

# Floating Point Arithmetic is not Real



**Tim Mattson**

git clone <https://github.com/tgmattso/Princeton2025.git>

Acknowledgements: I borrowed some content from lectures on floating point arithmetic by Ianna Osborne and Wahid Redjeb.

# Should we trust computer arithmetic?

*Sleipner Oil Rig Collapse (8/23/91). Loss: \$700 million.*



\$1.6 Billion in  
2024 dollars

See <http://www.ima.umn.edu/~arnold/disasters/sleipner.html>

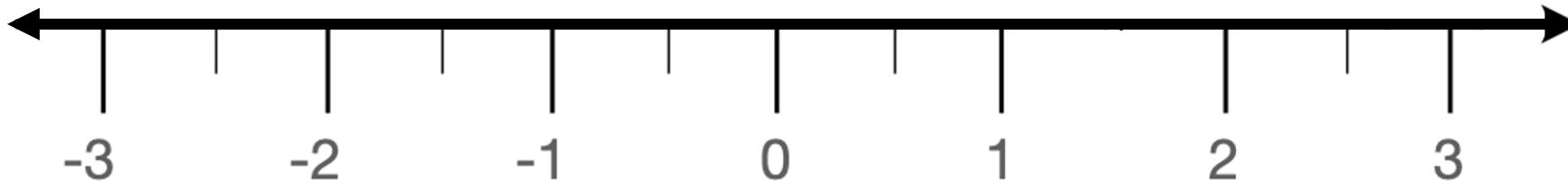
Linear elastic model using NASTRAN underestimated shear stresses by 47% resulted in concrete walls that were too thin.

NASTRAN is the world's most widely used finite element code ... in heavy use since 1968

# Outline

- ➡ • Numbers for humans.    Numbers for computers
- Finite precision, floating point numbers
  - General case
  - IEEE 754 floating point standard
- Working with IEEE 754 floating point arithmetic
  - Addition
  - Subtraction
  - Rounding
  - Algebraic Properties of Floating Point Arithmetic
- Wrap-up/Conclusion

# Numbers for Humans

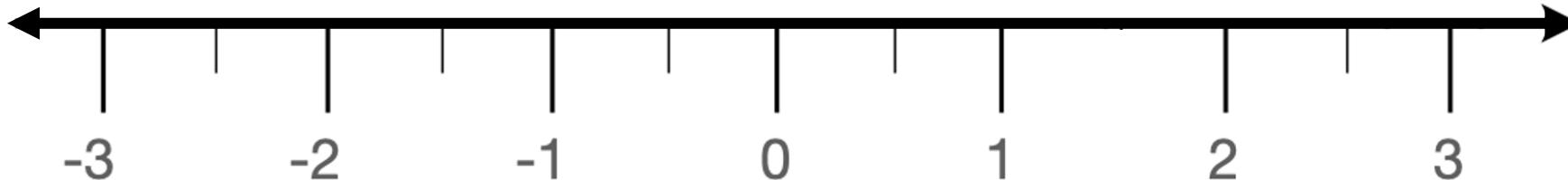


$\mathbb{R}$

**Real Numbers:** viewed as points on a line ... pairs of real numbers can be arbitrarily close

# Numbers for Humans

## Arithmetic over Real Numbers



$\mathbb{R}$

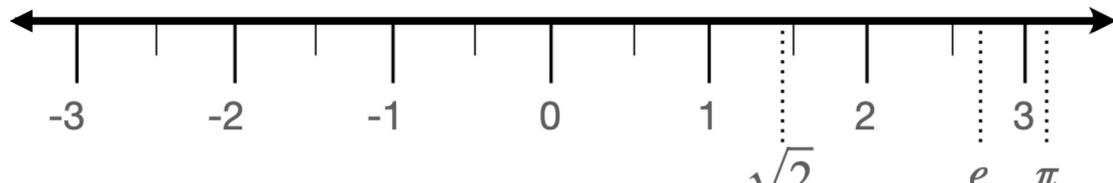
For the arithmetic operators, real numbers define a **closed set** ... for well defined operations and any input real numbers, the arithmetic operation returns a real number.

A few key properties of Real Arithmetic:

- **Commutative over addition and multiplication:**  $(a+b) = (b+a)$        $a*b = b*a$
- **Associative:**       $(a+b)+c = a+(b+c)$        $(a*b)*c = a*(b*c)$
- **Multiplication distributes over addition:**       $c * (a+b) = c*a + c*b$

# Numbers for Humans

People use many different kinds of numbers

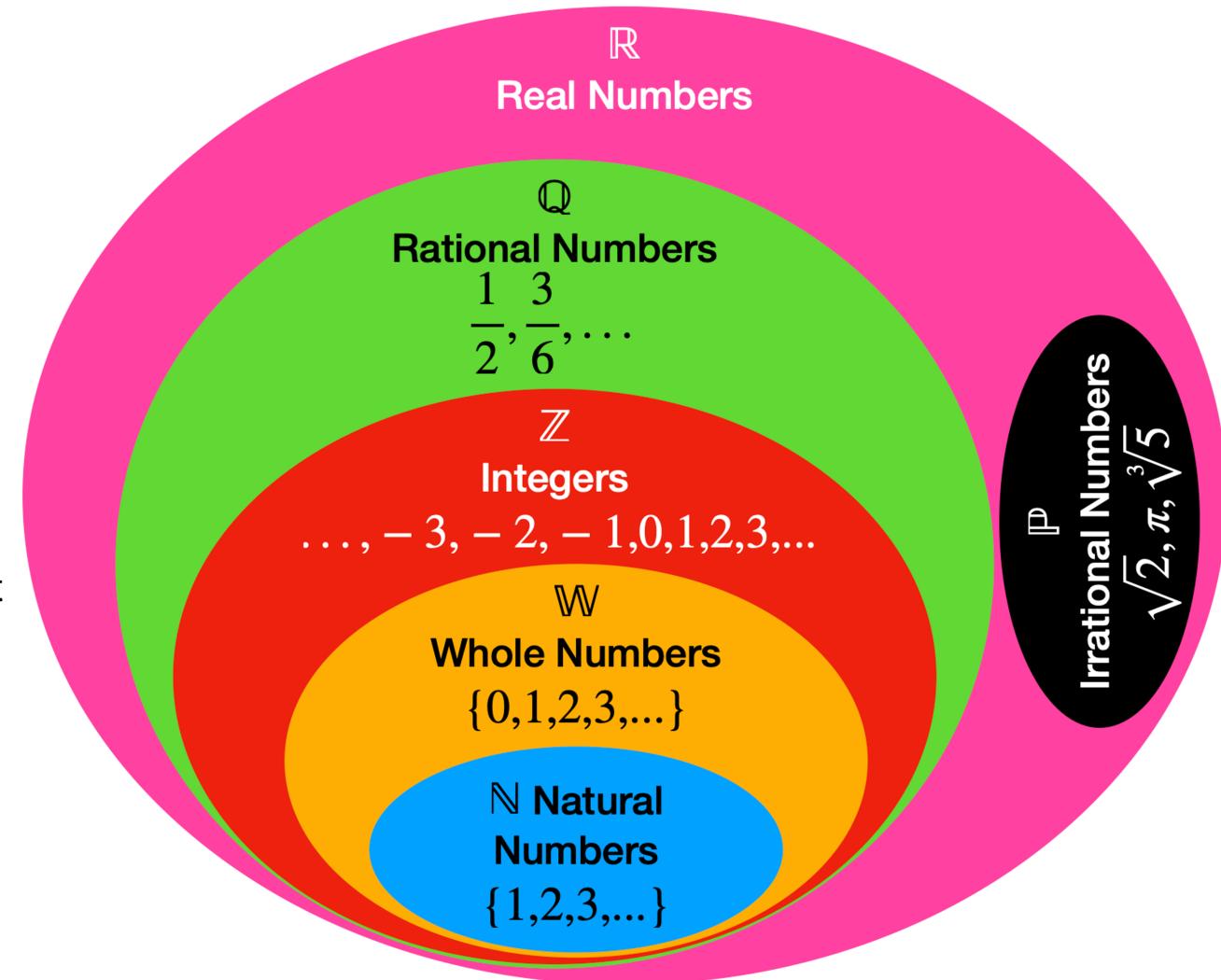


$\mathbb{R}$

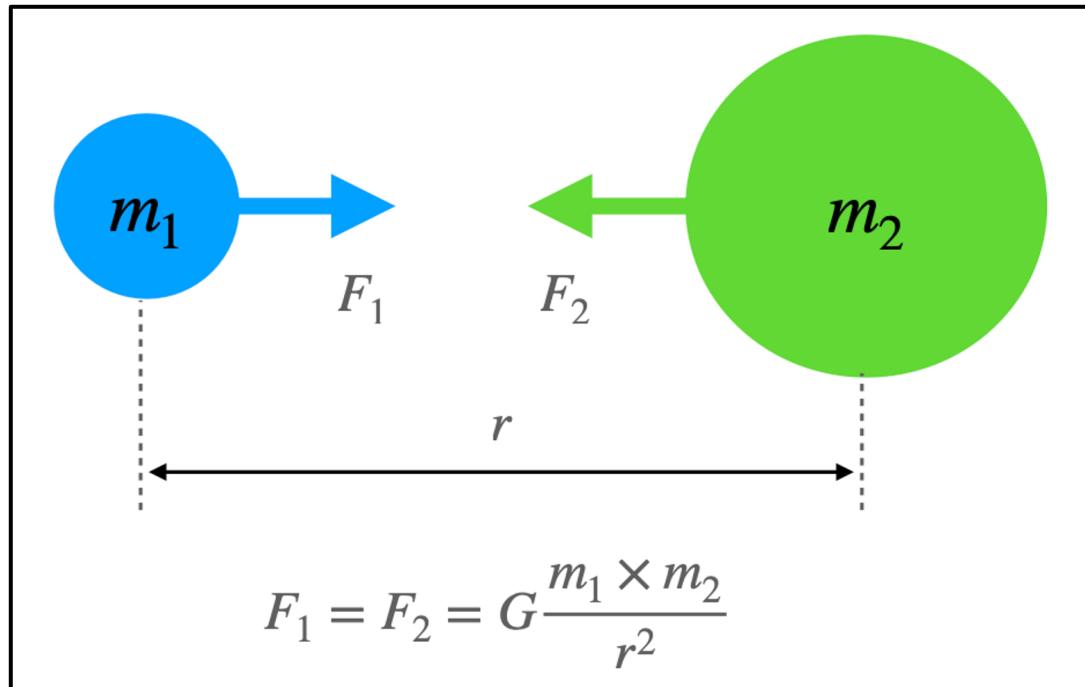
We are used to thinking of different kinds of numbers contained within the set of real numbers

- **Integers:** equally spaced numbers without a fractional part
- **Rational numbers:** Ratios of integers
- **Whole numbers:** Positive integers and zero
- **Natural numbers:** Positive integers and not zero
- **Irrational numbers:** numbers that cannot be represented as a ratio of integers

The numbers on a computer are just another set of numbers embedded in the set of real numbers



# Numbers for Humans: Example



$$G \approx 0.0000000006674 \frac{m^3}{kg * s^2}$$

Scientific Notation

$$0.0000000006674 \longrightarrow 6.674 \times 10^{-11}$$

The exponent tells us how far to “float” the decimal point.

