Machine Programming
CSE 351 Autumn 2016

Instructor:
Justin Hsia

Teaching Assistants:
Chris Ma
Hunter Zahn
John Kaltenbach
Kevin Bi
Sachin Mehta
Suraj Bhat
Thomas Neuman
Waylon Huang
Xi Liu
Yufang Sun

http://www.smbc-comics.com/?id=2999
Administrivia

- Homework 1 released
  - On number representation (signed, unsigned, floating point) and x86 (starting today)
- Section room change: AD/AH now in EEB 045
Floating point topics

- Fractional binary numbers
- IEEE floating-point standard
- Floating-point operations and rounding
- Floating-point in C

- There are many more details that we won’t cover
  - It’s a 58-page standard...
Rounding modes

- **Possible rounding modes (money example):**

<table>
<thead>
<tr>
<th></th>
<th>$1.40</th>
<th>$1.60</th>
<th>$1.50</th>
<th>$2.50</th>
<th>$-1.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round-toward-zero</td>
<td>$1</td>
<td>$1</td>
<td>$1</td>
<td>$2</td>
<td>$-1</td>
</tr>
<tr>
<td>Round-down (-∞)</td>
<td>$1</td>
<td>$1</td>
<td>$1</td>
<td>$2</td>
<td>$-2</td>
</tr>
<tr>
<td>Round-up (+∞)</td>
<td>$2</td>
<td>$2</td>
<td>$2</td>
<td>$3</td>
<td>$-1</td>
</tr>
<tr>
<td>Round-to-nearest</td>
<td>$1</td>
<td>$2</td>
<td>??</td>
<td>??</td>
<td>??</td>
</tr>
<tr>
<td>Round-to-even</td>
<td>$1</td>
<td>$2</td>
<td>$2</td>
<td>$2</td>
<td>$-2</td>
</tr>
</tbody>
</table>

- **Round-to-even avoids statistical bias in repeated rounding**
  - Rounds up about half the time, down about half the time
  - This is the default rounding mode for IEEE floating-point
Mathematical Properties of FP Operations

- Exponent overflow yields \(+\infty\) or \(-\infty\)
- Floats with value \(+\infty\), \(-\infty\), and NaN can be used in operations
  - Result usually still \(+\infty\), \(-\infty\), or NaN; but not always intuitive
- Floating point operations do not work like real math, due to rounding
  - Not associative: \((3.14+1e100)-1e100 \neq 3.14+(1e100-1e100)\)
    
    | 3.14 | 1e100 | 1e100 |
    |------|------|------|
    | 0.00 | 1.00 | 1.00 |
    | 3.14 |
  - Not distributive: \(100\times(0.1+0.2) \neq 100\times0.1+100\times0.2\)
    
    | 30.00 | 1.00 | 1.00 |
    | 30.00 |
  - 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" or quadruple) 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, so just avoid them!
Floating Point Conversions in C

- Casting between `int`, `float`, and `double` changes the bit representation
  - `int` → `float`
    - May be rounded (not enough bits in mantissa: 23)
    - Overflow impossible
  - `int` or `float` → `double`
    - Exact conversion (all 32-bit `int`s representable)
  - `long` → `double`
    - Depends on word size (32-bit is exact, 64-bit may be rounded)
  - `double` or `float` → `int`
    - Truncates fractional part (rounded toward zero)
    - “Not defined” when out of range or NaN: generally sets to $T_{\text{min}}$ (even if the value is a very big positive)
Floating Point and the Programmer

```c
#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
Floating Point Summary

- Floats also suffer from the fixed number of bits available to represent them
  - Can get overflow/underflow
  - “Gaps” produced in representable numbers means we can lose precision, unlike ints
    - Some “simple fractions” have no exact representation (e.g., 0.2)
    - “Every operation gets a slightly wrong result”

- Floating point arithmetic not associative or distributive
  - Mathematically equivalent ways of writing an expression may compute different results

- Never test floating point values for equality!
- Careful when converting between ints and floats!
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)
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg = c.getMPG();

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

Machine code:
0111010000011000  
1000110100000100  
0000000000010  
1100000111111010000011111

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)?

User program in C

$\text{\texttt{c}}$ file

$\text{\texttt{c}}$ compiler

Assembler

$\text{\texttt{exe}}$ file

Hardware

Code Time

Compile Time

Run Time
HW Interface Affects Performance

Source code
Different applications or algorithms

C Language
Program A
Program B
Your program

Compiler
Perform optimizations, generate instructions

 GCC
Clang

Architecture
Instruction set

 x86-64
 ARMv8 (AArch64/A64)

Hardware
Different implementations

 Intel Pentium 4
 Intel Core 2
 Intel Core i7
 AMD Opteron
 AMD Athlon
 ARM Cortex-A53
 Apple A7
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

<table>
<thead>
<tr>
<th><strong>x86</strong></th>
<th><strong>ARM architectures</strong></th>
<th><strong>MIPS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Designer</td>
<td>Intel, AMD</td>
<td>Designer</td>
</tr>
<tr>
<td>Bits</td>
<td>16-bit, 32-bit and 64-bit</td>
<td>Bits</td>
</tr>
<tr>
<td>Design</td>
<td>CISC</td>
<td>Design</td>
</tr>
<tr>
<td>Type</td>
<td>Register-memory</td>
<td>Type</td>
</tr>
<tr>
<td>Encoding</td>
<td>Variable (1 to 15 bytes)</td>
<td>Encoding</td>
</tr>
<tr>
<td>Endianness</td>
<td>Little</td>
<td>Endianness</td>
</tr>
</tbody>
</table>

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

### Smartphone-like devices
(iPhone, iPad, Raspberry Pi)
**ARM Instruction Set**

### Digital home & networking equipment
(Blu-ray, PlayStation 2)
**MIPS Instruction Set**
## Intel x86 Evolution: Milestones

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Transistors</th>
<th>MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>8086</td>
<td>1978</td>
<td>29K</td>
<td>5-10</td>
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<tr>
<td>386</td>
<td>1985</td>
<td>275K</td>
<td>16-33</td>
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<td>Pentium 4E</td>
<td>2004</td>
<td>125M</td>
<td>2800-3800</td>
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<tr>
<td>Core 2</td>
<td>2006</td>
<td>291M</td>
<td>1060-3500</td>
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<tr>
<td>Core i7</td>
<td>2008</td>
<td>731M</td>
<td>1700-3900</td>
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</tbody>
</table>

- First 16-bit Intel processor. Basis for IBM PC & DOS
- 1MB address space
- First 32 bit Intel processor, referred to as IA32
- Added “flat addressing,” capable of running Unix
- First 64-bit Intel x86 processor, referred to as x86-64
- First multi-core Intel processor
- 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

- **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:
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) and 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

