

CMSC216: Binary Floating Point Numbers

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*Last Updated:
Tue Oct 1 09:12:57 AM EDT 2024*

Logistics

Reading Bryant/O'Hallaron

- ▶ Ch 2.1-3: Integers
- ▶ Ch 2.4-5: Floats (Optional)
- ▶ [2021 Quick Guide to GDB](#)

Goals

- ▶ Finish Ints / Bitwise Ops
- ▶ Briefly: Floating Point layout
- ▶ Thu: Assembly

Grading on Exam 1 / Project 1 ongoing, release grades towards end of week

Assignments

- ▶ Lab05: Bits and GDB
- ▶ HW05: Assembly Intro
- ▶ Project 2: Bitwise Ops, GDB, C Application

P2 will go up within the next day

Announcements

Midterm Feedback Survey

- ▶ Available on Canvas; Anonymous Feedback
- ▶ Worth 1 Full Engagement Point (like labs)
- ▶ Due 11:59pm Wed 02-Oct

Exam 1 Makeup

- ▶ Prof K has emailed all students with permission to make up exam 1 about scheduling
- ▶ If you expected to take the makeup exam and have not heard from Prof K **email him ASAP**

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

Note on Float Coverage

- ▶ Floating point layout is complex and interesting but...
- ▶ It's not a core topic that will appear on any exams, only tangentially on assignments
- ▶ Our coverage will be brief, examine slides / textbook if you want more depth
- ▶ **GOAL:** Demonstrate that (1) Real numbers can be approximated and (2) doing so uses bits in a very different way than integer representations

Parts of a Fractional Number

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

$$\begin{aligned} 123.406_{10} &= 1 \times 10^2 + 2 \times 10^1 + 3 \times 10^0 + & 123 &= 100 + 20 + 3 \\ &4 \times 10^{-1} + 0 \times 10^{-2} + 6 \times 10^{-3} & 0.406 &= \frac{4}{10} + \frac{6}{1000} \\ & & & \\ &= 123.406_{10} & & \end{aligned}$$

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

$$\begin{aligned} 110.101_2 &= 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 + & 6 &= 4 + 2 \\ &1 \times 2^{-1} + 0 \times 2^{-2} + 1 \times 2^{-3} & 0.625 &= \frac{1}{2} + \frac{1}{8} \\ & & & \\ &= 6.625_{10} & & \end{aligned}$$

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

Standard	Scientific	<code>printf("%.4e",x);</code>
123.456	1.23456×10^2	1.2346e+02
50.01	5.001×10^1	5.0010e+01
3.14159	3.14159×10^0	3.1416e+00
0.54321	5.4321×10^{-1}	5.4321e-01
0.00789	7.89×10^{-3}	7.8900e-03