*significand      exponent*

$$G \approx 6.674 \times 10^{-11} \text{ m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}$$

*radix*

# Numbers for Humans

## How do we represent Real Numbers?

$$G \approx \underset{\text{significand}}{6.674} \times \underset{\text{radix}}{10^{-11}} \underset{\text{exponent}}{\text{m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}}$$

$$G \approx (6 \cdot 10^0 + 6 \cdot 10^{-1} + 7 \cdot 10^{-2} + 4 \cdot 10^{-3}) \cdot 10^{-11}$$

---

We can generalize the above to any real number as ...

$$x = (-1)^{\text{sign}} \sum_{i=0}^{\infty} d_i \underset{\text{radix}}{b}^{-i} \underset{\text{exp}}{b}^{\text{exp}} \quad \dots \text{ where } \underset{\text{radix}}{b} \text{ is the radix}$$

$$\text{sign} \in \{0,1\}, \quad b \geq 2, \quad d_i \in \{0, \dots, (b-1)\}, \quad d_0 > 0 \text{ when } x \neq 0, \quad \underset{\text{radix}}{b}, i, \text{exp} \in [\text{integer}]$$

# Numbers for Humans

## How do we represent Real Numbers?

$$G \approx 6.674 \times 10^{-11} \text{ m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}$$

*significand*      *exponent*  
*radix*

What about numbers  
for computers?

$$G \approx (6 \cdot 10^0 + 6 \cdot 10^{-1} + 7 \cdot 10^{-2} + 4 \cdot 10^{-3}) \cdot 10^{-11}$$

---

We can generalize the above to any real number as ...

$$x = (-1)^{\text{sign}} \sum_{i=0}^{\infty} d_i b^{-i} b^{\text{exp}}$$

Human's deal nicely with  $\infty$ .  
Computers do not.

$$\text{sign} \in \{0,1\}, \quad b \geq 2, \quad d_i \in \{0, \dots, (b-1)\}, \quad d_0 > 0 \text{ when } x \neq 0, \quad b, i, \text{exp} \in [\text{integer}]$$

Humans like a radix = 10.  
Which radix is best for a computer?

# Numbers for Computers

Computers work with a restricted subset of real numbers...

$$x = (-1)^{\text{sign}} \sum_{i=0}^N d_i b^{-i} b^{\text{exp}}$$

$\text{sign} \in \{0,1\}$ ,     $b \geq 2$ ,     $d_i \in \{0, \dots, (b-1)\}$ ,     $d_0 > 0 \text{ when } x \neq 0$ ,     $b, i, \text{exp} \in [\text{integer}]$

Finite precision ... restricted to N digits.

N is tied to the length of a “word” in a computer’s architecture. This is typically the width of the registers in a microprocessor’s register file.

Which radix (b) is best for a computer?

Binary has  $d_i \in \{0,1\}$ . Naturally maps onto representation as transistors used to implement computer logic.

Decimal has  $d_i \in \{0, \dots, 9\}$ . Requires four bits per digit ... which wastes space (since four bits can encode  $\{0, \dots, 15\}$ ).

# Exercise: Playing with “numbers for computers”

- You are a software engineer working on a device that tracks objects in time and space.
- The device increments time in “clock ticks” of 0.01 seconds.
- Write a program that tracks time by **accumulating N clock-ticks**. N is typically large ... around 100 thousand. Output from the function is elapsed seconds expressed as a float.
  - Assume you are working with an embedded processor that does not support the type double.
  - This is part of an interrupt driven, real time system, hence track “time” not “number of ticks” since this time may be needed at any moment.
- What does your program generate for large N?

# Accumulating clock ticks (0.01): Solution

```
#include <stdio.h>
#define time_step 0.01f

float CountTime(int Count)
{
    float sum = 0.0f;

    for (int i=0; i<Count;i++)
        sum += time_step;

    return sum;
}

int main()
{
    int Count = 500000;
    float time_val;

    time_val = CountTime(Count);
    printf(" sum = %f or %f\n",time_val,time_step*Count);
}
```

```
% gcc -O0 hundredth.c
% ./a.out
sum = 4982.411132. or 5000.000000
%
```

# Why did summing 0.01 fail?

I saw this slogan on  
a T-shirt years ago



# Converting a decimal number (0.01) to fixed point binary

0.01 is equal to  $\frac{1}{100}$ .

The fraction $\frac{1}{2^N}$ nearest but less than or equal to $\frac{1}{100}$ is $\frac{1}{128}$ (N=7)	$0.01_{10} \approx 0.0000001_2$
The remainder $\frac{1}{100} - \frac{1}{128} = \frac{7}{3200} \approx \frac{1}{457}$ . The fraction $\frac{1}{2^N}$ nearest but less than or equal to this remainder is $\frac{1}{512}$ (N=9)	$0.01_{10} \approx 0.000000101_2$
The remainder $\frac{7}{3200} - \frac{1}{512} = \frac{3}{12800} \approx \frac{1}{4266}$ . The fraction $\frac{1}{2^N}$ nearest but less than or equal to this remainder is $\frac{1}{8196}$ (N=13)	$0.01_{10} \approx 0.0000001010001_2$

- Continuing to 32 bits we get 0.0000001010001110101110000101000... but it's still not done.
- The denominator of the number 1/100 includes a relative prime (5) to the radix of binary numbers (2). Hence, there is no way to exactly represent 1/100 in binary!

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
$\frac{1}{2^N}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{1}{64}$	$\frac{1}{128}$	$\frac{1}{256}$	$\frac{1}{512}$	$\frac{1}{1024}$	$\frac{1}{2048}$	$\frac{1}{4096}$	$\frac{1}{8196}$	$\frac{1}{16384}$	$\frac{1}{32768}$	$\frac{1}{65536}$	$\frac{1}{131072}$

# Real numbers on a computer are represented as finite precision numbers

- **Conclusion:** Not all decimal numbers have an exact representation as binary numbers.
  - You can have computations where the answer does NOT have an exact binary representation ... in other words, **fixed precision arithmetic is NOT a closed set.**

```
float c, b = 1000.2f;  
c = b - 1000.0;  
printf ("%f", c);
```

Output: 0.200012

- The best we can hope for is that the computer does the computation “exactly” then rounds to the nearest binary number.

# Real numbers on a computer are represented as finite precision numbers

- **Conclusion:** Many decimal numbers do not have an exact representation as binary numbers.
  - You can have computations where the answer does NOT have an exact binary representation ... in other words, **fixed precision arithmetic is NOT a closed set.**

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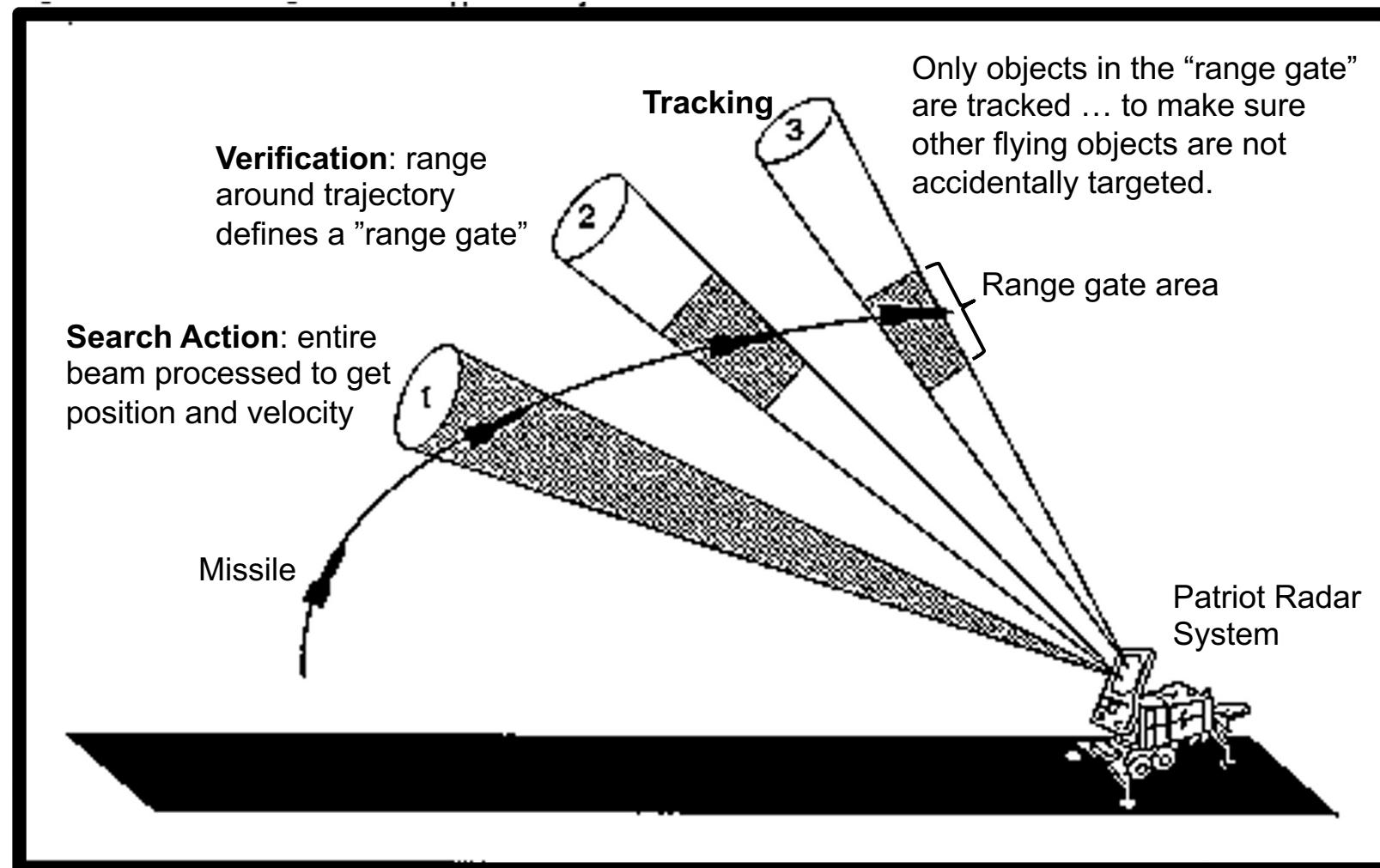
# Patriot Missile system

