

Computer arithmetic

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First we dig into bits
Integers
Floating point numbers
Floating point math
Examples
More

Justification

This short session will explain the basics of floating point arithmetic, mostly focusing on round-off and its influence on computations.

Numbers in scientific computing

- Integers: $\dots, -2, -1, 0, 1, 2, \dots$
- Rational numbers: $1/3, 22/7$: not often encountered
- Real numbers $0, 1, -1.5, 2/3, \sqrt{2}, \log 10, \dots$
- Complex numbers $1 + 2i, \sqrt{3} - \sqrt{5}i, \dots$

Computers use a finite number of bits to represent numbers, so only a finite number of numbers can be represented, and no irrational numbers (even some rational numbers).

Bit operations

| | boolean | bitwise (C) | bitwise (Py) |
|-----|---------|-------------|--------------|
| and | & & | & | & |
| or | | | |
| not | ! | | ~ |
| xor | | ^ | |

Bit string operations:

| | |
|-------------|----|
| left shift | << |
| right shift | >> |

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Exercise 1: Bit operations

Use bit operations to test whether a number is odd or even.

Integers

Scientific computation mostly uses real numbers. Integers are mostly used for array indexing.

16/32/64 bit: `short`, `int`, `long`, `long long` in C, size not standardized, use `sizeof(long)` et cetera. (Also `unsigned int` et cetera)

`INTEGER*2/4/8` Fortran, also `KIND`

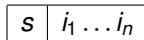
Exercise 2: Powers of two

Print 2^n for $n = 0, \dots, 31$. There are at least two ways of generating these powers.

Also print the bit pattern. What is unexpected?

Negative integers

Use of sign bit: typically first bit



Simplest solution: $n > 0$, $\text{rep}(n) = 0, i_1, \dots, i_{31}$, then
 $\text{rep}(-n) = 1, i_1, \dots, i_{31}$

Problem: $+0$ and -0 ; also impractical in other ways.

Sign bit

| | | | | | | |
|-----------------|--------|-----|--------------|----------|-----|---------------|
| bitstring | 00...0 | ... | 01...1 | 10...0 | ... | 11...1 |
| as unsigned int | 0 | ... | $2^{31} - 1$ | 2^{31} | ... | $2^{32} - 1$ |
| as naive signed | 0 | ... | $2^{31} - 1$ | -0 | ... | $-2^{31} + 1$ |

Shifting

Interpret unsigned number n as $n - B$

| | | | | | | |
|-----------------|-----------|-----|--------------|----------|-----|--------------|
| bitstring | 00...0 | ... | 01...1 | 10...0 | ... | 11...1 |
| as unsigned int | 0 | ... | $2^{31} - 1$ | 2^{31} | ... | $2^{32} - 1$ |
| as shifted int | -2^{31} | ... | -1 | 0 | ... | $2^{31} - 1$ |

2's Complement

Let m be a signed integer, then the 2's complement 'bit pattern' $\beta(m)$ is a non-negative integer defined as follows:

- If $0 \leq m \leq 2^{31} - 1$, the normal bit pattern for m is used, that is

$$0 \leq m \leq 2^{31} - 1 \Rightarrow \beta(m) = m.$$

- For $-2^{31} \leq n \leq -1$, n is represented by the bit pattern for $2^{32} - |n|$:

$$-2^{31} \leq n \leq -1 \Rightarrow \beta(m) = 2^{32} - |n|.$$

Bit pattern to integer: $\eta = \beta^{-1}$.

2's complement visualized

| | | | | | | |
|----------------------|--------|-----|--------------|-----------|-----|--------------|
| bitstring | 00...0 | ... | 01...1 | 10...0 | ... | 11...1 |
| as unsigned int | 0 | ... | $2^{31} - 1$ | 2^{31} | ... | $2^{32} - 1$ |
| as 2's comp. integer | 0 | ... | $2^{31} - 1$ | -2^{31} | ... | -1 |

Addition in 2's complement

Add $m + n$, where m, n are representable:

$$0 \leq |m|, |n| < 2^{31}.$$

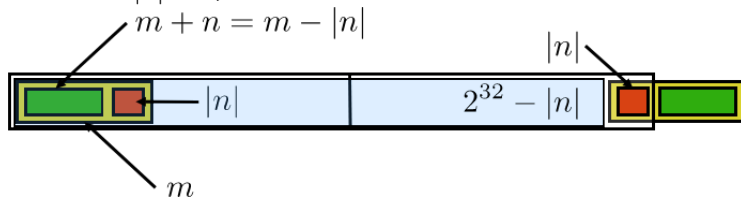
The easy case is $0 < m, n$, as long as there is no overflow.