```
C program (p1.c p2.c)
      \__________________________\                  
    Compiler (gcc -Og -S)

  text

C program (p1.c p2.c)
      \__________________________\                  
    Compiler (gcc -Og -S)

  text

Asm program (p1.s p2.s)
      \__________________________\                  
    Assembler (gcc or as)

  text

Object program (p1.o p2.o)
      \__________________________\                  
    Linker (gcc or ld)

  binary

Executable program (p)
      \__________________________\                  
    Static libraries (.a)

  binary
```
Compiling Into Assembly

- **C Code** *(sum.c)*
  ```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](https://godbolt.org/g/pQUhIZ))
  ```assembly
  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

- **C Code**
  - Store value \( t \) where designated by \( \text{dest} \)

- **Assembly**
  - Move 8-byte value to memory
    - Quad word (\( q \)) in x86-64 parlance
  - Operands:
    - \( t \) Register \( %rsi \)
    - \( \text{dest} \) Register \( %rdx \)
    - \( *\text{dest} \) Memory \( M[ %rdx ] \)

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

- **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

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
Disassembling Object Code

Disassembled:

<table>
<thead>
<tr>
<th>Address</th>
<th>Opcode</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000000000400536 &lt;sumstore&gt;:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400536:</td>
<td>48 01 fe</td>
<td>add %rdi,%rsi</td>
</tr>
<tr>
<td>400539:</td>
<td>48 89 32</td>
<td>mov %rsi,(%rdx)</td>
</tr>
<tr>
<td>40053c:</td>
<td>c3</td>
<td>retq</td>
</tr>
</tbody>
</table>

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 0xc3 0xc3

- Within gdb debugger (gdb sum):
  - disassemble sumstore: disassemble procedure
  - x/7bx sumstore: show 7 bytes starting at sumstore
What Can be Disassembled?

Anything that can be interpreted as executable code

Disassembler examines bytes and attempts to reconstruct assembly source

% 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

Reverse engineering forbidden by Microsoft End User License Agreement
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*
More details for the curious. We won’t be using or testing you on any of these extras in 351.

- 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 = $100..._2$

- **Examples**
  - Round to nearest 1/4 (2 bits right of binary point)

<table>
<thead>
<tr>
<th>Value</th>
<th>Binary</th>
<th>Rounded</th>
<th>Action</th>
<th>Round Val</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 + \frac{3}{32}$</td>
<td>$10.00011_2$</td>
<td>$10.00_2$</td>
<td>(&lt;1/2—down)</td>
<td>2</td>
</tr>
<tr>
<td>$2 + \frac{3}{16}$</td>
<td>$10.00110_2$</td>
<td>$10.01_2$</td>
<td>(&gt;1/2—up)</td>
<td>$2 + \frac{1}{4}$</td>
</tr>
<tr>
<td>$2 + \frac{7}{8}$</td>
<td>$10.11100_2$</td>
<td>$11.00_2$</td>
<td>(1/2—up)</td>
<td>3</td>
</tr>
<tr>
<td>$2 + \frac{5}{8}$</td>
<td>$10.10100_2$</td>
<td>$10.10_2$</td>
<td>(1/2—down)</td>
<td>$2 + \frac{1}{2}$</td>
</tr>
</tbody>
</table>
Floating Point Puzzles

For each of the following C expressions, either:

- Argue that it is true for all argument values
- Explain why not true

```c
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`