CSCI 2021: Binary Floating Point Numbers

Chris Kauffman

Last Updated:
Mon Oct 10 12:56:11 PM CDT 2022
Logistics

Reading Bryant/O’Hallaron
- Ch 2.4-5: Floats, Wed/Fri
- 2021 Quick Guide to GDB
- Next week: Ch 3.1-7: Assembly Intro

Goals this Week
- Discuss Bitwise ops from Integer Rep Slides
- Floating Point layout
- gdb introduction

Feedback Survey
- Open on Canvas
- Anonymous: be honest!
- Due Wed 5-Oct for 1 EP
  83% response rate so far

Labs/HW
- Lab05: Bit operations
- HW05: Bits, Floats, GDB

P2: Released Wed, due Thu 13-Oct
1. Bit shift operations for Battery (50%)
2. Puzzlebox via debugger (50% + Makeup Credit)
Don’t Give Up, Stay Determined!

- If Project 1 / Exam 1 went awesome, count yourself lucky
- If things did not go well, Don’t Give Up
- Spend some time contemplating why things didn’t go well, talk to course staff about it, learn from any mistakes
- There is a LOT of semester left and plenty of time to recover from a bad start
Parts of a Fractional Number

The meaning of the “decimal point” is as follows:

\[ 123.406_{10} = 1 \times 10^2 + 2 \times 10^1 + 3 \times 10^0 + 4 \times 10^{-1} + 0 \times 10^{-2} + 6 \times 10^{-3} \]

\[ = 123 \times 10^2 + 4 \times 10^{-1} + 0.406_{10} \]

\[ = 123 + 4 + 0.406 \]

\[ = 123.406_{10} \]

Changing to base 2 induces a “binary point” with similar meaning:

\[ 110.101_2 = 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 + 1 \times 2^{-1} + 0 \times 2^{-2} + 1 \times 2^{-3} \]

\[ = 6.625_{10} \]

One could represent fractional numbers with a fixed point e.g.

- 32 bit fractional number with
  - 10 bits left of Binary Point (integer part)
  - 22 bits right of Binary Point (fractional part)

**BUT** most applications require a more flexible scheme
Scientific Notation for Numbers

“Scientific” or “Engineering” notation for numbers with a fractional part is

<table>
<thead>
<tr>
<th>Standard</th>
<th>Scientific</th>
<th>printf(&quot;%.4e&quot;,x);</th>
</tr>
</thead>
<tbody>
<tr>
<td>123.456</td>
<td>1.2346 × 10²</td>
<td>1.2346e+02</td>
</tr>
<tr>
<td>50.01</td>
<td>5.001 × 10¹</td>
<td>5.0010e+01</td>
</tr>
<tr>
<td>3.14159</td>
<td>3.14159 × 10⁰</td>
<td>3.1416e+00</td>
</tr>
<tr>
<td>0.54321</td>
<td>5.4321 × 10⁻¹</td>
<td>5.4321e-01</td>
</tr>
<tr>
<td>0.00789</td>
<td>7.89 × 10⁻³</td>
<td>7.8900e-03</td>
</tr>
</tbody>
</table>

- **Always** includes one **non-zero** digit left of decimal place
- **Has some** **significant** digits after the decimal place
- **Multiplies by a** **power of 10** to get actual number

Binary Floating Point Layout Uses Scientific Convention

- **Some bits for integer/fractional part**
- **Some bits for exponent part**
- **All in base 2**: 1’s and 0’s, powers of 2
Conversion Example

Below steps convert a decimal number to a fractional binary number equivalent then adjusts to scientific representation.

float fl = -248.75;

\[
\begin{array}{ccccccccc}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 & -1 & -2 \\
-248.75 &=& -(128+64+32+16+8+0+0+0).&(1/2+1/4) \\
&=& -11111000.11 \times 2^0 \\
&=& -1111100.011 \times 2^1 \\
&=& -111110.0011 \times 2^2 \\
&\vdots& \\
MANTISSA & EXPONENT \\
&=& -1.111100011 \times 2^7 \\
&=& 0.123456789
\end{array}
\]

\text{Mantissa} \equiv \text{Significand} \equiv \text{Fractional Part}
In early computing, computer manufacturers used similar principles for floating point numbers but varied specifics.

