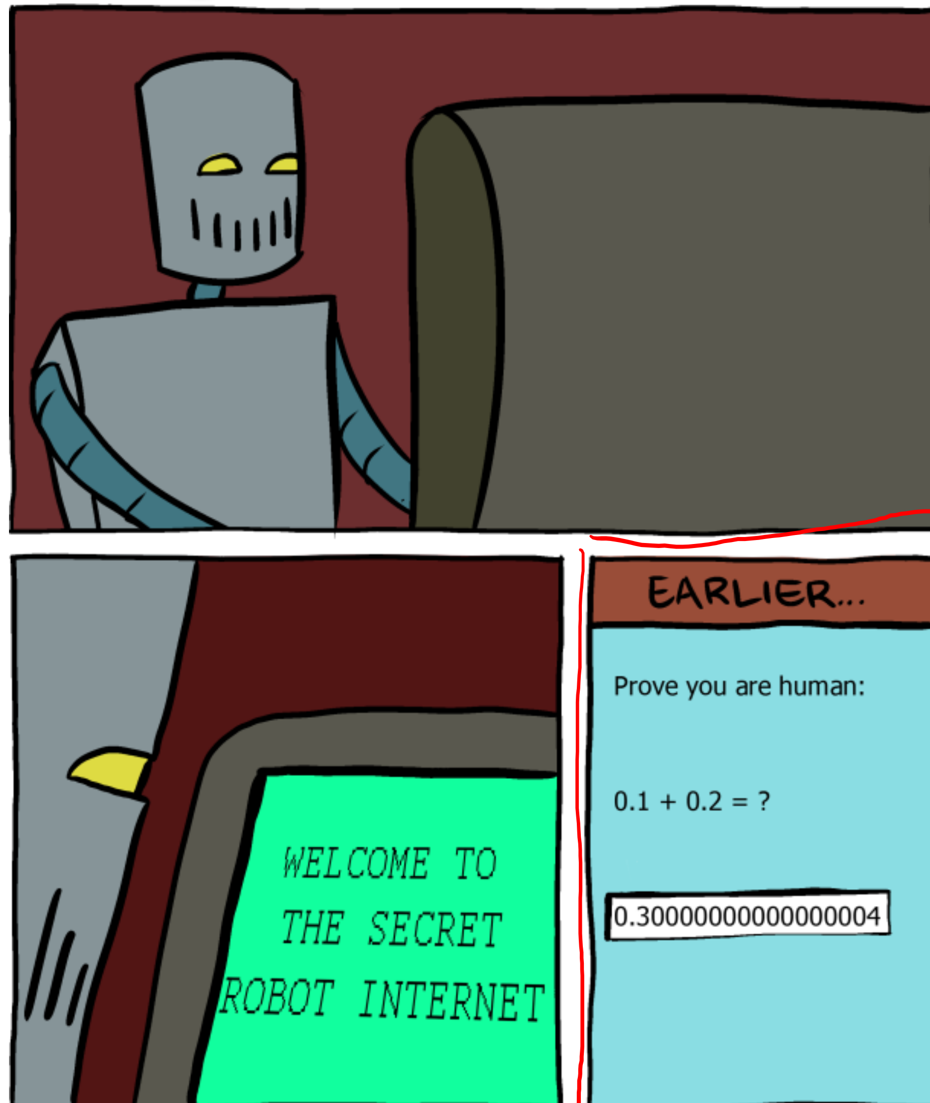
Machine Programming

CSE 351 Winter 2017



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Administrivia

- Lab 1 due today!
- Lab 2 out Monday ☺

Mathematical Properties of FP Operations

- Exponent overflow yields +∞ or -∞
- Floats with value +∞, -∞, and NaN can be used in operations
  - Result usually still +∞, -∞, or NaN; sometimes intuitive, sometimes not
- Floating point ops do not work like real math, due to rounding!
  - Not associative: (3.14 + 1e100) – 1e100 != 3.14 + (1e100 – 1e100)
  - Not distributive: 100 * (0.1 + 0.2) != 100 * 0.1 + 100 * 0.2

    30.000000000000003553 30
  - Not cumulative
    - Repeatedly adding a very small number to a large one may do nothing

Floating Point in C

!!!