*Patriot missile incident (2/25/91) . Failed to stop a scud missile from hitting a barracks,*



# Patriot missile system: how it works

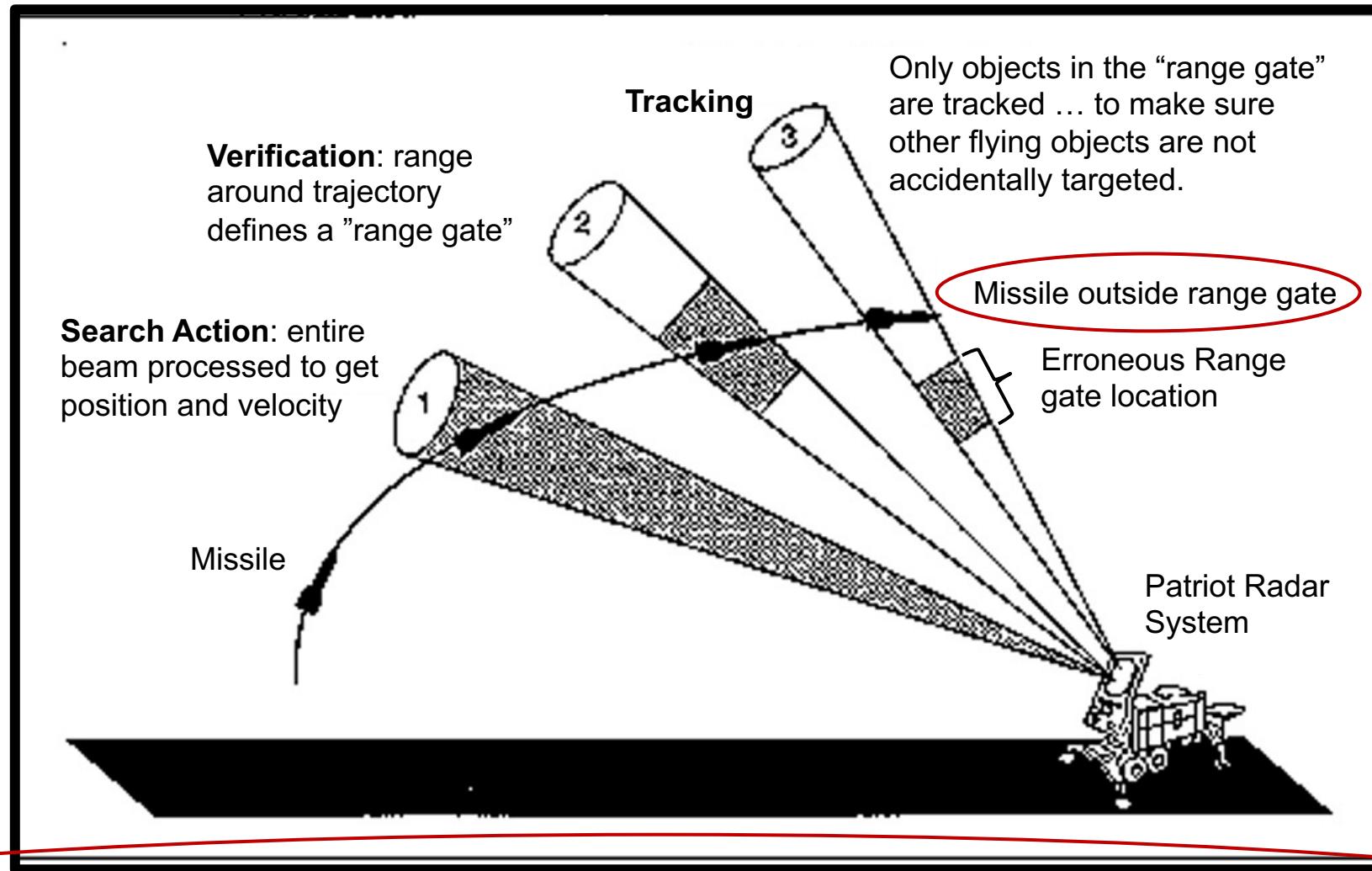
Incoming object detected as an enemy missile due to properties of the trajectory. Velocity and position from Radar fixes trajectory



24 bit clock counter defines time. Range calculations defined by real arithmetic, so convert to floating point numbers.

# Patriot missile system: Disaster Strikes

Incoming object detected as an enemy missile due to properties of the trajectory. Velocity and position from Radar fixes trajectory



28  
soldiers  
killed

Accumulating clock-ticks (int) by the float representation of 0.1 led to an error of 0.3433 seconds after 100 hours of operation which, when you are trying to hit a missile moving at Mach 5, corresponds to an error of 687 meters

# Exercise: Playing with “numbers for computers”

- You are a software engineer working on a device that tracks objects in time and space.
- The device increments time in “clock ticks” of 0.01 seconds. **Propose (and test) a value for the clock tick that makes the program work.**
- Write a program that tracks time by **accumulating N clock-ticks**. N is typically large ... around 100 thousand. Output from the function is elapsed seconds expressed as a float.
  - Assume you are working with an embedded processor that does not support the type double.
  - This is part of an interrupt driven, real time system, hence track “time” not “number of ticks” since this time may be needed at any moment.
- What does your program generate for large N?

# Exercise: Playing with “numbers for computers”

- You are a software engineer working on a device that tracks objects in time and space.
- The device increments time in “clock ticks” of 0.01 seconds. **Propose (and test) a value for the clock tick that makes the program work.**
- Write a C program that does the following:
  - Assume you are working with an embedded processor that does not support the type `double`.
  - This is part of an interrupt driven, real time system, hence track “time” not “number of ticks” since this time may be needed at any moment.
- What does your program generate for large N?

# Floating Point Numbers are not Real: Lessons Learned

Real Numbers	Floating Point numbers
Any number can be represented ... real numbers are a closed set	Not all numbers can be represented ... operations can produce numbers that cannot be represented ... that is, floating point numbers are NOT a closed set

# Outline

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  - IEEE 754 floating point standard
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# Floating-point Arithmetic Timeline

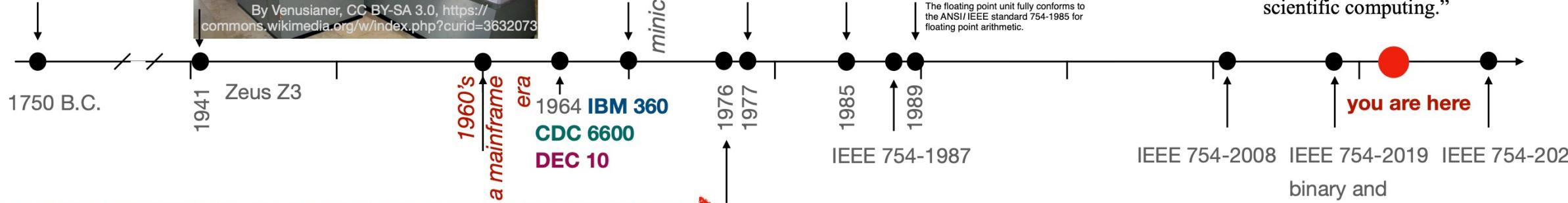
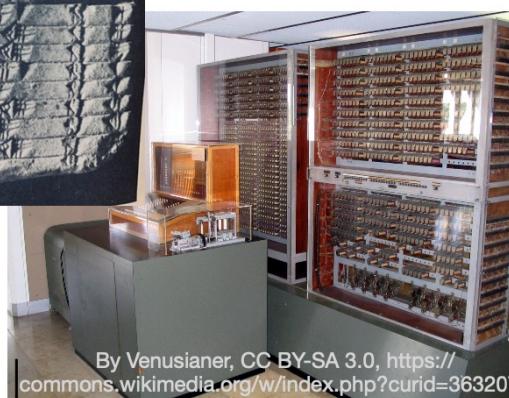
“...the next generation of application programmers and error analysts will face new challenges and have new requirements for standardization. Good luck to them!”

[https://grouper.ieee.org/groups/msc/ANSI\\_IEEE-Std-754-2019/background/ieee-computer.pdf](https://grouper.ieee.org/groups/msc/ANSI_IEEE-Std-754-2019/background/ieee-computer.pdf)



Babylonians worked with floating-point sexagesimal numbers

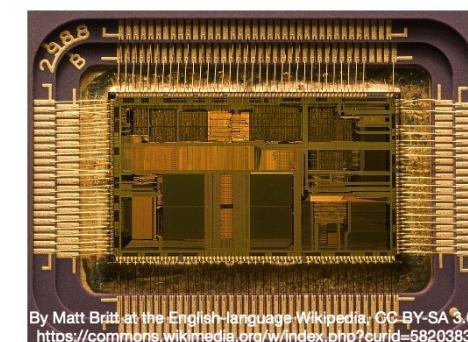
- Average calculation speed: addition – 0.8 seconds, multiplication – 3 seconds<sup>[1]</sup>
- Arithmetic unit: Binary floating-point, 22-bit, add, subtract, multiply, divide, square root<sup>[1]</sup>



- each hardware manufacturer had its own type of floating point
- different machines from the same manufacturer might have different types of floating point
- when floating point was not supported in the hardware, the different compilers emulated different floating point types

Intel began to design a floating-point co-processor for its i8086/8 and i432 microprocessors

Source: Ianna Osborne, CoDaS-HEP, July 19, 2023



The floating point unit fully conforms to the ANSI/IEEE standard 754-1985 for floating point arithmetic.

