CSCI 2021: Binary Floating Point Numbers

Chris Kauffman

Last Updated:
Fri Oct 9 01:06:01 PM CDT 2020
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
- gdb introduction
- Floating Point layout

Feedback Survey
- Open on Canvas
- Anonymous: be honest!
- Due Mon 10/12 for 1 EP

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

Project 2
- Problem 1: Bit shift operations (50%)
- Problem 2: Puzzlebox via debugger (50% + makeup)
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:

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

\[
123 = 100 + 20 + 3
\]

\[
0.406 = \frac{4}{10} + \frac{6}{1000}
\]

\[
= 123.406_{10}
\]

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

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

\[
6 = 4 + 2
\]

\[
0.625 = \frac{1}{2} + \frac{1}{8}
\]

\[
= 6.625_{10}
\]

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><code>printf(&quot;%.4e&quot;,x);</code></th>
</tr>
</thead>
<tbody>
<tr>
<td>123.456</td>
<td>1.23456 × 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.

```c
float fl = -248.75;
```

```
   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 *2^0
    76543210  12
 = -1111100.011 *2^1
    6543210   123
 = -111110.0011 *2^2
    543210    1234
...```

```
MANTISSA       EXPONENT
= -1.111100011 * 2^7
  0  123456789
```

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

\(^3\text{Wikipedia: IEEE 754}\)
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

- 1000_0110 - 0111_1111
- = 128+4+2 - 127
- = 134 - 127
- = 7

Fractional/Mantissa portion is

1.111100011...
^ |||||||||
| explicit low 23 bits
| implied leading 1
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: $-248.75 = -1.111100011 \times 2^7$

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 Bit</th>
<th>Exponent Bits</th>
<th>Bias</th>
<th>Exp Range</th>
<th>Mantissa Bits</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
float f = 0.1;
petsf("0.1 = %.20e\n",f);
0.1 = 1.00000001490116119385e-01
```

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

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

The diagram above may help in recalling IEEE 754 layout
Answers: Quick Checks

1. Represent 7.125 in binary using a “binary point”
   ▶ \(7_{10} = 111_2\)
   ▶ \(0.125_{10} = \frac{1}{8} = 2^{-3} = 0.001_2\)
   ▶ \(7.125_{10} = 111.001_2\)

2. What distinct parts are represented by bits in a floating point number (according to IEEE 754)
   ▶ Sign, Exponent, and Mantissa/Fractional Portion

3. What is the “bias” of the exponent for 32-bit floats (according to IEEE 754)
   ▶ Bias is -127 which is subtracted from the unsigned value of the 8 exponent bits to get the actual exponent

4. What does the number 1.0 look like as a float?
   ▶ Positive: sign bit of 0
   ▶ Exponent is 0, so sign bits total 127:
     \[0111\ 1111\]
     \[8\ 4\]
   ▶ Mantissa has implied leading 1 and all 0’s so:
     \[000\ 0000\ 0000\ 0000\ 0000\ 0000\]
     \[23\ 20\ 16\ 12\ 8\ 4\]
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*)

