

INTRO TO SCIENTIFIC COMPUTING

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INTRODUCTION

- We will mostly deal with numbers.
- Important to know how computers store and manipulate them.
- We will also introduce some basic concepts related to numerical analysis.

FLOATING POINT NUMBERS

- Floating point numbers are ubiquitous in scientific computing.
- Useful to have a basic understanding of them.

FLOATING POINT NUMBERS

- \mathbb{R} is large, but computers have finite memory.
- Fix a **base** β and integers p, m, M . Define floating point system as

$$\pm \left(\sum_{n=1}^p d_n \beta^{-n} \right) \times \beta^e,$$

where $d_n \in \{0, 1, \dots, \beta - 1\}$, $m \leq e \leq M$.

- We call elements of the floating point system **floating point numbers** or **floats**.

FLOATING POINT NUMBERS

$$\pm \left(\sum_{n=1}^p d_n \beta^{-n} \right) \times \beta^e, \quad \text{where } d_n \in \{0, 1, \dots, \beta - 1\}, m \leq e \leq M.$$

- Why “floating point”? By varying e we can represent numbers by shifting the decimal point.
- Consider $\beta = 10$ and two numbers $x_1 = 0.12 \times 10^1$ and $x_2 = 0.12 \times 10^2$. These are $x_1 = 1.20$ and $x_2 = 12.00$.

FLOATING POINT NUMBERS

- Focus on $\beta = 2$. We have **binary** floating point numbers.

$$\pm (-1)^s \times 2^e \times 1.f, \quad f = \left(\sum_{n=1}^p d_n 2^{-n} \right).$$

- We call f the **mantissa** or **significand**.
- e is the **exponent**.
- p is the **precision**.
- s is the **sign**.

IEEE 754

- IEEE 754: technical standard for floating-point arithmetic established in 1985 by the Institute of Electrical and Electronics Engineers (IEEE).
- Defines formats for floating point numbers with $\beta = 2$.
- Two formats: **single precision** (stored in 32 bits) and **double precision** (stored in 64 bits).
- A bit is a binary digit, i.e., 0 or 1.
- `Float32` and `Float64` in Julia.

DOUBLE PRECISION FORMAT

- The format for a double precision number is:

$$\# = (-1)^s \times 2^{(e-1023)} \times 1.f$$

- s is the sign bit (1 bit), e is the exponent (11 bits), and f is the fraction (52 bits).
- Note that only combinations of powers of 2 can be expressed exactly.
- Note the bias of 1023 in the exponent.

DOUBLE PRECISION FORMAT

- Consider the number 1.0.
- It has $s = 0$, $e = 1023$, and $f = 0$.

$$1.0 = (-1)^0 \times 2^{(1023-1023)} \times 1.0$$

$$\rightarrow \underbrace{0}_{\text{sign}} \underbrace{001111111111}_{1023 \text{ in base 2}} 0000 \dots 0000$$

DOUBLE PRECISION FORMAT

- Consider the number 2.0.
- It has $s = 0$, $e = 1024$, and $f = 0$.

$$2.0 = (-1)^0 \times 2^{(1024-1023)} \times 1.0$$

$$\rightarrow \underbrace{0}_{\text{sign}} \underbrace{100000000000}_{1024 \text{ in base 2}} 0000 \dots 0000$$

DOUBLE PRECISION FORMAT

- Consider the number 0.5.
- It has $s = 0$, $e = 1022$, and $f = 0$.

$$0.5 = (-1)^0 \times 2^{(1022-1023)} \times 1.0$$

$$\rightarrow \underbrace{0}_{\text{sign}} \underbrace{001111111110}_{1022 \text{ in base 2}} 0000 \dots 0000$$

DOUBLE PRECISION FORMAT

- Consider the number 0.2.
- it has $s = 0$, $e = 1020$, and $f = 0.6$.

$$0.2 = (-1)^0 \times \underbrace{2^{(1020-1023)}}_{=\frac{1}{8}} \times (1 + 0.6)$$

- This one **does not** have an exact binary representation.
- The problem is 0.6. How is it represented in binary?

DOUBLE PRECISION FORMAT

- How to represent fractions (0.6) in binary?
 1. Multiply by 2 ($2 \times 0.6 = 1.2$), record the integer part (1)
 2. Multiply the fraction part by 2 ($2 \times 0.2 = 0.4$), record the integer part (0).
 3. Multiply the fraction part by 2 ($2 \times 0.4 = 0.8$), record the integer part (0).
 4. Multiply the fraction part by 2 ($2 \times 0.8 = 1.6$), record the integer part (1).
 5. Multiply the fraction part by 2 ($2 \times 0.6 = 1.2$), record the integer part (1).
 6. Continue until the fraction part is 0.
 7. The binary representation is the integer parts of the results.