“new kinds of computational demands might eventually encompass new kinds of standards, particularly for fields like artificial intelligence, machine vision and speech recognition, and machine learning. Some of these fields obtain greater accuracy by processing more data faster rather than by computing with more precision – rather different constraints from those for traditional scientific computing.”

binary and decimal floating-point arithmetic

subjected to review at least every 10 years

# Floating-point Arithmetic Timeline

“...the next generation of application programmers and error analysts will face new challenges and have new requirements for standardization. Good luck to them!”

[https://grouper.ieee.org/groups/msc/ANSI\\_IEEE-Std-754-2019/background/ieee-computer.pdf](https://grouper.ieee.org/groups/msc/ANSI_IEEE-Std-754-2019/background/ieee-computer.pdf)



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By Venusianer, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=36320>

The concept of floating point numbers is very old (1750 BC)

heating point  
chaos

manufacturer had its own types from the same manufacturer point

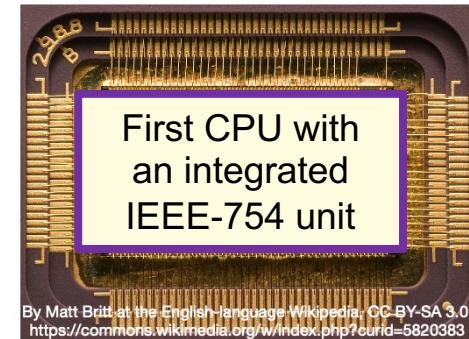
int was not supported in the hardware, the different floating point types

1970's

IEEE-754  
floating point is  
born ... thanks  
to a team led  
by William  
Kahan

Intel 80486

the first tightly-pipelined<sup>[6]</sup> x86 design as well as the first x86 chip to include more than one million transistors. It offered a large on-chip cache and an integrated floating-point unit.



By Matt Britt at the English-language Wikipedia, CC BY-SA 3.0,  
<https://commons.wikimedia.org/w/index.php?curid=5820383>

The floating point unit fully conforms to the ANSI/ IEEE standard 754-1985 for floating point arithmetic.

Intel produces the first chip to support IEEE-754 in 1980 (the 8087 coprocessor)

CoDaS-HEP, July 19, 2023

IEEE-754  
floating point  
continues to  
evolve ... next  
version  
expected in  
2029

## **you are here**

"new kinds of  
might eventual  
kinds of stand  
fields like arti  
machine visio  
recognition, a  
Some of these  
accuracy by p  
faster rather th  
more precision  
constraints fro  
scientific computin.

IEEE-754  
floating point  
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expected in  
2029

## binary and decimal floating-point arithmetic

subjected to review at least every 10 years

# Floating Point Number systems

Computers work with finite precision, floating point numbers ...

$$x = (-1)^{sign} \sum_{i=0}^p d_i b^{-i} b^e = \pm d_0.d_1 \dots d_{p-1} \times b^e$$

$sign \in \{0,1\}$   
 $d_i \in \{0, \dots, (b - 1)\}$   
 $e_{min} \leq e \leq e_{max}$

$b \geq 2$  The radix ... usually 2 or 10 (but occasionally 8 or 16)

$p \geq 1$  The precision ... the number of digits in the significand

$e_{max}$  The largest exponent

$e_{min}$  The smallest exponent (generally  $1 - e_{max}$ )

These four numbers define a unique set of floating point numbers ... written as

$F(b, p, e_{min}, e_{max})$

# Floating Point Number systems: Normalized numbers

Consider representations of the decimal number 0.1

$$1.0 \times 10^{-1}, \quad 0.1 \times 10^0, \quad 0.01 \times 10^1$$

- These are all the same number, just represented differently depending on the choice of exponent.
- That ambiguity is confusing, so we require that  $d_0 \neq 0$  so numbers between  $b^{\min}$  and  $b^{\max}$  have a single unique representation.
- We call these normalized floating point numbers

$$F^*(b, p, e_{\min}, e_{\max})$$

$$x = (-1)^{sign} \sum_{i=0}^p d_i b^{-i} b^e = \pm d_0.1.d_1 \dots d_{p-1} \times b^e$$

$sign \in \{0,1\}$

$d_i \in \{0, \dots, (b - 1)\}$

$d_0 \neq 0$

$e_{\min} \leq e \leq e_{\max}$

- $x = 0$  and  $x < b^{e_{\min}}$  do not have normalized representations.

$b \geq 2$  The radix ... usually 2 or 10 (but occasionally 8 or 16)

$p \geq 1$  The precision ... the number of digits in the significand

$e_{\max}$  The largest exponent

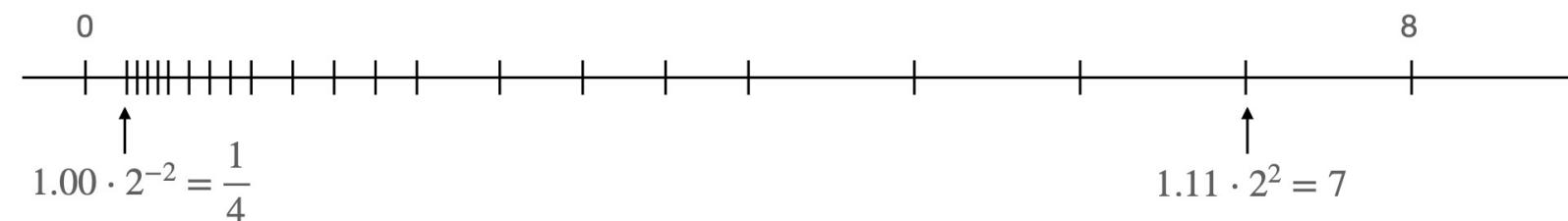
$e_{\min}$  The smallest exponent (generally  $1 - e_{\max}$ )

# Normalized Representation

$$F^*(2,3, -2,2)$$

$d_0 \cdot d_1 d_2$	$e = -2$	$e = -1$	$e = 0$	$e = 1$	$e = 2$
$1.00_2$	0.25	0.5	1	2	4
$1.01_2$	0.3125	0.625	1.25	2.5	5
$1.10_2$	0.375	0.75	1.5	3	6
$1.11_2$	0.4375	0.875	1.75	3.5	7

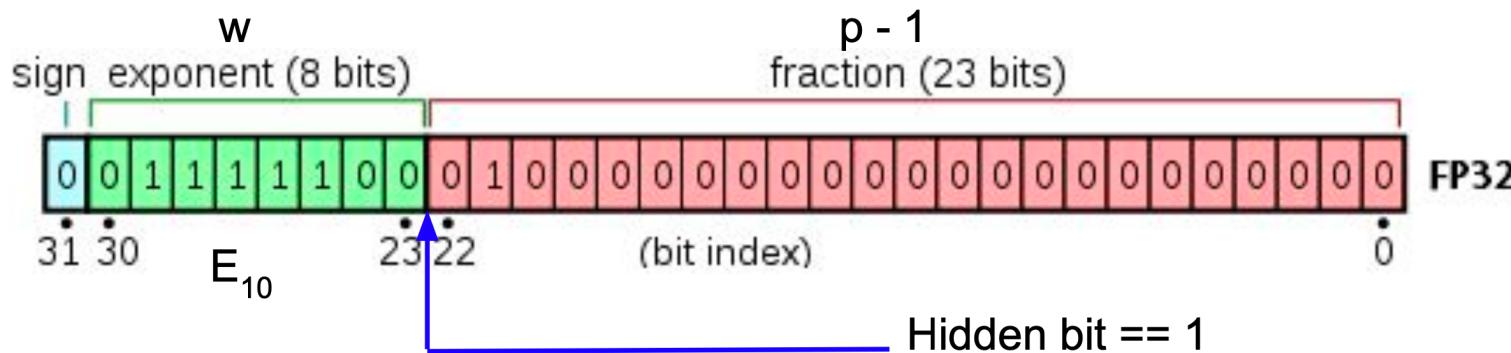
Equivalent decimal values for all patterns of normalized binary digits and exponents



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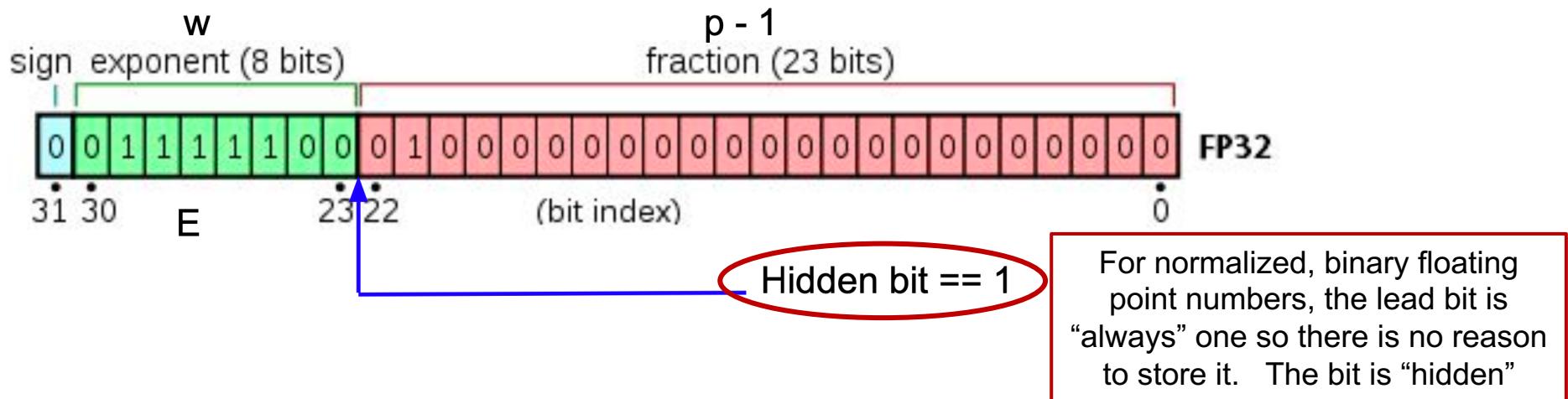
# IEEE 754 Floating Point Numbers