Example of Early float data/hardware:
- Univac: 36 bits, 1-bit sign, 8-bit exponent, 27-bit significand
- IBM: 32 bits, 1-bit sign, 7-bit exponent, 24-bit significand

Manufacturers implemented circuits with different rounding behavior, with/without infinity, and other inconsistencies.

Troublesome for reliability: code produced different results on different machines.

This was resolved with the adoption of the IEEE 754 Floating Point Standard which specifies:
- Bit layout of 32-bit float and 64-bit double
- Rounding behavior, special values like Infinity

Turing Award to William Kahan for his work on the standard.

---

1 Floating Point Arithmetic
2 IBM Hexadecimal Floats
### IEEE 754 Format: *The Standard for Floating Point*

<table>
<thead>
<tr>
<th>float</th>
<th>double</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>64</td>
<td>Total bits</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Bits for sign (1 neg / 0 pos)</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>Bits for Exponent multiplier (power of 2)</td>
</tr>
<tr>
<td>23</td>
<td>52</td>
<td>Bits for Fractional part or <em>mantissa</em></td>
</tr>
<tr>
<td>7.22</td>
<td>15.95</td>
<td>Decimal digits of accuracy$^3$</td>
</tr>
</tbody>
</table>

- Most commonly implemented format for floating point numbers in hardware to do arithmetic: processor has physical circuits to add/mult/etc. for this bit layout of floats
- Numbers/Bit Patterns divided into three categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized</td>
<td>most common like 1.0 and −9.56e37</td>
<td>mixed 0/1</td>
</tr>
<tr>
<td>Denormalized</td>
<td>very close to zero and 0.0</td>
<td>all 0’s</td>
</tr>
<tr>
<td>Special</td>
<td>extreme/error values like Inf and NaN</td>
<td>all 1’s</td>
</tr>
</tbody>
</table>

$^3$Wikipedia: IEEE 754
Example float Layout of -248.75: float_examples.c


Color: 8-bit blocks, **Negative**: highest bit, leading 1

Exponent: high 8 bits, $2^7$ encoded with bias of -127

\[
\begin{align*}
1000_0110 & - 0111_1111 \\
= 128+4+2 & - 127 \\
= 134 & - 127 \\
= 7
\end{align*}
\]

Fractional/Mantissa portion is

\[
1.111100011... \\
\sim |||||\\
| explicit low 23 bits \\
| implied leading 1 \\
\text{not in binary layout}
\]
Normalized Floating Point: General Case

- A “normalized” floating point number is in the standard range for float/double, bit layout follows previous slide

Example: $-248.75 = -1.111100011 * 2^7$

Exponent is in **Bias Form** (not Two’s Complement)

- Unsigned positive integer minus constant **bias number**
- **Consequence**: exponent of 0 is not bitstring of 0’s
- **Consequence**: tiny exponents like -125 close to bitstring of 0’s; this makes resulting number close to 0

8-bit exponent $1000\ 0110 = 128+4+2 = 134$
so exponent value is $134 - 127 = 7$

Integer and Mantissa Parts

- The leading 1 before the binary point is **implied** so does not show up in the bit string
- Remaining fractional/mantissa portion shows up in the low-order bits
Fixed Bit Standards for Floating Point

IEEE Standard Layouts

<table>
<thead>
<tr>
<th>Kind</th>
<th>Sign</th>
<th>Exponent</th>
<th>Bias</th>
<th>Exp Range</th>
<th>Mantissa</th>
</tr>
</thead>
<tbody>
<tr>
<td>float</td>
<td>31 (1)</td>
<td>30-23 (8 bits)</td>
<td>-127</td>
<td>-126 to +127</td>
<td>22-0 (23 bits)</td>
</tr>
<tr>
<td>double</td>
<td>63 (1)</td>
<td>62-52 (11 bits)</td>
<td>-1023</td>
<td>-1022 to +1023</td>
<td>51-0 (52 bits)</td>
</tr>
</tbody>
</table>

Standard allows hardware to be created that is as efficient as possible to do calculation on these numbers

Consequences of Fixed Bits

▶ Since a fixed # of bit is used, some numbers cannot be exactly represented, happens in any numbering system:

▶ Base 10 and Base 2 cannot represent $\frac{1}{3}$ in finite digits

▶ Base 2 cannot represent $\frac{1}{10}$ in finite digits

```c
defloat f = 0.1;
printf("0.1 = %.20e\n",f);
0.1 = 1.00000001490116119385e-01
```

Try show_float.c to see this in action
Exercise: Quick Checks

1. What distinct parts are represented by bits in a floating point number (according to IEEE)
2. What is the “bias” of the exponent for 32-bit floats
3. Represent 7.125 in binary using “binary point” notation
4. Lay out 7.125 in IEEE-754 format
5. What does the number 1.0 look like as a float?