- C offers two (well, 3) levels of precision

  float 1.0f single precision (32-bit)

  double 1.0 double precision (64-bit)

  long double 1.0L *(double double, quadruple, or "extended")* precision (64-128 bits)

- #include <math.h> to get INFINITY and NAN constants
- Equality (==) comparisons between floating point numbers are tricky, and often return unexpected results
  - Just avoid them!

Floating Point in C

!!!

- Conversions between data types:
  - Casting between int, float, and double **changes** the bit representation.
  - int → float
    - May be rounded (not enough bits in mantissa: 23)
    - Overflow impossible
  - int → double or float → double
    - Exact conversion (32-bit ints; 52-bit frac + 1-bit sign)
  - long → double
    - Rounded or exact, depending on word size (64-bit → 52 bit mantissa ⇒ round)
  - double or float → int
    - Truncates fractional part (rounded toward zero)
      - E.g. 1.999 → 1, -1.99 → -1
    - "Not defined" when out of range or NaN: generally sets to Tmin (even if the value is a very big positive)

Floating Point and the Programmer

```
#include <stdio.h>

int main(int argc, char* argv[]) {

  float f1 = 1.0;
  float f2 = 0.0;
  int i;
  for (i = 0; i < 10; i++) {
    f2 += 1.0/10.0;
  }

  printf("0x%08x  0x%08x\n", *(int*)&f1, *(int*)&f2);
  printf("f1 = %10.8f\n", f1);
  printf("f2 = %10.8f\n\n", f2);

  f1 = 1E30;
  f2 = 1E-30;
  float f3 = f1 + f2;
  printf("f1 == f3? %s\n", f1 == f3 ? "yes" : "no" );

  return 0;
}
```

```
$ ./a.out
0x3f800000  0x3f800001
f1 = 1.000000000
f2 = 1.000000119

f1 == f3? yes
```

Number Representation Really Matters

- 1991: Patriot missile targeting error
  - clock skew due to conversion from integer to floating point
- 1996: Ariane 5 rocket exploded ($1 billion)
  - overflow converting 64-bit floating point to 16-bit integer
- 2000: Y2K problem
  - limited (decimal) representation: overflow, wrap-around
- 2038: Unix epoch rollover
  - Unix epoch = seconds since 12am, January 1, 1970
  - signed 32-bit integer representation rolls over to TMin in 2038
- other related bugs
  - 1982: Vancouver Stock Exchange 10% error in less than 2 years
  - 1994: Intel Pentium FDIV (floating point division) HW bug ($475 million)
  - 1997: USS Yorktown “smart” warship stranded: divide by zero
  - 1998: Mars Climate Orbiter crashed: unit mismatch ($193 million)

Summary

- As with integers, floats suffer from the fixed number of bits available to represent them
  - Can get overflow/underflow, just like ints
  - Some "simple fractions" have no exact representation (e.g., 0.2)
  - Can also lose precision, unlike ints
    - "Every operation gets a slightly wrong result"
- Mathematically equivalent ways of writing an expression may compute different results
  - Violates associativity/distributivity
- Never test floating point values for equality!
- Careful when converting between ints and floats!

Roadmap

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:

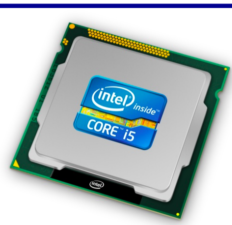
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

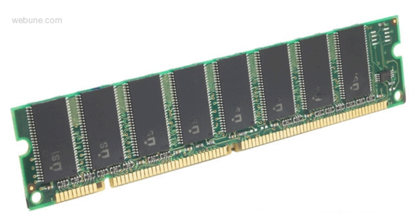
OS:

Windows 8

Mac

Computer system:



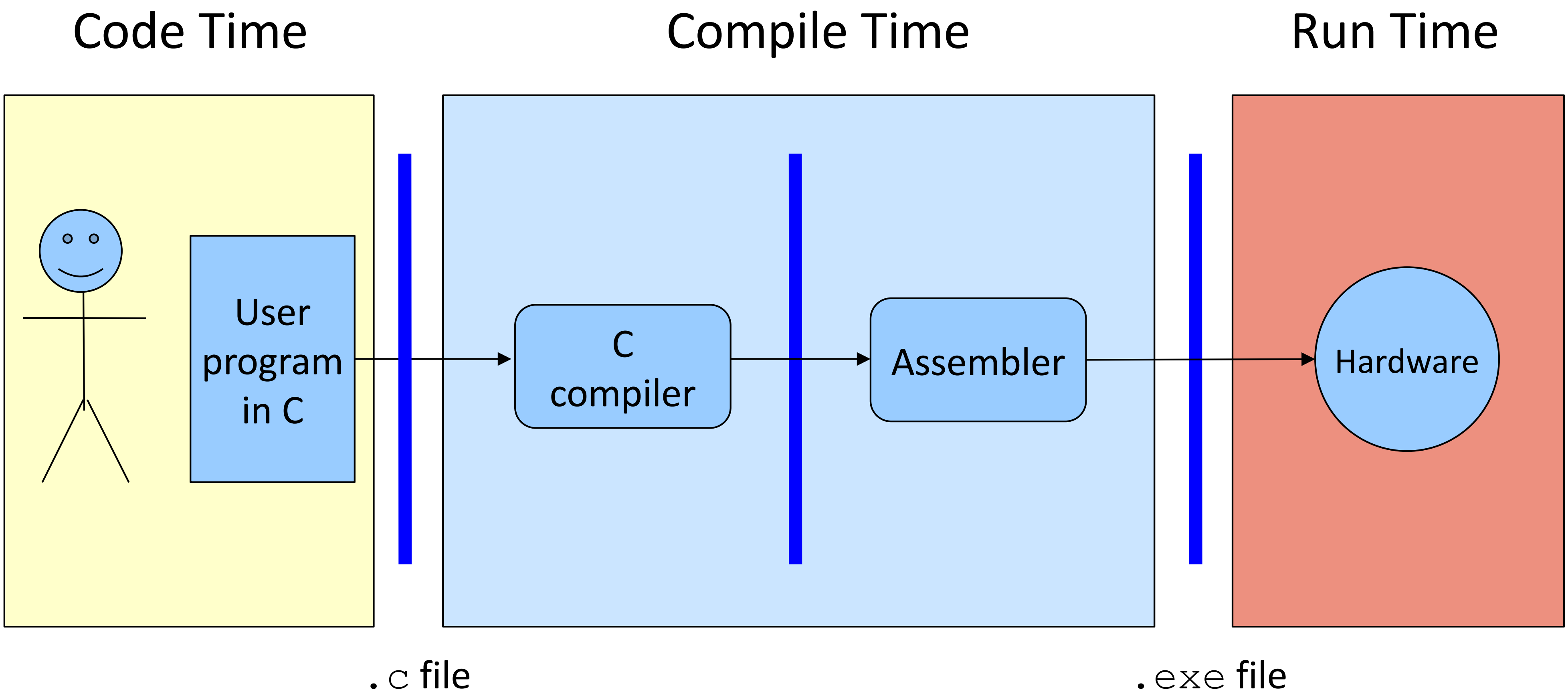


- Memory & data
- Integers & floats
- **Machine code & C**
- x86 assembly
- Procedures & stacks
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

Basics of Machine Programming & 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(er)?