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
  ```c
  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 $0.0 / 0.0$
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 routines
- Bit patterns for float follows are ordered 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 int
    int in; // a float
    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>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

\[
\text{FLOPS} = \frac{\text{number of floating ops done}}{\text{time taken in seconds}}
\]
## 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>
</tr>
</thead>
<tbody>
<tr>
<td>1</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>2</td>
<td>Tianhe-2 (MilkyWay-2) <em>China</em> TH-IVB-FEP Cluster</td>
<td>3,120,000</td>
<td>33,862.7</td>
<td>54,902.4</td>
<td>17,808</td>
</tr>
<tr>
<td>3</td>
<td>Piz Daint <em>Switzerland</em> Cray XC50</td>
<td>361,760</td>
<td>19,590.0</td>
<td>25,326.3</td>
<td>2,272</td>
</tr>
<tr>
<td>4</td>
<td>Gyoukou <em>Japan</em> ZettaScaler-2.2 HPC system</td>
<td>19,860,000</td>
<td>19,135.8</td>
<td>28,192.0</td>
<td>1,350</td>
</tr>
<tr>
<td>5</td>
<td>Titan <em>USA</em> Cray XK7</td>
<td>560,640</td>
<td>17,590.0</td>
<td>27,112.5</td>
<td>8,209</td>
</tr>
</tbody>
</table>

<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>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Summit United States</td>
<td>2,397,824</td>
<td>143,500.0</td>
<td>200,794.9</td>
<td>9,783</td>
</tr>
<tr>
<td></td>
<td>IBM POWER9 22C 3.07GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Sierra United States</td>
<td>1,572,480</td>
<td>94,640.0</td>
<td>125,712.0</td>
<td>7,438</td>
</tr>
<tr>
<td></td>
<td>IBM POWER9 22C 3.1GHz,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</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>
</tr>
<tr>
<td></td>
<td>Sunway MPP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Tianhe-2A China TH-IVB-FEP Cluster</td>
<td>4,981,760</td>
<td>61,444.5</td>
<td>100,678.7</td>
<td>18,482</td>
</tr>
<tr>
<td>5</td>
<td>Piz Daint Switzerland</td>
<td>387,872</td>
<td>21,230.0</td>
<td>27,154.3</td>
<td>2,384</td>
</tr>
<tr>
<td></td>
<td>Cray XC50, Xeon E5-2690v3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

https://www.top500.org/list/2018/11/
## Top 5 Super Computers Worldwide, Nov 2019

<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>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Summit, United States</td>
<td>2,397,824</td>
<td>143,500.0</td>
<td>200,794.9</td>
<td>9,783</td>
</tr>
<tr>
<td></td>
<td>IBM POWER9 22C 3.07GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Sierra, United States</td>
<td>1,572,480</td>
<td>94,640.0</td>
<td>125,712.0</td>
<td>7,438</td>
</tr>
<tr>
<td></td>
<td>IBM POWER9 22C 3.1GHz,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</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>
</tr>
<tr>
<td></td>
<td>Sunway MPP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Tianhe-2A, China</td>
<td>4,981,760</td>
<td>61,444.5</td>
<td>100,678.7</td>
<td>18,482</td>
</tr>
<tr>
<td></td>
<td>Xeon 2.2GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Frontera, United States</td>
<td>448,448</td>
<td>23,516.4</td>
<td>38,745.9</td>
<td>??</td>
</tr>
<tr>
<td></td>
<td>Dell 6420, Xeons 2.7GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[https://www.top500.org/list/2019/11/](https://www.top500.org/list/2019/11/)
## Top 5 Super Computers Worldwide, Jun 2020

<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>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fugaku, Japan / Fujitsu Fujitsu A64FX 2.2GhZ (Arm)</td>
<td>7,299,072</td>
<td>415,530.0</td>
<td>513,854.7</td>
<td>28,335</td>
</tr>
<tr>
<td>2</td>
<td>Summit United States IBM POWER9 22C 3.07GHz (Power)</td>
<td>2,397,824</td>
<td>143,500.0</td>
<td>200,794.9</td>
<td>10,096</td>
</tr>
<tr>
<td>3</td>
<td>Sierra United States IBM POWER9 22C 3.1GHz (Power)</td>
<td>1,572,480</td>
<td>94,640.0</td>
<td>125,712.0</td>
<td>7,438</td>
</tr>
<tr>
<td>4</td>
<td>Sunway TaihuLight China Sunway SW26010 (custom RISC)</td>
<td>10,649,600</td>
<td>93,014.6</td>
<td>125,435.9</td>
<td>15,371</td>
</tr>
<tr>
<td>5</td>
<td>Tianhe-2A China Intel Xeon 2.2GHz (x86-64)</td>
<td>4,981,760</td>
<td>61,444.5</td>
<td>100,678.7</td>
<td>18,482</td>
</tr>
</tbody>
</table>

[https://www.top500.org/lists/top500/2020/06/](https://www.top500.org/lists/top500/2020/06/)