FLOATING POINT FORMAT IEEE-754, 32 BITS

| S | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

- **SIGN BIT**: 1 = NEGATIVE, 0 = POSITIVE
- **EXAMPLE**: -248.75
- **HEXADECIMAL**: C3 78 C0 00


The diagram above may help in recalling IEEE 754 layout.
Special Cases: See float_examples.c

Special Values

- **Infinity**: exponent bits all 1, fraction all 0, sign bit indicates $+\infty$ or $-\infty$
- Infinity results from overflow/underflow or certain ops like `float x = 1.0 / 0.0;`
- `#include <math.h>` gets macro INFINITY and -INFINITY
- **NaN**: not a number, exponent bits all 1, fraction has some 1s
- Errors in floating point like `0.0 / 0.0`

Denormalized values: Exponent bits all 0

- Fractional/Mantissa portion evaluates *without* implied leading one, still an unsigned integer though
- Exponent is $Bias + 1$: $2^{-126}$ for float
- Result: very small numbers close to zero, smaller than any other representation, degrade uniformly to 0
- Zero: bit string of all 0s, optional leading 1 (*negative zero*)
Other Float Notes

**Approximations and Roundings**

- Approximate $\frac{2}{3}$ with 4 digits, usually 0.6667 with standard rounding in base 10
- Similarly, some numbers cannot be exactly represented with fixed number of bits: $\frac{1}{10}$ approximated
- IEEE 754 specifies various rounding modes to approximate numbers

**Clever Engineering**

- IEEE 754 allows floating point numbers to sort using signed integer sorting routines
- Bit patterns for float follows are ordered nearly the same as bit patterns for signed int
- Integer comparisons are usually fewer clock cycles than floating comparisons
Sidebar: The Weird and Wonderful Union

- Bitwise operations like `&` are not valid for `float`/`double`.
- Can use pointers/casting to get around this OR...
- Use a `union`: somewhat unique construct to C.
- Defined like a struct with several fields.
- BUT fields occupy the same memory location (!?!)?
- Allows one to treat a byte position as multiple different types, ex: `int` / `float` / `char[]`.
- Memory size of the union is the `max` of its fields.

```c
// union.c
typedef union {  // shared memory
    float fl;  // an float
    int in;    // a int
    char ch[4];  // char array
} flint_t;  // 4 bytes total

int main(){
    flint_t flint;
    flint.in = 0xC378C000;
    printf("%.4f\n", flint.fl);
    printf("%08x %d\n",flint.in,flint.in);
    for(int i=0; i<4; i++){
        unsigned char c = flint.ch[i];
        printf("%d: %02x '%c'\n",i,c,c);
    }
}
```

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Mem</th>
<th>Val</th>
</tr>
</thead>
<tbody>
<tr>
<td>---------------</td>
<td>-----</td>
<td>------</td>
</tr>
<tr>
<td>flint.ch[3]</td>
<td>#1027</td>
<td>0xC3</td>
</tr>
<tr>
<td>flint.ch[2]</td>
<td>#1026</td>
<td>0x78</td>
</tr>
<tr>
<td>flint.ch[1]</td>
<td>#1025</td>
<td>0xC0</td>
</tr>
<tr>
<td>flint.in/fl/ch[0]</td>
<td>#1024</td>
<td>0x00</td>
</tr>
<tr>
<td>i</td>
<td>#1020</td>
<td>?</td>
</tr>
</tbody>
</table>
Floating Point Operation Efficiencies

- Floating Point Operations per Second, **FLOPS** is a major measure for numerical code/hardware efficiency
- Often used to benchmark and evaluate scientific computer resources, (e.g. top super computers in the world)
- Tricky to evaluate because of
  - A single FLOP (add/sub/mul/div) may take 3 clock cycles to finish: **latency 3**
  - Another FLOP **can start** before the first one finishes: **pipelined**
  - Enough FLOPs lined up can get **average 1 FLOP per cycle**
  - FP Instructions may automatically operate on multiple FPs stored in memory to feed pipeline: **vectorized ops**
  - Generally referred to as **superscalar**
  - Processors schedule things **out of order** too
- All of this makes micro-evaluation error-prone and pointless
- Run a real application like an N-body simulation and compute

\[
FLOPS = \frac{\text{number of floating ops done}}{\text{time taken in seconds}}
\]
# Top 5 Super Computers Worldwide, June 2022