IEEE Name	Precision	N bits	Exponent w	Fraction p	$e_{\min}$	$e_{\max}$
Binary32	Single	32	8	24	-126	+127
Binary64	Double	64	11	53	-1022	+1023
Binary128	Quad	128	15	113	-16382	+16383

- **Exponent:**  $E = e - e_{\min} + 1$ ,  $w$  bits
- $e_{\max} = -e_{\min} + 1$

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# Special values

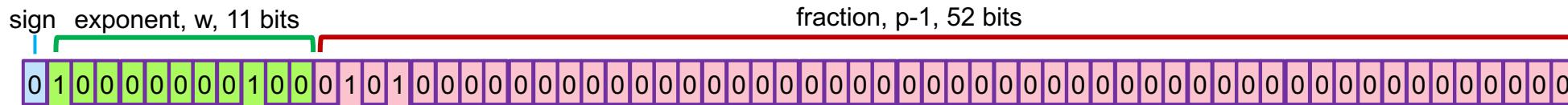
- The IEEE 754 standard defines a number of special values

	<b>The special value</b>	<b>exponent</b>	<b>fraction</b>
Regular normalized floating point numbers.	$1.f \times 2^e$	$e_{min} \leq e \leq e_{max}$	Any pattern of 1's and 0's
Denormalized Numbers ... too small to represent as a normalized number.	$0.f \times 2^{e_{min}}$	All 0's ( $e_{min} - 1$ )	$f \neq 0$
0 and $\infty$ have signs to work with limits	$\pm 0$	All 0's ( $e_{min} - 1$ )	$f = 0$
Not a Number (undefined math such as 0/0).	$\pm \infty$	All 1's ( $e_{max} + 1$ )	$f = 0$
	NaN	All 1's ( $e_{max} + 1$ )	$f \neq 0$

- Typically, we do not test for these cases in code, but they do show up from time to time (especially NaN) so its good to be aware of them.

# Writing IEEE 754 numbers in binary

- The number 42.0 written in binary



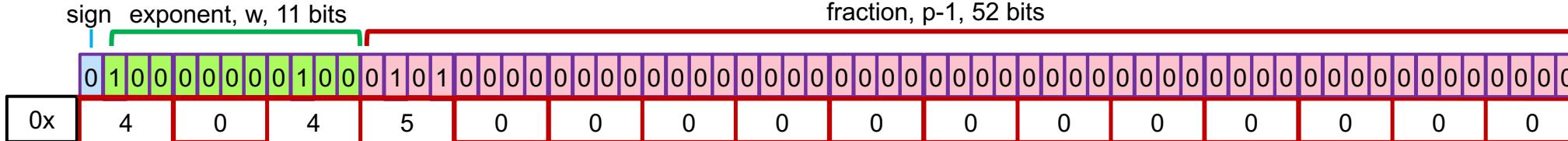
Keeping track of all 64 locations and writing all those zeros is painful

IEEE name	Precision	N bits	Exponent w	Fraction p	$e_{\min}$	$e_{\max}$
Binary 64	double	64	11	53	-1022	1023

## Writing IEEE 754 numbers in binary/hexadecimal

- The number 42.0 written in binary with the equivalent hexadecimal (base 16) form beneath.

## Decimal, hexadecimal, and binary



- It is dramatically easier to write things down in hexadecimal than binary.
  - The following are notable examples of key “numbers” in hexadecimal.

-42	0xC045000000000000
Largest normal	0x7FEFFFFFFFFFFFFF
Smallest normal	0x0010000000000000
Largest subnormal	0x000FFFFFFFFFFFFF
Smallest subnormal	0X0000000000000001

+ zero	0x0000000000000000
-zero	0x8000000000000000
+infinity	0x7FF0000000000000
-infinity	0x8FF0000000000000
NaN	0X7FF-anything but all-zero

IEEE name	Precision	N bits	Exponent w	Fraction p	$e_{min}$	$e_{max}$
Binary 64	double	64	11	53	-1022	1023

NaN: not a number

A normal is a number that can be written in a normalized floating point format

A subnormal is too small to be written as a normalized number ... the exponent would need to be less than  $e_{\min}$ .

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# Addition with floating point numbers

- Lets keep things simple ... we will use  $F^*(10, 3, -2, 2)$
- Find the sum ...  $1.23 \times 10^1 + 3.11 \times 10^{-1}$ 
  - Align smaller number to the exponent of the larger number  
 $0.0311 \times 10^1$
  - Add the two aligned numbers .....

$$\begin{array}{r} 1 . \quad 2 \quad 3 \\ + \quad 0 . \quad 0 \quad 3 \quad 1 \quad 1 \\ \hline 1 . \quad 2 \quad 6 \quad 1 \quad 1 \end{array} \times 10^1$$

- Round to nearest (the default rounding in IEEE 754).

$$1 . \quad 2 \quad 6 \times 10^1$$

**Adding numbers with greatly different magnitudes causes loss of precision**  
(you lose the low order bits from the exact result).

# Exercise: summing numbers

- Compute the finite sum:

$$sum = \sum_{i=1}^N \frac{1.0}{i}$$

- This is a simple loop. Run it forward ( $i=1,N$ ) and backwards ( $i=N,1$ ) for large  $N$  (10000000). Try both double and float
- Are the results different? Why?

```
#include<stdio.h>
int main(){
    float sum=0.0;
    long N = 10000000;

    for(int i= 1;i<N;i++){
        sum += 1.0/(float)i;
    }
    printf(" sum forward = %14.8f\n",sum);

    sum = 0.0;
    for(int i= N-1;i>=1;i--){
        sum += 1.0/(float)i;
    }
    printf(" sum backward = %14.8f\n",sum);
}
```

**float or double**

# Exercise: summing numbers

- Compute the finite sum:

$$sum = \sum_{i=1}^N \frac{1.0}{i}$$

- This is a simple loop. Run it forward ( $i=1,N$ ) and backwards ( $i=N,1$ ) for large  $N$  (10000000). Try both double and float

- Are the results different? Why?

- In the forward direction, the terms in the sum get smaller as you progress. This leads to loss of precision as the smaller terms lates in the summation are added to the much larger accumulated partials sum.
- In the backwards direction, the terms in the sum start small and grow ... so reduced loss of precision adding small numbers to much larger numbers.
- Using double precision eliminated this problem.

```
#include<stdio.h>
int main(){
    float sum=0.0;
    long N = 10000000;

    for(int i= 1;i<N;i++){
        sum += 1.0/(float)i;
    }
    printf(" sum forward = %14.8f\n",sum);

    sum = 0.0;
    for(int i= N-1;i>=1;i--){
        sum += 1.0/(float)i;
    }
    printf(" sum backward = %14.8f\n",sum);
}
```

	double	float
forward	16.695311265857270655	15.40368271
backward	16.695311265859963612	16.68603134

# Floating Point Numbers are not Real: Lessons Learned

Real Numbers	Floating Point numbers
Any number can be represented ... real numbers are a closed set	Not all numbers can be represented ... operations can produce numbers that cannot be represented ... that is, floating point numbers are NOT a closed set
With arbitrary precision, there is no loss of accuracy when adding real numbers	Adding numbers of different sizes can cause loss of low order bits.

# Outline

- Numbers for humans.    Numbers for computers
- Finite precision, floating point numbers
  - General case
  - IEEE 754 floating point standard
- Working with IEEE 754 floating point arithmetic
  - Addition
  - Subtraction
  - Rounding
  - Algebraic Properties of Floating Point Arithmetic
- Wrap-up/Conclusion

# What can go wrong with subtraction? Cancellation

- Consider two numbers ...

3.141592653589793      16 digits of pi

3.14159265358~~5682~~      12 digits of pi

Their difference (in real arithmetic) →      0.0000000000004111       $= 4.111 \times 10^{-12}$

Storage of numbers and difference with float →      0.000000e+00

**Complete loss of accuracy**

Storage of numbers and difference with double →      4.110933815582030e-12

**Partial loss of accuracy**

- The machine epsilon for a double is  $2.22045e-16$ . The above error is large compared to epsilon.

**Subtracting two number of similar magnitude cancels high order bits.**

# Exercise: Implement a Series summation to find e<sup>x</sup>

- A Taylor/Maclaurin series expansion for e<sup>x</sup>

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots = \sum_{n=0}^{\infty} \frac{x^n}{n!}$$

1. Compare to the exp(x) function in math.h for a range of x values **greater than zero**.
  - How do your results compare to the exp(x) library function?
2. Compute e<sup>x</sup> for x<0. Consider small negative to large negative values.
  - Do you continue to match the exp(x) library function?

# Exercise: Implement a Series summation to find $e^x$

- A Taylor/Maclaurin series expansion for  $e^x$

Compare computation of  $e^x$  directly and as  $e^{-x} = 1 / e^x$ .

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots = \sum_{n=0}^{\infty} \frac{x^n}{n!}$$

- The computation of  $x^n$  and  $n!$  are expensive but worse ... they lead to large numbers that could overflow the storage format.
- A better approach is to use the relation:

$$\frac{x^n}{n!} = \frac{x}{n} \bullet \frac{x^{n-1}}{(n-1)!}$$

- Terminating the sum ... obviously you don't want to go to infinity. How do you terminate the sum? A good approach is to end the sum when new terms do not significantly change the sum. Or think about what you did when computing the machine epsilon.

