1>: mov    %rdx,%rbx
 0x0000000000400599 <+4>: callq  0x400590 <plus>
 0x000000000040059e <+9>: mov    %rax,(%rbx)
 0x00000000004005a1 <+12>:pop    %rbx
 0x00000000004005a2 <+13>:retq
```

- **Within gdb Debugger**

  `gdb sum`

  `disassemble sumstore`

  - Disassemble procedure

  `x/14bx sumstore`

  - Examine the 14 bytes starting at `sumstore`

# 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:
30001001:
30001003:
30001005:
3000100a:
```

**Reverse engineering forbidden by Microsoft End User License Agreement**

- **Anything that can be interpreted as executable code**
- **Disassembler examines bytes and reconstructs assembly source**