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<tr>
<td>1</td>
<td>Frontier, USA / Oak Ridge Cray EX235a, AMD EPYC 2GHz (x86-64)</td>
<td>8,730,112</td>
<td>1,102.00</td>
<td>1,685.65</td>
<td>21,100</td>
</tr>
<tr>
<td>2</td>
<td>Fugaku, Japan / Fujitsu Fujitsu A64FX 2.2GHz (Arm)</td>
<td>7,630,848</td>
<td>442,010.0</td>
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<td>29,899</td>
</tr>
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<td>LUMI Finland / EuroHPC Cray EX235a, AMD EPYC 2GHz (x86-64)</td>
<td>1,110,144</td>
<td>151.90</td>
<td>214.35</td>
<td>2,942</td>
</tr>
<tr>
<td>4</td>
<td>Summit United States IBM POWER9 22C 3.07GHz (Power)</td>
<td>2,414,592</td>
<td>148,600.0</td>
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</tr>
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https://www.top500.org/lists/top500/2022/06/

*: An average US Home uses 909 kWh of power per month
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<td>10,649,600</td>
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<td>5</td>
<td>Perlmutter, <em>United States</em> AMD EPYC 2.45GHz, Cray (x86-64)</td>
<td>706,304</td>
<td>64,590.0</td>
<td>89,794.5</td>
<td>2,528</td>
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<td>513,854.7</td>
<td>28,335</td>
</tr>
<tr>
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<td>Fujitsu A64FX 2.2GhZ (Arm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>555,520</td>
<td>63,460.0</td>
<td>79,215.0</td>
<td>2,646</td>
</tr>
<tr>
<td></td>
<td>AMD EPYC 7742 64C 2.25GHz (x86-64)</td>
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<td>??</td>
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[https://www.top500.org/list/2019/11/](https://www.top500.org/list/2019/11/)
## Top 5 Super Computers Worldwide, Nov 2018

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<tr>
<td>2</td>
<td>Sierra <em>United States</em> IBM POWER9 22C 3.1GHz,</td>
<td>1,572,480</td>
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<td>125,712.0</td>
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<tr>
<td>3</td>
<td>Sunway TaihuLight <em>China</em> Sunway MPP</td>
<td>10,649,600</td>
<td>93,014.6</td>
<td>125,435.9</td>
<td>15,371</td>
</tr>
<tr>
<td>4</td>
<td>Tianhe-2A <em>China</em> TH-IVB-FEP Cluster</td>
<td>4,981,760</td>
<td>61,444.5</td>
<td>100,678.7</td>
<td>18,482</td>
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<tr>
<td>5</td>
<td>Piz Daint <em>Switzerland</em> Cray XC50, Xeon E5-2690v3</td>
<td>387,872</td>
<td>21,230.0</td>
<td>27,154.3</td>
<td>2,384</td>
</tr>
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</table>

[https://www.top500.org/list/2018/11/](https://www.top500.org/list/2018/11/)
## Top 5 Super Computers Worldwide, Nov 2017

<table>
<thead>
<tr>
<th>Rank</th>
<th>System</th>
<th>#Cores</th>
<th>Rmax (TFlop/s)</th>
<th>Rpeak (TFlop/s)</th>
<th>Power (kW)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Sunway TaihuLight, China</td>
<td>10,649,600</td>
<td>93,014.6</td>
<td>125,435.9</td>
<td>15,371</td>
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<td>Sunway MPP</td>
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<td>Tianhe-2 (MilkyWay-2), China</td>
<td>3,120,000</td>
<td>33,862.7</td>
<td>54,902.4</td>
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<tr>
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<td>19,590.0</td>
<td>25,326.3</td>
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<td>Gyoukou, Japan</td>
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<td>19,135.8</td>
<td>28,192.0</td>
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<td>ZettaScaler-2.2 HPC system</td>
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<td>17,590.0</td>
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<td>Cray XK7</td>
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https://www.top500.org/lists/2017/11/