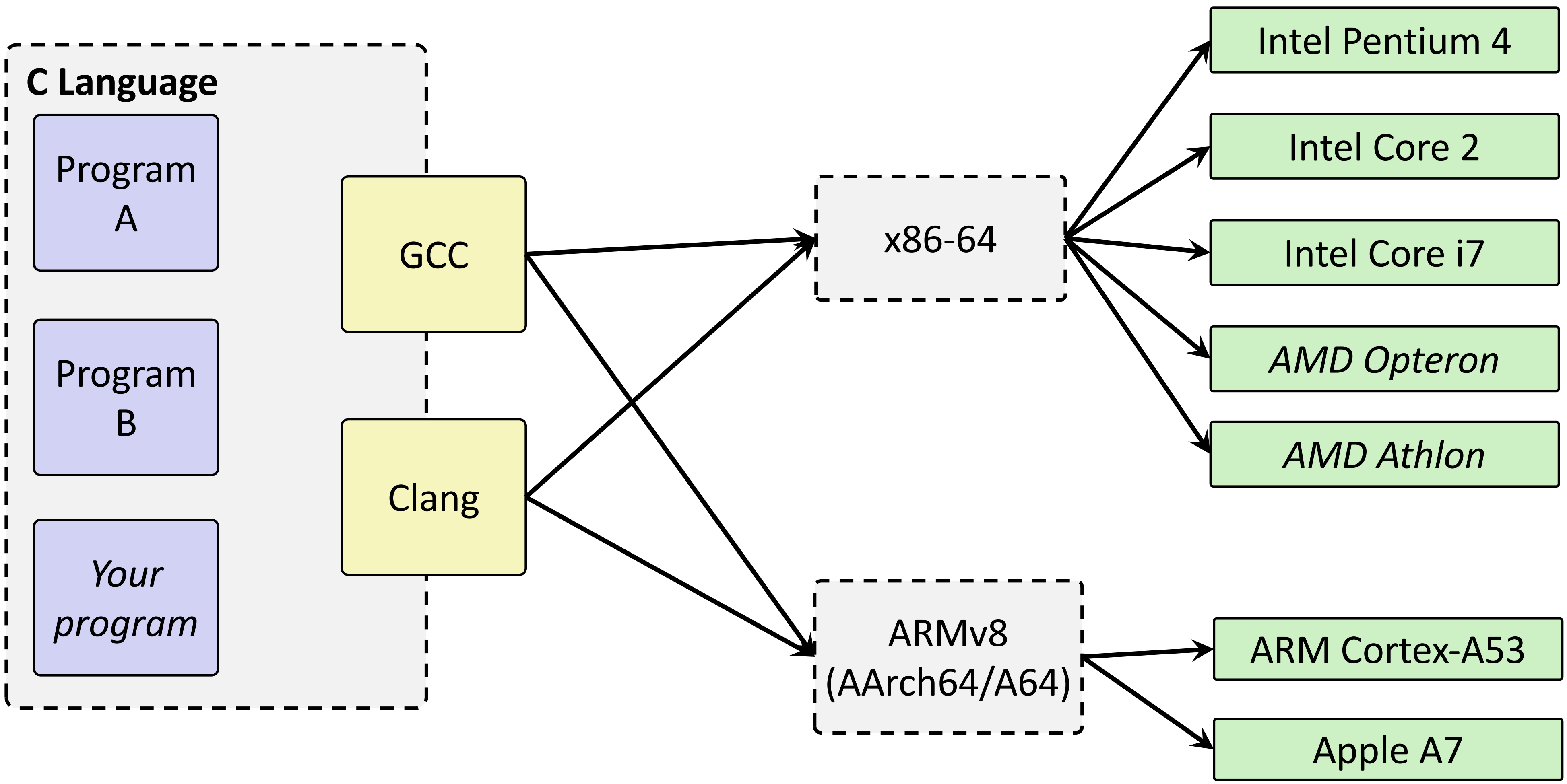
Translation

Source code
Different applications or algorithms

Compiler
Perform optimizations, generate instructions

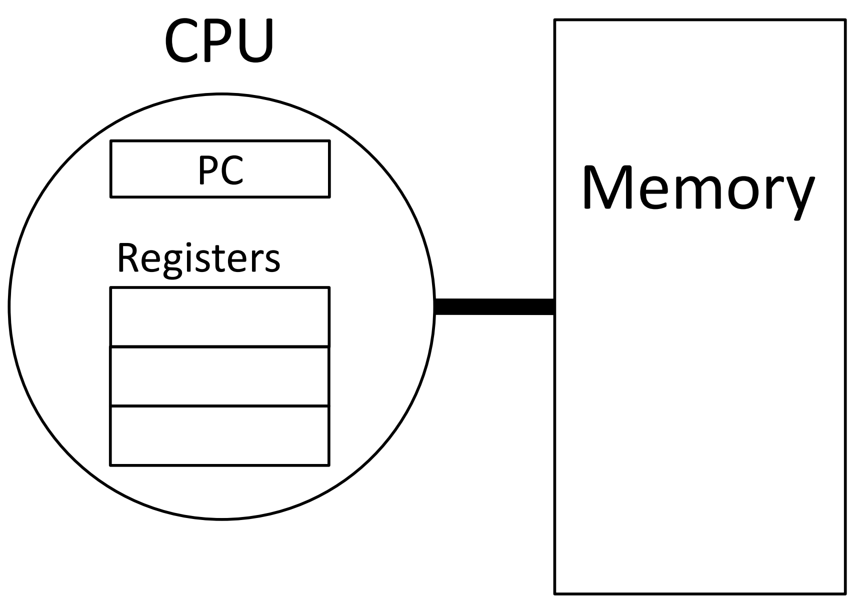
Architecture
Instruction set

Hardware
Different implementations



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



Instruction Set Philosophies

- *Complex Instruction Set Computing* (CISC): Add more and more elaborate and specialized instructions as needed
  - Lots of tools for programmers to use, but hardware must be able to handle all instructions
  - x86-64 is CISC, but only a small subset of instructions encountered with Linux programs
- *Reduced Instruction Set Computing* (RISC): Keep instruction set small and regular
  - Easier to build fast hardware
  - Let software do the complicated operations by composing simpler ones

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?

Mainstream ISAs

x86

Designer	Intel, AMD
Bits	16-bit, 32-bit and 64-bit
Introduced	1978 (16-bit), 1985 (32-bit), 2003 (64-bit)
Design	CISC
Type	Register-memory
Encoding	Variable (1 to 15 bytes)
Endianness	Little

Macbooks & PCs
(Core i3, i5, i7, M)
[x86-64 Instruction Set]

ARM architectures

Designer	ARM Holdings
Bits	32-bit, 64-bit
Introduced	1985; 31 years ago
Design	RISC
Type	Register-Register