Addition in 2's complement (cont'd)

Case $m > 0$, $n < 0$, and $m + n > 0$. Then $\beta(m) = m$ and $\beta(n) = 2^{32} - |n|$, so the unsigned addition becomes

$$\beta(m) + \beta(n) = m + (2^{32} - |n|) = 2^{32} + m - |n|.$$

Since $m - |n| > 0$, this result is $> 2^{32}$.



However, this is basically $m + n$ with the overflow bit set.

Subtraction in 2's complement

Subtraction $m - n$:

- Case: $m < n$. Observe that $-n$ has the bit pattern of $2^{32} - n$. Also, $m + (2^{32} - n) = 2^{32} - (n - m)$ where $0 < n - m < 2^{31} - 1$, so $2^{32} - (n - m)$ is the 2's complement bit pattern of $m - n$.
- Case: $m > n$. The bit pattern for $-n$ is $2^{32} - n$, so $m + (-n)$ as unsigned is $m + 2^{32} - n = 2^{32} + (m - n)$. Here $m - n > 0$. The 2^{32} is an overflow bit; ignore.

Overflow

There is a limited number of bits, so numbers that are too large in absolute value can not be represented.

Overflow.

This is not a fatal error: your program continues with the wrong result.

Exercise 3: Integer overflow

Investigate what happens when you perform an integer calculation that leads to overflow. What does your compiler say if you try to write down a nonrepresentable number explicitly, for instance in a declaration or assignment statement?

Floating point numbers

Analogous to scientific notation $x = 6.022 \cdot 10^{23}$:

$$x = \pm \sum_{i=0}^{t-1} d_i \beta^{-i} \beta^e$$

- sign bit
- β is the base of the number system
- $0 \leq d_i \leq \beta - 1$ the digits of the *mantissa*:
one digit before the *radix point*, so mantissa $< \beta$
- $e \in [L, U]$ exponent, stored with bias: unsigned int where $\text{fl}(L) = 0$

Examples of floating point systems

| | β | t | L | U |
|----------------------|---------|-----|--------|-------|
| IEEE single (32 bit) | 2 | 24 | -126 | 127 |
| IEEE double (64 bit) | 2 | 53 | -1022 | 1023 |
| Old Cray 64bit | 2 | 48 | -16383 | 16384 |
| IBM mainframe 32 bit | 16 | 6 | -64 | 63 |
| packed decimal | 10 | 50 | -999 | 999 |

BCD is tricky: 3 decimal digits in 10 bits

(we will often use $\beta = 10$ in the examples, because it's easier to read for humans, but all practical computers use $\beta = 2$)

Internal processing in 80 bit

Limitations

Overflow: more than $\beta(1 - \beta^{-t+1})\beta^U$ or less than $\beta(1 - \beta^{-t+1})\beta^L$

Underflow: numbers less than $\beta^{-t+1} \cdot \beta^L$

Exercise 4: Floating point overflow

For real numbers x, y , the quantity $g = \sqrt{(x^2 + y^2)/2}$ satisfies

$$g \leq \max\{|x|, |y|\}$$

so it is representable if x and y are. What can go wrong if you compute g using the above formula? Can you think of a better way?

The normalization problem

Do we allow

$$1.100 \cdot 10^0, \quad 0.110 \cdot 10^1, \quad 0.011 \cdot 10^2?$$

This makes testing for equality hard.

Solution: normalized numbers have one nonzero before the radix point.

Normalized floating point numbers

Require first digit in the mantissa to be nonzero.

Equivalent: mantissa part $1 \leq x_m < \beta$

Unique representation for each number,

also: in binary this makes the first digit 1, so we don't need to store that.

(do you see a problem?)

With normalized numbers, underflow threshold is $1 \cdot \beta^L$;

'gradual underflow' possible, but usually not efficient.