- ▶ **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 f1 = -248.75;
```

$$\begin{aligned} & \qquad \qquad \qquad 7 \ 6 \ 5 \ 4 \ 3 \ 2 \ 1 \ 0 \quad -1 \ -2 \\ -248.75 &= -(128+64+32+16+8+0+0+0) \cdot (1/2+1/4) \\ &= -11111000.11 \cdot 2^0 \\ & \qquad \qquad \qquad 76543210 \ 12 \\ &= -1111100.011 \cdot 2^1 \\ & \qquad \qquad \qquad 6543210 \ 123 \\ &= -111110.0011 \cdot 2^2 \\ & \qquad \qquad \qquad 543210 \ 1234 \\ & \qquad \qquad \dots \\ & \qquad \qquad \text{MANTISSA} \quad \text{EXPONENT} \\ &= -1.111100011 \cdot 2^7 \\ & \qquad \qquad \qquad 0 \ 123456789 \end{aligned}$$

Mantissa \equiv Significand \equiv Fractional Part

Principle and Practice of Binary Floating Point Numbers

- ▶ 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 significand¹
 - ▶ IBM: 32 bits, 1-bit sign, 7-bit exponent, 24-bit significand²
- ▶ 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

¹Floating Point Arithmetic

²IBM Hexadecimal Floats

IEEE 754 Format: *The Standard for Floating Point*

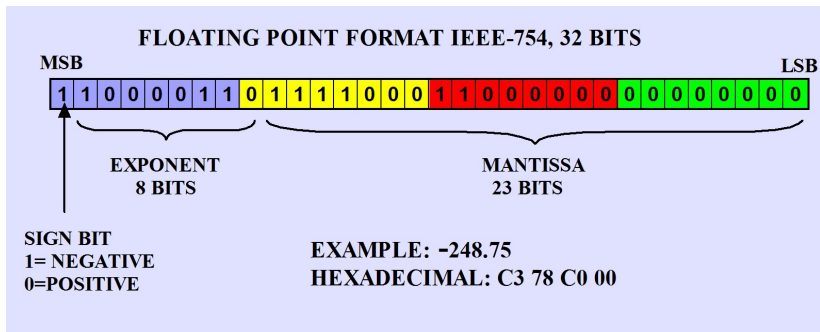
float	double	Property
32	64	Total bits
1	1	Bits for sign (1 neg / 0 pos)
8	11	Bits for Exponent multiplier (power of 2)
23	52	Bits for Fractional part or mantissa
7.22	15.95	Decimal digits of accuracy ³

- ▶ 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

Category	Description	Exponent
Normalized	most common like 1.0 and $-9.56e37$	mixed 0/1
Denormalized	very close to zero and 0.0	all 0's
Special	extreme/error values like Inf and NaN	all 1's

³[Wikipedia: IEEE 754](#)

Example float Layout of -248.75: float_examples.c



Source: IEEE-754 Tutorial, www.puntoflotante.net

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

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

$$\begin{aligned} & 1000_0110 - 0111_1111 \\ &= 128+4+2 - 127 \\ &= 134 - 127 \\ &= 7 \end{aligned}$$

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

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

Kind	Sign Bit	Exponent Bits	Bias	Exp Range	Mantissa Bits
float	31 (1)	30-23 (8 bits)	-127	-126 to +127	22-0 (23 bits)
double	63 (1)	62-52 (11 bits)	-1023	-1022 to +1023	51-0 (52 bits)

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

Consequences of Fixed Bits

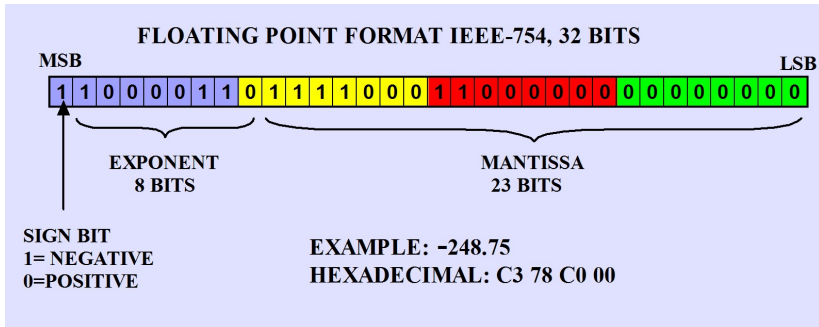
- ▶ Since a fixed # of bit is used, **some numbers cannot be exactly represented**, happens in any numbering system:
- ▶ Base 10 and Base 2 cannot represent $\frac{1}{3}$ in finite digits
- ▶ Base 2 cannot represent $\frac{1}{10}$ in finite digits

```
float 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?



Source: IEEE-754 Tutorial, www.puntoflotante.net

The diagram above may help in recalling IEEE 754 layout

Special Cases: See `float_examples.c`

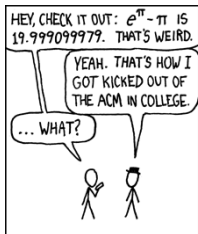
Special Values

- ▶ **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*);

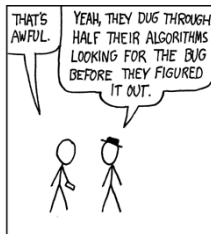
Other Float Notes



DURING A COMPETITION, I TOLD THE PROGRAMMERS ON OUR TEAM THAT $e^\pi - \pi$ WAS A STANDARD TEST OF FLOATING-POINT HANDLERS -- IT WOULD COME OUT TO 20 UNLESS THEY HAD ROUNDING ERRORS.



Source: XKCD #217



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

```
// union.c
typedef union { // shared memory
    float fl;    // float 4 bytes
    int in;     // int 4 bytes
    char ch[4]; // array 4 bytes
} flint_t;      // 4 bytes total (!!)
// all fields are in the same memory
// so max of (4,4,4) rather than sum

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);
    }
}
```

Symbol	Mem	Val
flint.ch[3]	#1027	0xC3
flint.ch[2]	#1026	0x78
flint.ch[1]	#1025	0xC0
flint.in/fl/ch[0]	#1024	0x00
i	#1020	?

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, June 2023

Rank	System	#Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power* (kW)
1	Frontier, <i>USA / Oak Ridge</i> Cray EX235a, AMD EPYC 2GHz (x86-64)	8,699,904	1,194.00	1,679.82	22,703
2	Fugaku, <i>Japan / Fujitsu</i> Fujitsu A64FX 2.2GHz (Arm)	7,630,848	442,010.0	537.21	29,899
3	LUMI <i>Finland / EuroHPC</i> Cray EX235a, AMD EPYC 2GHz (x86-64)	2,220,288	309.10	428.70	6,016
4	Leonardo <i>Italy / EuroHPC</i>	1,824,768	238.70	304.47	7,404
5	Summit <i>United States</i> IBM POWER9 22C 3.07GHz (Power)	2,414,592	148,600.0	200,794.9	10,096