Encoding	AArch64/A64 and AArch32/A32 use 32-bit instructions, T32 (Thumb-2) uses mixed 16- and 32-bit instructions. ARMv7 user-space compatibility[1]
Endianness	Bi (little as default)

Smartphone-like devices
(iPhone, iPad, Raspberry Pi)
[ARM Instruction Set]

MIPS

Designer	MIPS Technologies, Inc.
Bits	64-bit (32→64)
Introduced	1981; 35 years ago
Design	RISC
Type	Register-Register
Encoding	Fixed
Endianness	Bi

Digital home & networking equipment
(Blu-ray, PlayStation 2)
[MIPS Instruction Set]

Intel x86 Evolution: Milestones

	Name	*Date*	*Transistors*	*MHz*

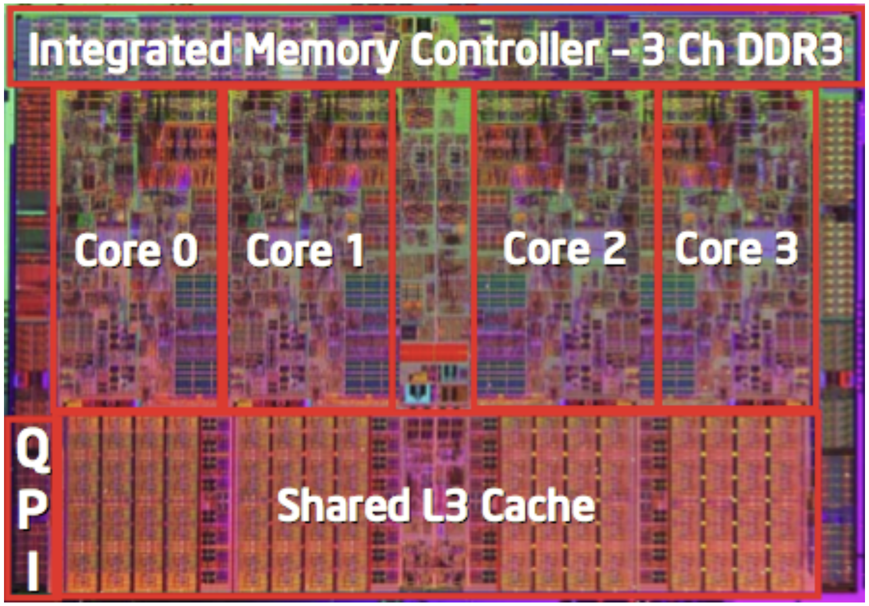
- 8086 — 1978 — 29K — 5-10
  - First 16-bit Intel processor. Basis for IBM PC & DOS
  - 1MB address space
- 386 — 1985 — 275K — 16-33
  - First 32 bit Intel processor , referred to as IA32
  - Added "flat addressing," capable of running Unix
- Pentium 4E — 2004 — 125M — 2800-3800
  - First 64-bit Intel 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
Pentium Pro	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 ("SIMD")
  - Instructions to enable more efficient conditional operations
  - Hardware support for virtualization (virtual machines)
  - 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 Corporation (DEC) 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