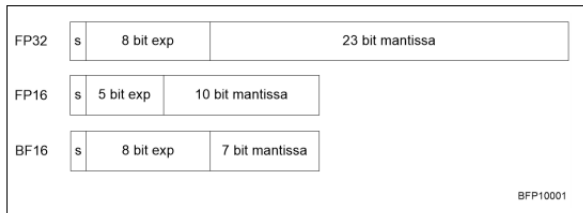
IEEE 754, 32-bit

| sign | exponent | mantissa |
|------|------------------|---------------------|
| s | $e_1 \cdots e_8$ | $s_1 \cdots s_{23}$ |
| 31 | 30 \cdots 23 | 22 \cdots 0 |

| $(e_1 \cdots e_8)$ | numerical value |
|----------------------|---|
| $(0 \cdots 0) = 0$ | $\pm 0.s_1 \cdots s_{23} \times 2^{-126}$ |
| $(0 \cdots 01) = 1$ | $\pm 1.s_1 \cdots s_{23} \times 2^{-126}$ |
| $(0 \cdots 010) = 2$ | $\pm 1.s_1 \cdots s_{23} \times 2^{-125}$ |
| \cdots | |
| $(01111111) = 127$ | $\pm 1.s_1 \cdots s_{23} \times 2^0$ |
| $(10000000) = 128$ | $\pm 1.s_1 \cdots s_{23} \times 2^1$ |
| \cdots | |
| $(11111110) = 254$ | $\pm 1.s_1 \cdots s_{23} \times 2^{127}$ |
| $(11111111) = 255$ | $\pm \infty$ if $s_1 \cdots s_{23} = 0$, otherwise NaN |

Other precisions

- There is a 64-bit format, with 53 bits mantissa.
- IEEE envisioned a sliding scale of precisions: see Intel 80-bit registers
- Half precision, and recent invention `bfloat16`



Representation error

Error between number x and representation \tilde{x} :

absolute $x - \tilde{x}$ or $|x - \tilde{x}|$

relative $\frac{x - \tilde{x}}{x}$ or $|\frac{x - \tilde{x}}{x}|$

Equivalent: $\tilde{x} = x \pm \epsilon \Leftrightarrow |x - \tilde{x}| \leq \epsilon \Leftrightarrow \tilde{x} \in [x - \epsilon, x + \epsilon]$.

Also: $\tilde{x} = x(1 + \epsilon)$ often shorthand for $|\frac{\tilde{x} - x}{x}| \leq \epsilon$

Example

Decimal, $t = 3$ digit mantissa: let $x = 1.256$, $\tilde{x}_{\text{round}} = 1.26$,
 $\tilde{x}_{\text{truncate}} = 1.25$

Error in the 4th digit: $|\epsilon| < \beta^{t-1}$ (this example had no exponent, how about if it does?)

Exercise 5: Round-off

The number $e \approx 2.72$, the base for the natural logarithm, has various definitions. One of them is

$$e = \lim_{n \rightarrow \infty} (1 + 1/n)^n.$$

Write a single precision program that tries to compute e in this manner. Evaluate the expression for an upper bound $n = 10^k$ with $k = 1, \dots, 10$. Explain the output for large n . Comment on the behaviour of the error.

Machine precision

Any real number can be represented to a certain precision:

$\tilde{x} = x(1 + \varepsilon)$ where

truncation: $\varepsilon = \beta^{-t+1}$

rounding: $\varepsilon = \frac{1}{2}\beta^{-t+1}$

This is called *machine precision*: maximum relative error.

32-bit single precision: $mp \approx 10^{-7}$

64-bit double precision: $mp \approx 10^{-16}$

Maximum attainable accuracy.

Another definition of machine precision: smallest number ε such that
 $1 + \varepsilon > 1$.

Exercise 6: Machine epsilon

Write a small program that computes the machine epsilon for both single and double precision. Does it make any difference if you set the *compiler optimization levels* low or high?

(For C++ programmers: can you write a templated program that works for single and double precision?)

Addition

1. align exponents
2. add mantissas
3. adjust exponent to normalize

Example: $1.00 + 2.00 \times 10^{-2} = 1.00 + .02 = 1.02$. This is exact, but what happens with $1.00 + 2.55 \times 10^{-2}$?

Example: $5.00 \times 10^1 + 5.04 = (5.00 + 0.504) \times 10^1 \rightarrow 5.50 \times 10^1$

Any error comes from limiting the mantissa: if x is the true sum and \tilde{x} the computed sum, then $\tilde{x} = x(1 + \epsilon)$ with $|\epsilon| < 10^{-2}$

The ‘correctly rounded arithmetic’ model

Assumption (enforced by IEEE 754):

The numerical result of an operation is the rounding of the exactly computed result.

$$\text{fl}(x_1 \odot x_2) = (x_1 \odot x_2)(1 + \epsilon)$$

where $\odot = +, -, *, /$

Note: this holds only for a single operation!