DOUBLE PRECISION FORMAT

- Note that the binary representation of 0.6 is **infinite** ($0.\overline{1001}$).
- We use only 52 bits for the fraction part.
- We then write 0.6 as $0.\underbrace{1001\ 1001\ \dots\ 1010}_{52\ 0s\ and\ 1s}$ where we have rounded the repetitive end to the nearest binary number 1010.

DOUBLE PRECISION FORMAT

- The largest e value is $1111\ 1111\ 111 = 2047$.
 - When $f = 0$ we use this to represent ∞ .
 - When $f \neq 0$ we use this to represent NaN (not a number).
- The largest positive double precision number has $s = 0, e = 2046$, $f = 1111 \dots 1111 = 1 - 2^{-52}$. It is $\approx 1.797710^{308}$
- **Overflow** occurs when a number is too big to be represented.
- Usually the result will be represented as ∞ .

DOUBLE PRECISION FORMAT

- The smallest e value is $0000\ 0000\ 000 = 0$.
- It is reserved to represent numbers for which representation changes from $1.f$ to $0.f$ (*denormalized numbers*)
- The smallest positive double precision number has $s = 0, e = 1, f = 0000 \dots 0000$. It is $\approx 2.225110^{-308}$
- **Underflow** occurs when a (positive) number is too small to be represented. Gradual underflow.
- Usually the result will be represented as 0.0.

MACHINE EPSILON

- Machine epsilon, ϵ is the distance between 1 and the next largest number that can be represented.
- For any $0 < \delta < \epsilon/2$ we have $1 + \delta$ represented as 1.
- In double precision: $\epsilon \approx 2.2204 \times 10^{-16}$.
- In Julia `eps(Float64)`.
- Note: the distance between 1 and the next smallest number is $\epsilon/2$.
- Generally: numbers in double precision are not equally spaced.

DIGITS OF PRECISION

- In double precision format we have 52 bits for the mantissa.
- $2^{52} = 4,503,599,627,370,496$. We can represent all numbers with 15 digits and some with 16 digits.
- Exponent just shifts the decimal point.
- That means doubles have between 15 and 16 digits of precision.
- **Implication:** numbers like 10000000000000000001 and 10000000000000000002 are stored as the same float.

ERRORS

- **Takeaway:** numbers stored on a computer are approximations.
 - Let \tilde{x} be the approximation of x (for example, as a floating point number).
 - The **absolute error** is $|\tilde{x} - x|$.
 - The **relative error** is $|\tilde{x} - x|/|x|$.
-
- Let $fl(x)$ be the floating point representation of x .
 - We have $fl(x) = x(1 + \delta)$, with $|\delta| \leq \epsilon/2$. δ is the **relative error**.
 - Similarly, let \odot be $+$, $-$, \cdot , $/$. We have $fl(x \odot y) = (x \odot y)(1 + \delta)$.

ROUNDING ERROR

- Suppose we add two numbers x and y . The result will be represented as $(x + y)(1 + \delta)$. What is δ ?

$$\begin{aligned}(x + y)(1 + \delta) &= fl(fl(x) + fl(y)) \\ &= fl(x(1 + \delta_x) + y(1 + \delta_y)) \\ &= [x(1 + \delta_x) + y(1 + \delta_y)](1 + \delta_{x+y})\end{aligned}$$

so

$$\delta = \frac{x\delta_x + y\delta_y + (x + y)\delta_{x+y}}{x + y}.$$

ROUNDING ERROR

- Let $|d_x|, |d_y|, |d_{x+y}| \leq \epsilon$. Then

$$|\delta| \leq \frac{|x| + |y| + |x + y|}{|x + y|} \epsilon.$$

- Caution: the relative error can be **much larger** than ϵ .
- **Catastrophic cancellation.**
- This happens when $x \approx -y$.

ORDER OF OPERATIONS MIGHT MATTER

- By representing numbers as floats operations cease to be associative and distributive.
- We do not necessarily have $(x + y) + z = x + (y + z)$.
- We do not necessarily have $(x + y) \cdot z = x \cdot z + y \cdot z$.
- Order of operations might matter. Start addition from small numbers.

EXAMPLE

- Suppose we want find the roots of the quadratic equation

$$ax^2 + bx + c = 0.$$

- We could use the formula: $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$.
- Problems:
 1. b^2 and $4ac$ might be close to each other.
 2. If $4ac \approx 0$, b and $\sqrt{b^2 - 4ac}$ might be close to each other.

CONDITION NUMBERS

- Let $x \in \mathbb{R}$ be data and $f : \mathbb{R} \rightarrow \mathbb{R}$ be a function.
- Recall we have $f(x) = x(1 + \delta)$ with $|\delta| \leq \epsilon/2$.
- We are interested in how much the output of f changes when the input changes.
- We can measure it as

$$\frac{\frac{|f(x) - f(x(1+\delta))|}{|f(x)|}}{\frac{|x - x(1+\delta)|}{|x|}}$$

- It looks like elasticity of f with respect to x .