# Solution: Implement a Series summation to find $e^x$

- A Taylor/Maclaurin series expansion for  $e^x$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots = \sum_{n=0}^{\infty} \frac{x^n}{n!}$$

- The computation of  $x^n$  and  $n!$  are expensive but worse ... they lead to large numbers that could overflow the storage format.
- A better approach is to use the relation:

$$\frac{x^n}{n!} = \frac{x}{n} \cdot \frac{x^{n-1}}{(n-1)!}$$

- Terminating the sum ... obviously you don't want to go to infinity. How do you terminate the sum? A good approach is to end the sum when new terms do not significantly change the sum.
- For  $x < 0$ , compare computation of  $e^x$  directly and as  $e^x = 1 / e^{-x}$ .

```
#define TYPE float
TYPE MyExp (TYPE x) {
    long counter = 0;
    TYPE delta = (TYPE)1.0;
    TYPE e_tothe_x = (TYPE)1.0;
    while((1.0 + delta) != 1.0) {
        counter++;
        delta *= x/counter;
        e_tothe_x += delta;
    }
    return e_tothe_x;
```

When  $x > 0$  in series, no cancellation and MyExp matches exp from the standard math library (math.h)

x	exp(x) math.h	MyExp(x)
5	148.413	148.413
10	22026.5	22026.5
15	3.26902e+06	3.26902e+06
20	4.85165e+08	4.85165e+08

x	exp(x) math.h	MyExp(x)	1/MyExp( x )
-5	6.73795e-03	6.73714e-03	6.73795e-03
-10	4.53999e-05	-5.23423e-05	4.53999e-05
-15	3.05902e-07	-2.23869e-02	3.05902e-07
-20	2.06115e-09	-1.79703	2.06115e-09

When  $x < 0$  in series, MyExp does not match exp from math.h due to cancellation. Results become nonsensical for  $x = -10$  and beyond.

# Floating Point Numbers are not Real: Lessons Learned

Real Numbers	Floating Point numbers
Any number can be represented ... real numbers are a closed set	Not all numbers can be represented ... operations can produce numbers that cannot be represented ... that is, floating point numbers are NOT a closed set
With arbitrary precision, there is no loss of accuracy when adding real numbers	Adding numbers of different sizes can cause loss of low order bits.
With arbitrary precision, there is no loss of accuracy when subtracting real numbers	Subtracting two numbers of similar size cancels higher order bits

# Outline

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  - Subtraction
  - – Rounding
  - Algebraic Properties of Floating Point Arithmetic
- Wrap-up/Conclusion

# IEEE 754 arithmetic and rounding

- The IEEE 754 standard requires that the result of basic arithmetic ops (+, -, \*, /, FMA) be equal to the result from “infinitely precise arithmetic” rounded to the storage format (e.g., float or double).
- Consider the following problem ... subtract two IEEE 754 32 bit numbers ( $F^*(2,24,-126,127)$ ):

$$\begin{aligned} & (1.000000000000000000000000000000)_2 \cdot 2^0 \\ - & (1.000000000000000000000000000001)_2 \cdot 2^{-25} \end{aligned}$$

- We normalize them to the same exponent and carry out the operation exactly

$$\begin{aligned} & (1.000000000000000000000000000000)_2 \cdot 2^0 \\ - & (0.000000000000000000000000000001)10000000000000000000000000000001)_2 \cdot 2^0 \\ = & (0.1111111111111111111111111111111011111111111111111111111111111110)_2 \cdot 2^0 \end{aligned}$$

- Then normalize the result

$$(1.11111111111111111111111111111101111111111111111111111111111111)_2 \cdot 2^{-1}$$

- Then round to nearest to fit into the destination format

$$(1.111111111111111111111111111111)_2 \cdot 2^{-1}$$

# IEEE 754 arithmetic and rounding

- The IEEE 754 standard requires that the result of basic arithmetic ops (+, -, \*, /, FMA) be equal to the result from “infinitely precise arithmetic” rounded to the storage format (e.g., float or double).
- Consider the following problem ... subtract two IEEE 754 32 bit numbers ( $F^*(2,24,-126,127)$ ):

$$\begin{aligned} & (1.000000000000000000000000000000)_2 \cdot 2^0 \\ - & (1.000000000000000000000000000001)_2 \cdot 2^{-25} \end{aligned}$$

- We normalize them to the same exponent and carry out the operation exactly

$$\begin{aligned} & \begin{array}{r} (1.000000000000000000000000000000) \\ - (0.000000000000000000000000000001) \\ \hline = (0.111111111111111111111111111111) \end{array} \\ & )_2 \cdot 2^0 \\ & - (0.000000000000000000000000000001)_2 \cdot 2^0 \\ & \hline \\ & = (0.111111111111111111111111111111)_2 \cdot 2^0 \end{aligned}$$

- Then normalize the result

$$(1.1111111111111111111111111111)_2 \cdot 2^{-1}$$

- Then round to nearest to fit into the destination format

$$(1.1111111111111111111111111111)_2 \cdot 2^{-1}$$

The exact result doubled the number of bits in the fraction. Do we really need all those bits?

# IEEE 754 arithmetic and rounding

- Turns out you only need three extra bits ... the **Guard** bit, the **Rounding** bit, and the **Sticky Bit (GRS)**

Normalize       $(1.00000000000000000000000000) \cdot 2^0$

Round to nearest       $(1.11111111111111111111111111) \cdot 2^{-1}$

$$\begin{array}{r} (1.00000000000000000000000000)_2 \\ - (0.00000000000000000000000000)_2 \\ \hline (0.11111111111111111111111111)_2 \end{array} \cdot 2^0$$

$$\begin{array}{r} (1.11111111111111111111111111)_2 \\ - (1.11111111111111111111111111)_2 \\ \hline (0.00000000000000000000000000)_2 \end{array} \cdot 2^{-1}$$

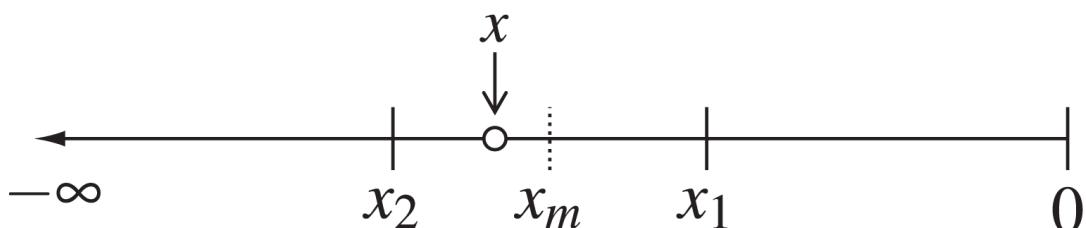
Next 2 bits in the answer:  
the **guard** and **rounding** bits

The Sticky bit: the logical or of all the other bits  
(i.e., if any bit is “1” then the sticky bit is “1”)

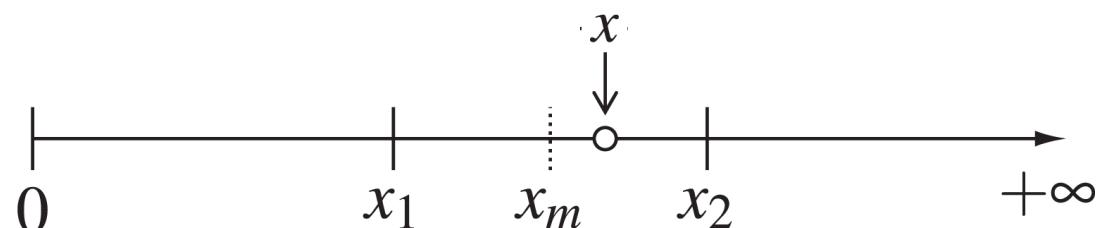
- The Guard, Rounding, and Sticky bits are sufficient to support all the IEEE 754 rounding modes to yield the same result you'd get from an exact computation followed by rounding into the target format.
- Exactly rounded results are required for the basic arithmetic operations (including FMA) but also **square root**, **remainder**, and **conversion between Integer and Floating point numbers** ... but not for conversion between decimal and binary floating point.

# IEEE 754 Rounding Modes

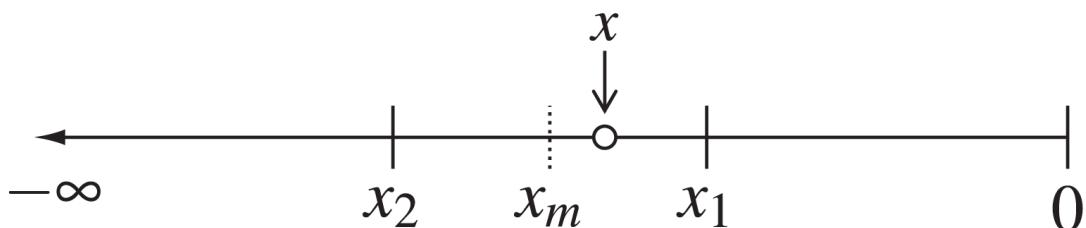
Consider a real number  $x$  that falls between its two nearest floating point numbers ( $x_1$  and  $x_2$ ). At the midpoint between  $x_1$  and  $x_2$  is the real number  $x_m$ . We have four cases to consider when thinking about rounding.