Guard digits

Correctly rounding is not trivial, especially for subtraction.

Example: $t = 2, \beta = 10$: $1.0 - 9.5 \times 10^{-1}$, exact result
 $0.05 = 5.0 \times 10^{-2}$.

- Simple approach:

$$1.0 - 9.5 \times 10^{-1} = 1.0 - 0.9 = 0.1 = 1.0 \times 10^{-1}$$

- Using 'guard digit':

$$1.0 - 9.5 \times 10^{-1} = 1.0 - 0.95 = 0.05 = 5.0 \times 10^{-2}, \text{ exact.}$$

In general 3 extra bits needed.

Fused Mul-Add instructions

$$a \leftarrow a * b + c \quad \text{or} \quad c \leftarrow a * b + c$$

- Addition plus multiplication, but not independent
- Processors can have dedicated hardware for FMA (also IEEE 754-2008)
- Internally evaluated in higher precision: 80-bit.
- Very useful for certain linear algebra (which?) Not for other operations (examples?)

Associativity

Compute $4 + 6 + 7$ in one significant digit.

Evaluation left-to-right gives:

$$\begin{aligned}(4 \cdot 10^0 + 6 \cdot 10^0) + 7 \cdot 10^0 &\Rightarrow 10 \cdot 10^0 + 7 \cdot 10^0 && \text{addition} \\ &\Rightarrow 1 \cdot 10^1 + 7 \cdot 10^0 && \text{rounding} \\ &\Rightarrow 1.0 \cdot 10^1 + 0.7 \cdot 10^1 && \text{using guard digit} \\ &\Rightarrow 1.7 \cdot 10^1 \\ &\Rightarrow 2 \cdot 10^1 && \text{rounding}\end{aligned}$$

On the other hand, evaluation right-to-left gives:

$$\begin{aligned}4 \cdot 10^0 + (6 \cdot 10^0 + 7 \cdot 10^0) &\Rightarrow 4 \cdot 10^0 + 13 \cdot 10^0 && \text{addition} \\ &\Rightarrow 4 \cdot 10^0 + 1 \cdot 10^1 && \text{rounding} \\ &\Rightarrow 0.4 \cdot 10^1 + 1.0 \cdot 10^1 && \text{using guard digit} \\ &\Rightarrow 1.4 \cdot 10^1 \\ &\Rightarrow 1 \cdot 10^1 && \text{rounding}\end{aligned}$$

Error propagation under addition

Let $s = x_1 + x_2$, and $x = \tilde{s} = \tilde{x}_1 + \tilde{x}_2$ with $\tilde{x}_i = x_i(1 + \varepsilon_i)$

$$\begin{aligned}\tilde{x} &= \tilde{s}(1 + \varepsilon_3) \\ &= x_1(1 + \varepsilon_1)(1 + \varepsilon_3) + x_2(1 + \varepsilon_2)(1 + \varepsilon_3) \\ &= x_1 + x_2 + x_1(\varepsilon_1 + \varepsilon_3) + x_2(\varepsilon_2 + \varepsilon_3) \\ \Rightarrow \tilde{x} &= s(1 + 2\varepsilon)\end{aligned}$$

\Rightarrow errors are added

Assumptions: all ε_i approximately equal size and small;
 $x_i > 0$

Multiplication

1. add exponents
2. multiply mantissas
3. adjust exponent

Example:

$$.123 \times .567 \times 10^1 = .069741 \times 10^1 \rightarrow .69741 \times 10^0 \rightarrow .697 \times 10^0.$$

What happens with relative errors?

Subtraction

Correct rounding only applies to a single operation.

Example: $1.24 - 1.23 = 0.01 \rightarrow 1. \times 10^{-2}$:
result is exact, but only one significant digit.

What if $1.24 = \text{fl}(1.244)$ and $1.23 = \text{fl}(1.225)$? Correct
result 1.9×10^{-2} ; almost 100% error.

- *Cancellation* leads to loss of precision
- subsequent operations with this result are inaccurate
- this can not be fixed with guard digits and such
- \Rightarrow avoid subtracting numbers that are likely close.