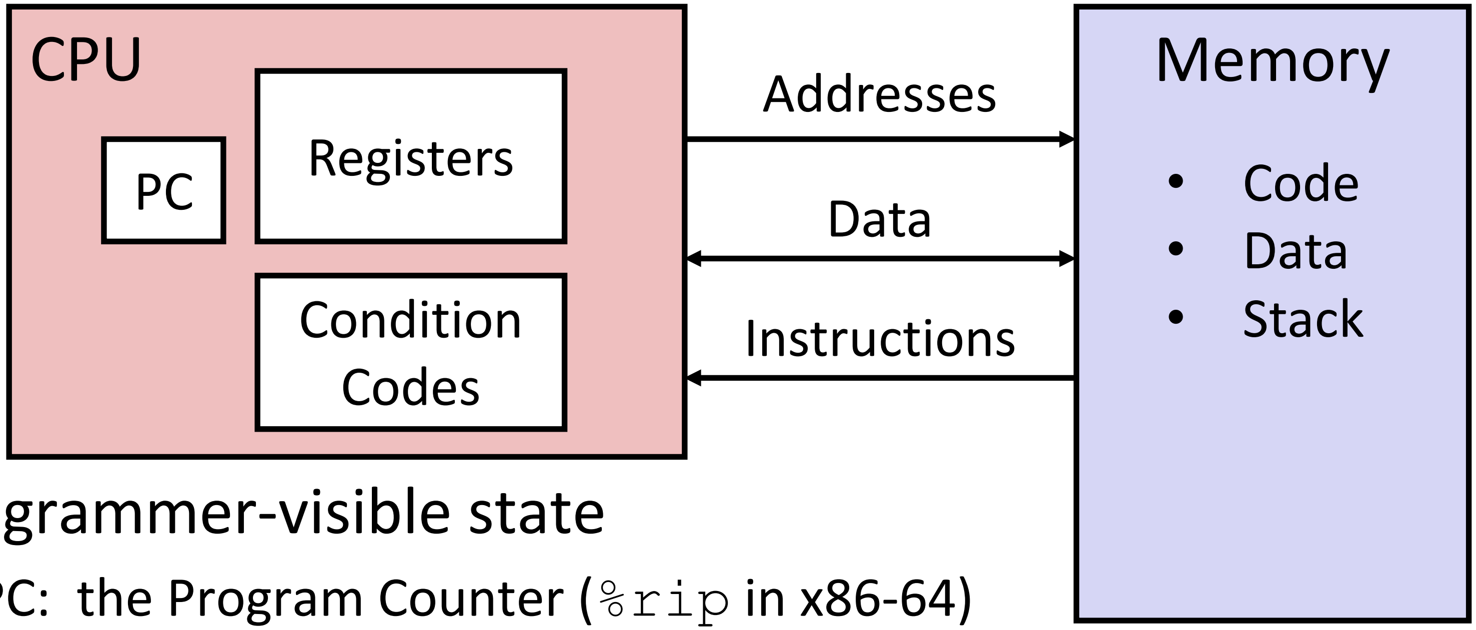
- Previous versions of CSE 351 and 2nd edition of textbook covered IA32 (traditional 32-bit x86 ISA) **<u>and</u>** x86-64
  - We will only cover x86-64 this quarter

Definitions

- **Architecture (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/EE 469, 470

- Are the following part of the architecture?
  - Number of registers?
  - How about CPU frequency?
  - Cache size? Memory size?

