CS170: Discrete Methods in Computer Science
Summer 2023
Runtime and Order Notation

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[1] These slides adapt some content from similar slides by Aaron Cote.

Outline

Comparing Algorithms

- An algorithm takes an input and produces an output
  - E.g. Takes in an unsorted array, and sorts it
- There are often different algorithms for the same task
  - Bubble sort vs mergesort vs quicksort vs insertion sort . . .
- How to compare them?
  - Runtime
  - Memory
  - Simplicity
  - Communication bandwidth
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We go with number of operations:

- Different instruction sets / programming languages tend to be effectively equivalent here (more on this later).

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Usually, and for all our purposes in this class, f is non-decreasing. But what is the "size" of an input?

- In the strictest sense, it is the number of bits used to write that input down
- Sometimes, we cut corners and quantify size differently
  - E.g. By the length of the array in sorting
- So long as you're clear about what your n "means", you can choose the measure of size that best suits your problem.

Worst-Case vs Average Case

In CS, it is most common to consider worst-case runtime, instead of "average case". Why?

- Gives iron-clad gaurantees that always hold regardless of real-world setting
- Tends to be predictive in practice
- No need to make assumptions on real-world inputs, which often are hard to formulate.
  - What is "average case" array, social network, image?
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Nevertheless, sometimes average case, or something between average and worst case, makes sense. We won't get into that in this class.

Common Examples of Runtimes

- Constant: 3, 5, 134893430
- Linear: n, $2n + 1$, $100n + 3$, ...
- Quadratic: n^2, $3n^2 + 1000n - 1$, ...
- Polynomial: $2n^5 + n^3 - n + 2$, ...
- Logarithmic: $\log n$, $5 \log n \log \log n + 3$, ...
- Exponential: 2^n, $3 \cdot 5^n + n^2$, ...
- ...

Granularity of Runtimes

At what granularity do we want to quantify runtime?

- Capture aspects of runtime that persist as we tweak architecture, basic instructions, increase number of cores,
  - Ignore constant multiples. n^2 and $5n^2$ should be "effectively the same"
- Judge runtime "as input grows large"
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This is what Order Notation does (Next)

Outline

Big-O

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For two functions $f, g : \mathbb{N} \to \mathbb{N}$, we say $f(n) = O(g(n))$ if there are constants n_0 and c such that $f(n) \leq cg(n)$ for all $n \geq n_0$.

In other words, $f(n)$ eventually less than $g(n)$, if you don't care about constants. We refer to this as asymptotic order of growth.

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Another Definition of big-O

$f(n) = O(g(n))$ if $\lim_{n\to\infty} \frac{f(n)}{g(n)} < \infty$.

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This is abuse of the $=$ symbol

If $f = O(g)$, we can't say $O(g) = f$. Really, it should be $f \in O(g)$, where $O(g)$ is the class of functions that asymptotically grow no faster than g, but this abuse of notation is with us for historical reasons.

Examples

- $10n^3 = O(n^3)$
- $10000n = O(n^2)$
- $\log n = O(n)$
- $10000n^{100} = O(2^n)$
- $\ldots$

Friends of Big-O

- $f(n) = \Omega(g(n))$: $\exists c, n_0 \; \forall n \geq n_0 \;\; f(n) \geq cg(n)$
  - Equivalent to $g(n) = O(f(n))$.
- $f(n) = \Theta(g(n))$: Both $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$
  - f and g are within a constant of each other for large enough n.
- $f(n) = o(g(n))$: $\forall c > 0 \; \exists n_0 \; \forall n \geq n_0 \;\; f(n) < cg(n)$
  - When limit ratio exists: Same as $\lim_{n \to \infty} \frac{f(n)}{g(n)} = 0$. Also same as $f(n) = O(g(n)$ but not $f(n) = \Omega(g(n))$.
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Think of $O, \Omega, \theta, o, \omega$ as $\leq, \geq, =, <, >$ respectively for comparing order of growth.

Outline

Exercise

Compare $\log n$ and $\sqrt{n}$. (Hint: Use L'Hopital's rule)

Common Rules of Thumb

- Constants are best
- Then logs and polylogs
- Then polynomials
- Then exponentials

These are the most common, but there is other stuff between them, and also beyond exponentials.

Exercise

Order the following runtimes

- n^n
- $\log^2 n$
- $n^{1.01}$
- 1.01^n
- $2^{\sqrt{\log n}}$
- $n \log^{1000} n$