ABC-formula

Example: $ax^2 + bx + c = 0 \rightarrow x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

suppose $b > 0$ and $b^2 \gg 4ac$ then the '+' solution will be inaccurate

Better: compute $x_- = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$ and use $x_+ \cdot x_- = -c/a$.

Serious example

Evaluate $\sum_{n=1}^{10000} \frac{1}{n^2} = 1.644834$

in 6 digits: machine precision is 10^{-6} in single precision

First term is 1, so partial sums are ≥ 1 , so $1/n^2 < 10^{-6}$ gets ignored,
 \Rightarrow last 7000 terms (or more) are ignored, \Rightarrow sum is 1.644725: 4 correct digits

Solution: sum in reverse order; exact result in single precision

Why? Consider ratio of two terms:

$$\frac{n^2}{(n-1)^2} = \frac{n^2}{n^2 - 2n + 1} = \frac{1}{1 - 2/n + 1/n^2} \approx 1 + \frac{2}{n}$$

with aligned exponents:

$$\begin{array}{r|l} n-1: & .00 \cdots 0 \quad 10 \cdots 00 \\ n: & .00 \cdots 0 \quad 10 \cdots 01 \quad 0 \cdots 0 \\ & k = \log(n/2) \text{ positions} \end{array}$$

The last digit in the smaller number is not lost if $n < 2/\epsilon$

Another serious example

Previous example was due to finite representation; this example is more due to algorithm itself.

Consider $y_n = \int_0^1 \frac{x^n}{x-5} dx = \frac{1}{n} - 5y_{n-1}$ (monotonically decreasing)
 $y_0 = \ln 6 - \ln 5$.

In 3 decimal digits:

computation

correct result

$$y_0 = \ln 6 - \ln 5 = .182|322 \times 10^1 \dots$$

1.82

$$y_1 = .900 \times 10^{-1}$$

.884

$$y_2 = .500 \times 10^{-1}$$

.0580

$$y_3 = .830 \times 10^{-1}$$

going up? .0431

$$y_4 = -.165$$

negative? .0343

Reason? Define error as $\tilde{y}_n = y_n + \epsilon_n$, then

$$\tilde{y}_n = 1/n - 5\tilde{y}_{n-1} = 1/n + 5\epsilon_{n-1} = y_n + 5\epsilon_{n-1}$$

so $\epsilon_n \geq 5\epsilon_{n-1}$: exponential growth.

Stability of linear system solving

Problem: solve $Ax = b$, where b inexact.

$$A(x + \Delta x) = b + \Delta b.$$

Since $Ax = b$, we get $A\Delta x = \Delta b$. From this,

$$\left\{ \begin{array}{l} Ax = b \\ \Delta x = A^{-1} \Delta b \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} \|A\| \|x\| \geq \|b\| \\ \|\Delta x\| \leq \|A^{-1}\| \|\Delta b\| \end{array} \right.$$
$$\Rightarrow \frac{\|\Delta x\|}{\|x\|} \leq \|A\| \|A^{-1}\| \frac{\|\Delta b\|}{\|b\|}$$

‘Condition number’. Attainable accuracy depends on matrix properties

Consequences of roundoff

Multiplication and addition are not associative:
problems for parallel computations.

| compute $a + b + c + d$ | |
|-------------------------|---------------|
| sequential | parallel |
| $((a + b) + c) + d$ | $(a+b)+(c+d)$ |

Operations with “same” outcomes are not equally stable:
matrix inversion is unstable, elimination is stable

Exercise 7: Fixed-point iteration

Consider the iteration

$$x_{n+1} = f(x_n) = \begin{cases} 2x_n & \text{if } 2x_n < 1 \\ 2x_n - 1 & \text{if } 2x_n \geq 1 \end{cases}$$

Does this function have a fixed point, $x_0 \equiv f(x_0)$, or is there a cycle $x_1 = f(x_0)$, $x_0 \equiv x_2 = f(x_1)$ et cetera?

Now code this function and see what happens with various starting points x_0 . Can you explain this?

Complex numbers

Two real numbers: real and imaginary part.

Storage:

- Store real/imaginary adjacent: easy to pass address of one number
- Store array of real, then array of imaginary. Better for stride 1 access if only real parts are needed. Other considerations.

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Other arithmetic systems

Some compilers support higher precisions.

Arbitrary precision: GMPlib

Interval arithmetic