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

- $\mathbb{R}$ (real numbers) is large, but computers have finite memory.
- We need to find some representation of $\mathbb{R}$.
- Fix a base β and integers p, m, M. Define a floating point system as

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

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

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

FLOATING POINT NUMBERS

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

- Why “floating point”? By varying e we can represent numbers by shifting the decimal point.

- Example: Consider $\beta = 10$ and two numbers $x_1 = 0.12 \times 10^1$ and $x_2 = 0.12 \times 10^2$.

  These are $x_1 = 1.200$ and $x_2 = 12.00$. The location of the decimal point is different.

FLOATING POINT NUMBERS

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

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

- We use the following names:
  - 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 $f = 0$.

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

$$\rightarrow \underbrace{0}_{\text{sign}} \; \underbrace{001111111111}_{\text{1023 in base 2}} \; 0000\ldots0000$$

DOUBLE PRECISION FORMAT

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

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

$$\rightarrow \underbrace{\;0\;}_{\text{sign}} \; \underbrace{100000000000}_{\text{1024 in base 2}} \; 0000\ldots0000$$

DOUBLE PRECISION FORMAT

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

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

$$\rightarrow \underbrace{\ 0\ }_{\text{sign}}\ \underbrace{00111111110}_{\text{1022 in base 2}}\ 0000\ldots0000$$

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?
- Note: it is similar to representing 1/3 in the decimal system.

DOUBLE PRECISION FORMAT

- How to represent fractions (here 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 $0.\underbrace{1001\,1001\ldots1010}_{\text{52 0s and 1s}}$ 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 $s = 0, e = 2046$, $f = 1111\ldots1111 = 1 - 2^{-52}$. 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 $s = 0, e = 1, f = 0000\ldots0000$. It is $\approx 2.225110^{-308}$
- Underflow occurs when a (positive) number is too small to be represented.
- 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 (i.e., the number just below 1) 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?

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

so

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

ROUNDING ERROR

- Let $|\delta_x|, |\delta_y|, |\delta_{x+y}| \leq \epsilon$. 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 neccesarily have $(x + y) + z = x + (y + z)$.
- We do not neccesarily 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.
- Solution?

LOSS OF PRECISION

- Interested in solving $x^2 - 26x + 1 = 0$. True solution:

$$x_1 = 13 - \sqrt{168} \approx 0.03852, \quad x_2 = 13 + \sqrt{168} \approx 25.961.$$

- Assume we use a format with 5 signiciant digits: $\sqrt{168}$ is represented as 12.961.
- We calculate the first root as $13.000 - 12.961 = 0.03900$ instead of 0.03852.
- Only two digits (0 and 3) are correct. We lost three digits of precision.
- Instead, we can use $13 - \sqrt{168} = \frac{1}{13+\sqrt{168}}$ to get a more accurate result: 0.93852.

CONDITION NUMBERS

- Let $x \in \mathbb{R}$ be data and $f : \mathbb{R} \to \mathbb{R}$ be a function.
- Recall we have $fl(x) = x(1 + \delta)$ 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 $\delta \to 0$ 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 $f : \mathbb{N} \to \mathbb{R}_+$ and $g : \mathbb{N} \to \mathbb{R}_+$.
- 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 $n \to \infty$.
- $f(n)$ 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 $n \to \infty$.

LITTLE “OH” - BIG “OH”

- Let $f(n) = a_1 n^3 + b_1 n^2 + c_1 n$ and $g(n) = a_2 n^3$.
- We have

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

- 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 $n\,(n + n - 1)$ flops, or $\mathcal{O}\left(n^2\right)$.

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.