CONDITION NUMBERS

- The expression can be simplified to

$$\frac{|f(x + \delta x) - f(x)|}{|\delta f(x)|}$$

- Take the limit as $\delta \rightarrow 0$ and suppose f is differentiable. We define the **relative condition number** as

$$\kappa_f(x) = \left| \frac{xf'(x)}{f(x)} \right|$$

- For small δ we have

$$\frac{|f(x + \delta x) - f(x)|}{|\delta f(x)|} \approx \kappa_f(x) |\delta|.$$

- The relative perturbation in the input, δ , is amplified by the relative condition number.

CONDITION NUMBERS

- If the relative condition number is large, we call a problem **ill-conditioned**. Otherwise, we call it **well-conditioned**.
- In an ill-conditioned problem, small perturbations in the input can lead to large changes in the output.
- If $\kappa_f(x) = 10^k$, you might lose up to k digits of accuracy due to f itself.
- For example, if $\kappa_f(x) = 10^{16}$ `Float64` is useless.

CONDITION NUMBERS

- Most problems have more than one input and output.
- We can generalize the concepts of relative condition numbers to accomodate these cases.
- We will also see later how to extend the concept of condition numbers to matrices.

CONDITION NUMBERS

- Consider again the quadratic equation $ax^2 + bx + c = 0$.
- Let's pick one root, x_1 and consider what happens to it as we vary a .
- We have $f(a) = x_1$ with $f'(a) = -\frac{x_1^2}{2ax_1 + b}$.
- The condition number is

$$\kappa_f(a) = \left| \frac{ax_1}{2ax_1 + b} \right| = \left| \frac{x_1}{x_1 - x_2} \right|$$

- The problem is ill-conditioned when $x_1 \approx x_2$.
- Think of the extreme case with a repeated root.

LITTLE “OH” - BIG “OH”

- Let $f : \mathbb{N} \rightarrow \mathbb{R}_+$ and $g : \mathbb{N} \rightarrow \mathbb{R}_+$.
- We say that $f = \mathcal{O}(g)$ (f is “big-Oh” of g) if there exists $c > 0$ and $n_0 \in \mathbb{N}$ such that

$$f(n) \leq cg(n) \text{ for all } n \geq n_0.$$

- This says that the ratio $f(n)/g(n)$ is bounded from above as $n \rightarrow \infty$.
- $f(n)$ might be much smaller than $g(n)$, this is just a bound.

LITTLE “OH” - BIG “OH”

- We say that $f = o(g)$ (f is “little-oh” of g) if for any $c > 0$ there exists $n_0 \in \mathbb{N}$ such that

$$f(n) \leq cg(n) \text{ for all } n \geq n_0.$$

- For strictly positive g this says that the ratio $f(n)/g(n)$ goes to zero as $n \rightarrow \infty$.

LITTLE “OH” - BIG “OH”

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$$f(n) \leq cg(n) \text{ for all } n \geq n_0.$$

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LITTLE “OH” - BIG “OH”

- Let $f(n) = a_1n^3 + b_1n^2 + c_1n$ and $g(n) = a_2n^3$.
- We have

$$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = \frac{a_1}{a_2}.$$

- This means that $f = \mathcal{O}(g)$.
- At the same time f is not $o(g)$.

FLOPS

- A **flop** is a **floating point operation**.
- We count flops to measure the complexity of an algorithm.
- Suppose A is an $n \times n$ matrix and b is an $n \times 1$ vector.
- We want to calculate Ab .
- To calculate one element of Ab :

$$\sum_{i=1}^n A_{ij} b_j.$$

- There are n multiplications and $n - 1$ additions.
- We need to do it n times. In total we have $n(n - 1)$ flops, or $\mathcal{O}(n^2)$.

FLOPS

- If the run time of an algorithm is dominated by flops, we expect

$$\text{run time} \approx c \times \text{flops}$$

for some constant c .

- In our example, if $n_1 = 1000$ and $n_2 = 2000$, we expect the run time of the algorithm for n_2 to be four times longer than for n_1 .

FLOPS

- Suppose A, B are $n \times n$ matrices. We want to calculate AB .
- To calculate one element of AB :

$$\sum_{k=1}^n A_{ik} B_{kj}.$$

- There are n multiplications and $n - 1$ additions.
- We need to do it n^2 times. In total we have $2n^3$ flops, or $\mathcal{O}(n^3)$.
- In our example, if $n_1 = 1000$ and $n_2 = 2000$, we expect the run time of the algorithm for n_2 to be eight times longer than for n_1 .
- Matrix multiplication using this algorithm is expected to take n times longer than matrix-vector multiplication.