Assembly Programmer's View

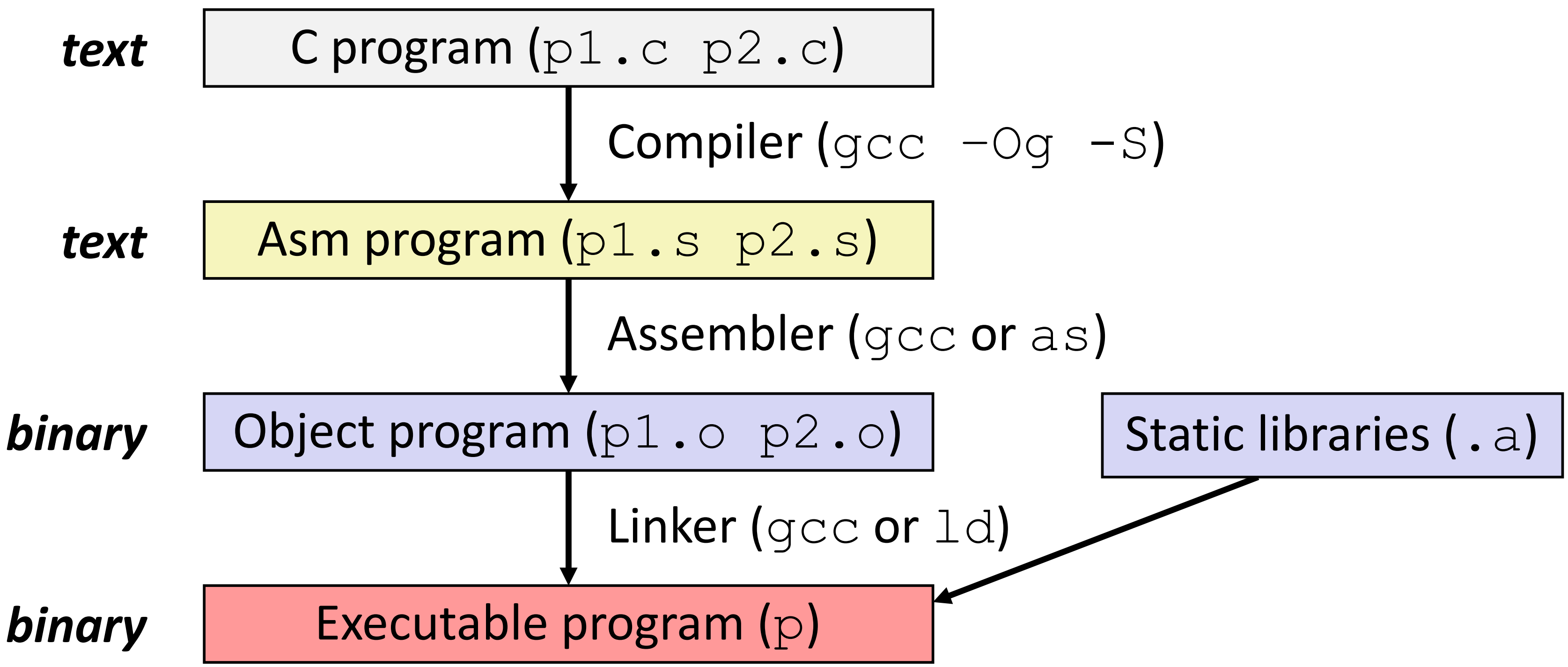


- Programmer-visible state
  - PC: the Program Counter (`%rip` in x86-64)
    - Address of next instruction
  - Named registers
    - Together in "register file"
    - Heavily used program data
  - Condition codes
    - Store status information about most recent arithmetic operation
    - Used for conditional branching

- Memory
  - Byte-addressable array
  - Code and user data
  - Includes *the Stack* (for supporting procedures)

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`)

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

- x86-64 assembly (`gcc –Og –S sum.c`)
  - Generates file `sum.s` (see https://godbolt.org/g/pQUhIZ)

```
sumstore(long, long, long*):
  addq    %rdi, %rsi
  movq    %rsi, (%rdx)
  ret
```

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

Machine Instruction Example

```
*dest = t;
```

- C Code
  - Store value `t` where designated by `dest`

```
movq %rsi, (%rdx)
```