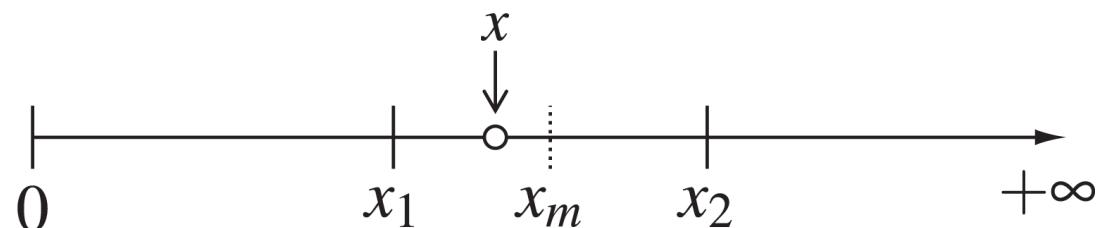
(a)  $x < x_m < 0$



(b)  $x > x_m > 0$



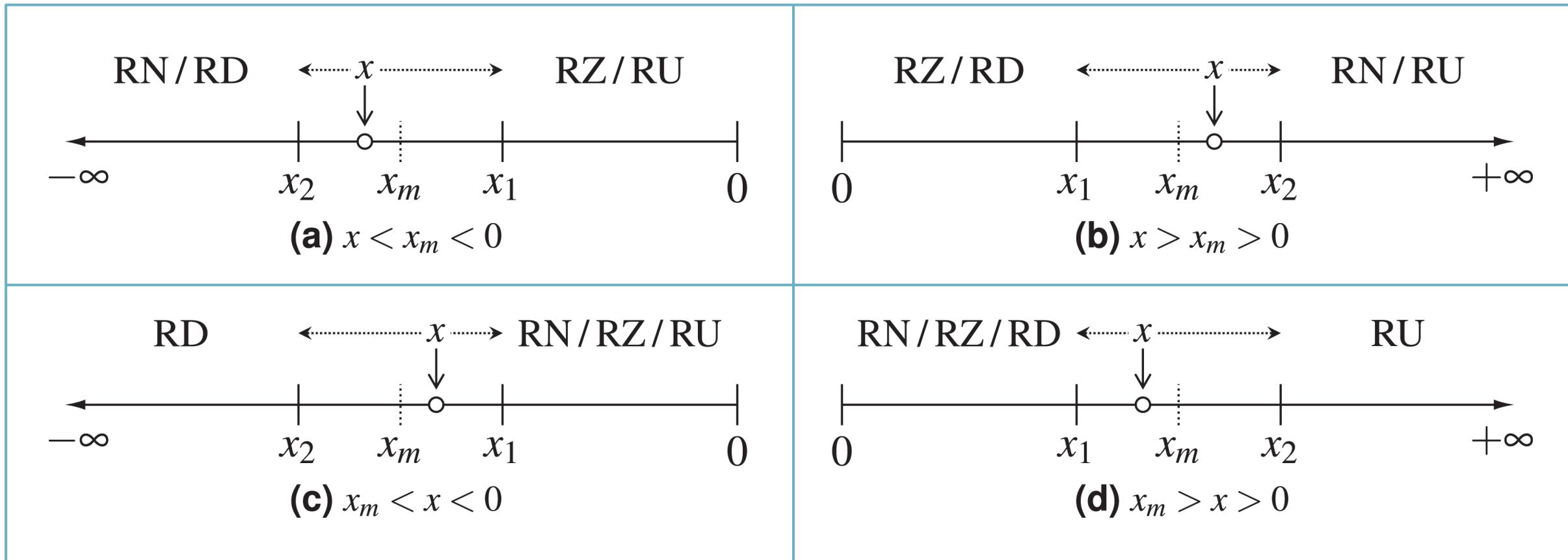
(c)  $x_m < x < 0$



(d)  $x_m > x > 0$

# IEEE 754 Rounding Modes

Consider a real number  $x$  that falls between its two nearest floating point numbers ( $x_1$  and  $x_2$ ). At the midpoint between  $x_1$  and  $x_2$  is the real number  $x_m$ . The horizontal dotted line shows the floating point numbers selected for the different rounding modes (RN, RD, RZ, RU) for position of  $x$  vs  $x_m$  and which side of zero  $x$  is on.



RN: Round to Nearest.

RD: Round Downward

RZ: Round towards zero

RU: Round upward

# You must be careful how you manage rounding...

*Vancouver stock exchange index undervalued by 50%*  
(Nov. 25, 1983)



See <http://ta.twi.tudelft.nl/usersvuik/wi211/disasters.html>

Index managed on an IBM/370. 3000 trades a day and for each trade, the index was truncated to the machine's REAL\*4 format, loosing 0.5 ULP per transaction. After 22 months, the index had lost half its value.

ULP: Unit in the last place

# Working with IEEE 754 rounding modes

Default rounding mode

- Two versions of round to nearest...
- Nearest, on a tie, round to even
  - Nearest, on a tie, away from zero

C

```
#include <fenv.h>
// #pragma STDC FENV_ACCESS ON

// store the original rounding mode
const int originalRounding = fegetround( );

// establish the desired rounding mode
fesetround(FE_TOWARDZERO);

// do whatever you need to do ...
// ... and restore the original mode afterwards
fesetround(originalRounding);
```

The 4 rounding modes in IEEE 754

rounding mode	C name
to nearest	FE_TONEAREST
toward zero	FE_TOWARDZERO
to +infinity	FE_UPWARD
to -infinity	FE_DOWNWARD

Three directed roundings

C++

```
#include <cfenv>
// #pragma STDC FENV_ACCESS ON

// store the original rounding mode
const int originalRounding = std::fegetround( );

// establish the desired rounding mode
std::fesetround(FE_TOWARDZERO);

// do whatever you need to do ...
// ... and restore the original mode afterwards
std::fesetround(originalRounding);
```

Clang and GCC compilers do not recognize the STDC pragma (even though they are technically required to).

Fortunately, rounding mode control seems to work without it.

If not, try the compiler flag  
-frounding-math

# Exercise: IEEE 754 rounding modes

- Explore how different rounding modes change the answers of programs you have on your system.
- What does it tell you if answers change as rounding modes change?

C

```
#include <fenv.h>
// #pragma STDC FENV_ACCESS ON

// store the original rounding mode
const int originalRounding = fegetround( );

// establish the desired rounding mode
fesetround(FE_TOWARDZERO);

// do whatever you need to do ...
// ... and restore the original mode afterwards
fesetround(originalRounding);
```

Clang and GCC compilers do not recognize the STDC pragma (even though they are technically required to).

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The 4 rounding modes in IEEE 754

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to nearest	FE_TONEAREST
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to +infinity	FE_UPWARD
to -infinity	FE_DOWNWARD

C++

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#include <cfenv>
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std::fesetround(FE_TOWARDZERO);

// do whatever you need to do ...
// ... and restore the original mode afterwards
std::fesetround(originalRounding);
```

# Outline

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# Properties of Floating point arithmetic

- IEEE 754 defines the concept of an ***exactly rounded*** results of operation.
  - An exactly rounded result is equivalent to a computation carried out to infinite precision rounded to fit in the designated storage format (e.g., float or double).
- The standard requires a set of operations that must be exactly rounded
  - Add, subtract, multiply, divide, remainder
  - Square root, fused multiply-add, minimum, maximum
  - Comparisons and total ordering
  - Conversions between formats
- Exact rounding is recommended (but not required) for:
  - Exponentials
  - Logarithms
  - Reciprocal square root
  - Trigonometric functions

# Floating point arithmetic is not associative or distributive

- IEEE 754 guarantees that a single arithmetic operation produces a correctly rounded result ... but that guarantee does not apply to multiple operations in sequence.
- Floating point numbers are:
  - Commutative:  $A * B = B * A$
  - NOT Associative:  $A * (C * B) \neq (A * C) * B$
  - NOT Distributive:  $A * (B + C) \neq A * B + A * C$
- All these computations were done in a C program using type float

```
a = 11111113; b= -11111113; c = 7.51111111f;  
      (a + b) + c = 7.511111  
      a + (b + c) = 8.000000
```

Correct answer: 7.511111

```
a = 20000; b= -6; c = 6.000003;  
      (a*b + a*c) = 0.007812  
      a*(b + c) = 0.009537
```

Correct answer: 0.006000

- Python promotes floating point number to double, but even with the extra precision, you can run into trouble

Python

```
a = 1.e20; b= -1.e20; c=1.0  
      (a+b) + c = 1.0  
      a+(b+c) = 0.0
```

Correct answer: 1.0

... But C using  
float gets this  
case right



```
a = 1.e20f; b= -1.e20f; c=1.0f  
      (a + b) + c = 1.000000  
      a + (b + c) = 1.000000
```

# Exercise: Summation with floating point arithmetic

- We have provided a C program called summation.c
- In the program, we generate a sequence of floating point numbers (all greater than zero).
  - **Don't look at how we create that sequence** ... treat the sequence generator as a black box (in other words, just work on the sequence, don't use knowledge of how it was generated).
- Write code to sum the sequence of numbers. You can compare your result to the estimate of the correct result provided by the sequence generator.
  - Only use float types (it's cheating to use double ... at least to start with).
- Using what you know about floating point arithmetic, is there anything you can think of doing to improve the quality of your sum?

# Summation program

```
#include "UtilityFunctions.h" // FillSequence() comes from this module

#define N 100000                //length of sequence of numbers to work with
int main ()
{
    float seq[N];      //Sequence to sum
    float True_sum;    //The best estimate of the actual sum
    float sum = 0.0f;

    FillSequence(N, seq, &True_sum); // Fill seq with N values > 0

    for(int i=0; i<N; i++)sum += seq[i];

    printf(" Sum = %f, Estimated sum = %f\n",sum,True_sum);
}
```

```
> gcc summation.c UtilityFunctions.c
> ./a.out
> Sum = 2502476.500000, Estimated sum = 2502458.750000
```

This result is kind  
of awful

# Summation program

Let's do the sum in parallel and see how the answer varies with the number of threads

```
#include <omp.h>
#include "UtilityFunctions.h" // FillSequence() comes from this module

#define N 100000                //length of sequence of numbers to work with
int main ()
{
    float seq[N];      //Sequence to sum
    float True_sum;    //The best estimate of the actual sum
    float sum = 0.0f;

    FillSequence(N, seq, &True_sum); // Fill seq with N values > 0

    #pragma omp parallel for reduction(+:sum)
    for(int i=0; i<N; i++)sum += seq[i];

    printf(" Sum = %f, Estimated sum = %f\n",sum,True_sum);
}
```

Values with 1 to 8 threads

1	2502476.5
2	2502457.0
4	2502459.25
8	2502459.0

True value = 2502458.75

# Sequence Generation

- I created a particularly awful sequence to sum

```
void FillSequence(int N, float *seq, float *True_sum)
{
    float shift_up    = 100.0f;
    float shift_down =      0.000001f;
    double up_sum     = 0.0d,   down_sum = 0.0d;

    for(int i=0;i<N; i++){
        if(i%2==0){
            seq[i]    = (float) frandom() * shift_up;
            up_sum    += (double) seq[i];
        }
        else {
            seq[i]    = (float) frandom() * shift_down;
            down_sum += (double) seq[i];
        }
    }
    *True_sum = (float)(up_sum + down_sum);
}
```

Alternating big and small numbers to maximize opportunities for loss of precision when summing the numbers.

Notice how I estimate the “true” value by summing big numbers and little numbers separately before combining them.

# Summation program

Sort from small to large before summing the sequence

```
#include "UtilityFunctions.h" // FillSequence() comes from this module

#define N 100000                //length of sequence of numbers to work with
int main ()
{
    float seq[N];      //Sequence to sum
    float True_sum;    //The best estimate of the actual sum
    float sum = 0.0f;