<https://www.top500.org/lists/top500/2022/06/>

*: An average US Home uses 909 kWh of power per month

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2	Fugaku, Japan / Fujitsu Fujitsu A64FX 2.2GHz (Arm)	7,630,848	442,010.0	537,212.0	29,899
3	LUMI Finland / EuroHPC Cray EX235a, AMD EPYC 2GHz (x86-64)	1,110,144	151.90	214.35	2,942
4	Summit United States IBM POWER9 22C 3.07GHz (Power)	2,414,592	148,600.0	200,794.9	10,096
5	Sierra United States IBM POWER9 22C 3.1GHz (Power)	1,572,480	94,640.0	125,712.0	7,438

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2	Summit <i>United States</i> IBM POWER9 22C 3.07GHz (Power)	2,414,592	148,600.0	200,794.9	10,096
3	Sierra <i>United States</i> IBM POWER9 22C 3.1GHz (Power)	1,572,480	94,640.0	125,712.0	7,438
4	Sunway TaihuLight <i>China</i> Sunway SW26010 (custom RISC)	10,649,600	93,014.6	125,435.9	15,371
5	Perlmutter, <i>United States</i> AMD EPYC 2.45GHz, Cray (x86-64)	706,304	64,590.0	89,794.5	2,528

<https://www.top500.org/lists/top500/2021/06/>

Top 5 Super Computers Worldwide, Nov 2020

Rank	System	#Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	Fugaku, <i>Japan / Fujitsu</i> Fujitsu A64FX 2.2GHz (Arm)	7,299,072	415,530.0	513,854.7	28,335
2	Summit <i>United States</i> IBM POWER9 22C 3.07GHz (Power)	2,397,824	143,500.0	200,794.9	10,096
3	Sierra <i>United States</i> IBM POWER9 22C 3.1GHz (Power)	1,572,480	94,640.0	125,712.0	7,438
4	Sunway TaihuLight <i>China</i> Sunway SW26010 (custom RISC)	10,649,600	93,014.6	125,435.9	15,371
5	Selene <i>USA, NVIDIA/AMD</i> AMD EPYC 7742 64C 2.25GHz (x86-64)	555,520	63,460.0	79,215.0	2,646

<https://www.top500.org/lists/top500/2020/06/>

Top 5 Super Computers Worldwide, June 2020

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

<https://www.top500.org/lists/top500/2020/06/>

Top 5 Super Computers Worldwide, Nov 2019

Rank	System	#Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	Summit <i>United States</i> IBM POWER9 22C 3.07GHz	2,397,824	143,500.0	200,794.9	9,783
2	Sierra <i>United States</i> IBM POWER9 22C 3.1GHz,	1,572,480	94,640.0	125,712.0	7,438
3	Sunway TaihuLight <i>China</i> Sunway MPP	10,649,600	93,014.6	125,435.9	15,371
4	Tianhe-2A <i>China</i> Xeon 2.2GHz	4,981,760	61,444.5	100,678.7	18,482
5	Frontera, <i>United States</i> Dell 6420, Xeons 2.7GHz	448,448	23,516.4	38,745.9	??

<https://www.top500.org/list/2019/11/>

Top 5 Super Computers Worldwide, Nov 2018

Rank	System	#Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	Summit <i>United States</i> IBM POWER9 22C 3.07GHz	2,397,824	143,500.0	200,794.9	9,783
2	Sierra <i>United States</i> IBM POWER9 22C 3.1GHz,	1,572,480	94,640.0	125,712.0	7,438
3	Sunway TaihuLight <i>China</i> Sunway MPP	10,649,600	93,014.6	125,435.9	15,371
4	Tianhe-2A <i>China</i> TH-IVB-FEP Cluster	4,981,760	61,444.5	100,678.7	18,482
5	Piz Daint <i>Switzerland</i> Cray XC50, Xeon E5-2690v3	387,872	21,230.0	27,154.3	2,384

<https://www.top500.org/list/2018/11/>

Top 5 Super Computers Worldwide, Nov 2017

Rank	System	#Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	Sunway TaihuLight <i>China</i> Sunway MPP	10,649,600	93,014.6	125,435.9	15,371
2	Tianhe-2 (MilkyWay-2) <i>China</i> TH-IVB-FEP Cluster	3,120,000	33,862.7	54,902.4	17,808
3	Piz Daint <i>Switzerland</i> Cray XC50	361,760	19,590.0	25,326.3	2,272
4	Gyokou <i>Japan</i> ZettaScaler-2.2 HPC system	19,860,000	19,135.8	28,192.0	1,350
5	Titan <i>USA</i> Cray XK7	560,640	17,590.0	27,112.5	8,209

<https://www.top500.org/lists/2017/11/>