- Assembly
  - Move 8-byte value to memory
    - Quad word (`q`) in x86-64 parlance
  - Operands:

`t`	Register `%rsi`
`dest`	Register `%rdx`
`*dest`	Memory M[`%rdx`]

```
0x400539:  48 89 32
```

- Object Code
  - 3-byte instruction (in hex)
  - Stored at address `0x40059e`

Object Code

Function *starts* at this address

```
0x00400536 <sumstore>:
   0x48
   0x01
   0xfe
   0x48
   0x89
   0x32
   0xc3
```

Total of 7 bytes

- Each instruction here is 1-3 bytes long

- **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:

```
0000000000400536 <sumstore>:
  400536:  48 01 fe        add    %rdi,%rsi
  400539:  48 89 32        mov    %rsi,(%rdx)
  40053c:  c3              retq
```

- **Disassembler** (`objdump -d sum`)
  - Useful tool for examining object code (`man 1 objdump`)
  - Analyzes bit pattern of series of instructions
  - Produces approximate rendition of assembly code
  - Can run on either `a.out` (complete executable) or `.o` file

Alternate Disassembly in GDB

```
$ gdb sum
(gdb) disassemble sumstore
Dump of assembler code for function sumstore:
   0x0000000000400536 <+0>:      add    %rdi,%rsi
   0x0000000000400539 <+3>:      mov    %rsi,(%rdx)
   0x000000000040053c <+6>:      retq
End of assembler dump.

(gdb) x/7bx sumstore
0x400536 <sumstore>:0x48   0x01   0xfe   0x48   0x89   0x32   0xc3
```

- Within gdb debugger (`gdb sum`):
  - `disassemble sumstore`: disassemble procedure
  - `x/7bx sumstore`: show 7 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 attempts to reconstruct assembly source

Summary

- Converting between integral and floating point data types *does* change the bits
- Floating point rounding is a HUGE issue!
  - Limited mantissa bits cause inaccurate representations
  - In general, floating point arithmetic is NOT associative or distributive
- x86-64 is a complex instruction set computing (CISC) architecture
- An executable binary file is produced by running code through a **compiler**, **assembler**, and **linker**

BONUS SLIDES

More details for the curious.

- Rounding strategies
- Floating Point Puzzles

Closer Look at Round-To-Even

- Default Rounding Mode
  - Hard to get any other kind without dropping into assembly
  - All others are statistically biased
    - Sum of set of positive numbers will consistently be over- or under- estimated

- Applying to Other Decimal Places / Bit Positions
  - When exactly halfway between two possible values
    - Round so that least significant digit is even
  - E.g., round to nearest hundredth

1.2349999	1.23	(Less than half way)
1.2350001	1.24	(Greater than half way)
1.2350000	1.24	(Half way—round up)
1.2450000	1.24	(Half way—round down)

Rounding Binary Numbers

- Binary Fractional Numbers
  - "Half way" when bits to right of rounding position = $100\ldots_2$
- Examples
  - Round to nearest 1/4 (2 bits right of binary point)

Value	Binary	Rounded	Action	Round Val
$2 + \frac{3}{32}$	10.00011_2	10.00_2	(<1/2—down)	2
$2 + \frac{3}{16}$	10.00110_2	10.01_2	(>1/2—up)	$2 + \frac{1}{4}$
$2 + \frac{7}{8}$	10.11100_2	11.00_2	(1/2—up)	3
$2 + \frac{5}{8}$	10.10100_2	10.10_2	(1/2—down)	$2 + \frac{1}{2}$

Floating Point Puzzles

s	exp	mantissa
1 bit	8 bits	23 bits

s	exp	mantissa
1 bit	11 bits	52 bits

- For each of the following C expressions, either:
  - Argue that it is true for all argument values
  - Explain why not true

```
int x = …;
float f = …;
double d = …;
double d2 = …;
```

Assume neither `d` nor `f` is NaN

```
1) x == (int)(float) x
2) x == (int)(double) x
3) f == (float)(double) f
4) d == (double)(float) d
5) f == -(-f);
6) 2/3 == 2/3.0
7) (d+d2)-d == d2
```