    FillSequence(N, seq, &True_sum); // Fill seq with N values > 0

    qsort(seq, N, sizeof(int), compare); // Sort from smallest to largest
    for(int i=0; i<N; i++)sum += seq[i];

    printf(" Sum = %f, Estimated sum = %f\n",sum,True_sum);
}
```

```
> gcc summation.c UtilityFunctions.c
> ./a.out
> Sum = 2502455.500000, Estimated sum = 2502458.750000
```

The sorted sequence decreases loss of precision since magnitudes of numbers are closer together in a sorted sequence

From 2502476.5 to 2502455.5 That's a big improvement

# Numerical Analysis

- The details of how we do arithmetic on computers and the branch of mathematics that studies the consequences of computer arithmetic (numerical analysis) is fundamentally boring.
  - Even professionals who work on computer arithmetic (other than W. Kahan\*) admit (maybe only in private) that it's boring.

Computer Science has changed over my lifetime. Numerical Analysis seems to have turned into a sliver under the fingernails of computer scientists

Prof. W. Kahan, Desperately needed Remedies ... Oct. 14, 2011

- It's fine to take floating point arithmetic for granted ... until something breaks.
- The scary part of this ... is that you don't know something is wrong with your program until disaster strikes!!!!

You don't need to be paranoid, but be skeptical of *ANYTHING* you compute on a computer.

# Compensated summation

## (i.e., Kahan Summation)

- Summation is notorious for errors from loss of precision when two numbers of widely different magnitudes are added. Kahan Summation corrects for this error.

Input: a sequence of N values,  $x[i]$   $i=1, N$

```
cor = 0.0  
sum = 0.0
```

```
for i = 1 to N:
```

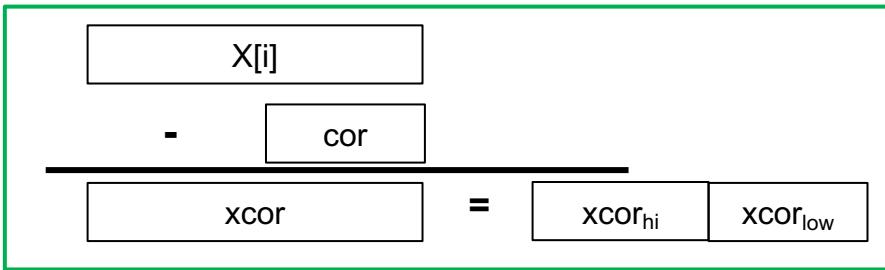
```
    xcor = x[i] - cor
```

```
    tmpSum = sum + xcor
```

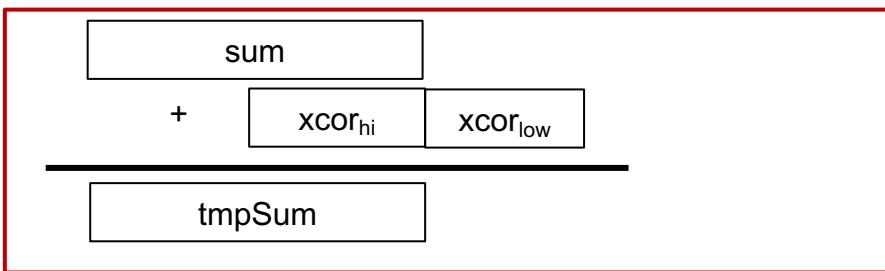
```
    cor = (tmpSum - sum) - xcor
```

```
    sum = tmpSum  
}
```

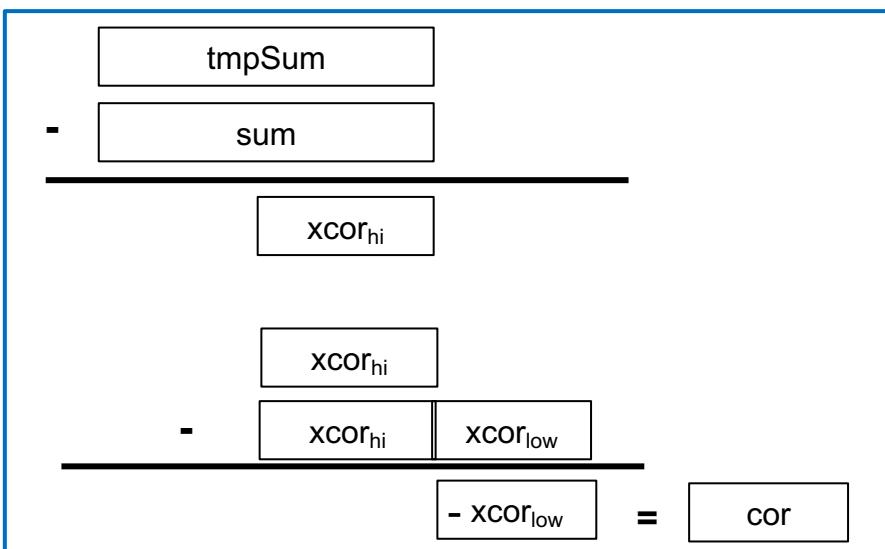
Output: sum



Apply a correction to  $x[i]$  to account for bits lost in the previous loop iteration



Sum grows to be a “big” number. Add a small number ( $\text{xcor}$ ) and you loose low order bits ( $\text{xcor}_{\text{low}}$ )



Recover high order bits from  $\text{xcor}$

Recover the lost low order bits from  $\text{xcor}$  and apply them as a correction for the next term in the sum

# Summation program

```
#include "UtilityFunctions.h" // FillSequence() comes from this module

#define N 100000                //length of sequence of numbers to work with
int main ()
{
    float seq[N];      //Sequence to sum
    float True_sum;    //The best estimate of the actual sum
    float sum = 0.0f;

    FillSequence(N, seq, &True_sum); // Fill seq with N values > 0

    KahanSummation(N, seq, sum);

    printf(" Kahan Sum = %f, Estimated sum = %f\n",sum,True_sum);
}
```

Our original sum value  
was 2502476.50 which  
was an awful result

The Kahan Sum and the  
estimated correct sum  
match  
2502458.75

```
> gcc summation.c UtilityFunctions.c
> ./a.out
> Kahan sum = 2502458.750000, Estimated sum = 2502458.750000
```

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## Here is a famous example ...

*Sleipner Oil Rig Collapse (8/23/91). Loss: \$700 million.*



See <http://www.ima.umn.edu/~arnold/disasters/sleipner.html>

Inaccurate linear elastic model used with NASTRAN underestimated shear stresses by 47% resulted in concrete walls that were too thin.

# We can't trust FLOPS ... let's give up and return to slide rules



(an elegant weapon for a more civilized age)

# *Sleipner Oil Rig Collapse: The slide-rule wins!!!*

It was recognized that finding and correcting the flaws in the computer analysis and design routines was going to be a major task. Further, with the income from the lost production of the gas field being valued at perhaps \$1 million a day, it was evident that a replacement structure needed to be designed and built in the shortest possible time.

A decision was made to proceed with the design using the pre-computer, slide-rule era techniques that had been used for the first Condeep platforms designed 20 years previously. By the time the new computer results were available, all of the structure had been designed by hand and most of the structure had been built. On April 29, 1993 the new concrete gravity base structure was successfully mated with the deck and Sleipner was ready to be towed to sea (See photo on title page).



The failure of the Sleipner base structure, which involved a total economic loss of about \$700 million, was probably the most expensive shear failure ever. The accident, the subsequent investigations, and the successful redesign offer several lessons for structural engineers. No matter how complex the structure or how sophisticated the computer software it is always possible to obtain most of the important design parameters by relatively simple hand calculations. Such calculations should always be done, both to check the computer results and to improve the engineers' understanding of the critical design issues. In this respect it is important to note that the design errors in Sleipner were not detected by the extensive and very formal quality assurance procedures that were employed.

# How should we respond?

- Programmers should conduct mathematically rigorous analysis of their floating point intensive applications to validate their correctness.
- But this won't happen ... training of modern programmers all but ignores numerical analysis.  
The following tricks\* help and are better than nothing ...
  1. Repeat the computation with arithmetic of increasing precision, increasing it until a desired number of digits in the results agree.
  2. Repeat the computation in arithmetic of the same precision but rounded differently, say *Down* then *Up* and perhaps *Towards Zero*, then compare results (this wont work with libraries that require a particular rounding mode).
  3. Repeat computation a few times in arithmetic of the same precision but with slightly different input data, and see how widely results vary.

These are useful techniques, but they don't go far enough. How can the discerning skeptic confidently use FLOPs?

\*Source: W. Kahan: How futile are mindless Assessments of Roundoff in floating-point computation?

# Floating Point Numbers are not Real: Lessons Learned

Real Numbers	Floating Point numbers
Any number can be represented ... real numbers are a closed set	Not all numbers can be represented ... operations can produce numbers that cannot be represented ... that is, floating point numbers are NOT a closed set
With arbitrary precision, there is no loss of accuracy when adding real numbers	Adding numbers of different sizes can cause loss of low order bits.
With arbitrary precision, there is no loss of accuracy when subtracting real numbers	Subtracting two numbers of similar size cancels higher order bits
Basic arithmetic operations over Real numbers are commutative, distributive and associative.	Basic operations over floating point numbers are commutative, but NOT associative or distributive.

# Conclusion

- Floating point arithmetic usually works and you can “almost always” be comfortable using it.
- We covered the most famous issues with floating point arithmetic, but we largely skipped numerical analysis. Floating point arithmetic is mathematically rigorous. You can prove theorems and develop formal error bounds.
- Unfortunately, almost nobody learns numerical analysis these days ... so be careful.
  - Modify rounding modes as an easy way to see if round-off errors are a problem.
  - Recognize that unless you impose an order of association, every order is equally valid. If your answers change as the number of threads changes, that is valuable information suggesting an ill-conditioned problem.
  - Anyone who suggests the need for bitwise identical results from a parallel code should be harshly criticized/punished.

My favorite picture of my wife



Kayaker: Pat Welle at Cascade head. Photo by T. Mattson.

# References

- What every computer computer scientist should know about floating point arithmetic, David Goldberg, Computing Surveys, 1991.
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- W. Kahan: How futile are mindless Assessments of Roundoff in floating-point computation?
  - <https://people.eecs.berkeley.edu/~wkahan/Mindless.pdf>
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git clone <https://github.com/tgmattso/CompSciForPhys.git>