

Lecture 5

Comparison-based Lower Bounds for Sorting

5.1 Overview

In this lecture we discuss the notion of *lower bounds*, in particular for the problem of sorting. We show that any deterministic comparison-based sorting algorithm must take $\Omega(n \log n)$ time to sort an array of n elements in the worst case. We then extend this result to average case performance, and to randomized algorithms. In the process, we introduce the 2-player game view of algorithm design and analysis.

5.2 Sorting lower bounds

So far we have been focusing on the question: “given some problem X , can we construct an algorithm that runs in time $O(f(n))$ on inputs of size n ?” This is often called an upper bound problem because we are determining an upper bound on the inherent difficulty of problem X , and our goal here is to make $f(n)$ as small as possible. In this lecture we examine the “lower bound problem.” Here, the goal is to prove that *any* algorithm must take time $\Omega(g(n))$ time to solve the problem, where now our goal is to do this for $g(n)$ as large as possible. Lower bounds help us understand how close we are to the best possible solution to some problem: e.g., if we have an algorithm that runs in time $O(n \log^2 n)$ and a lower bound of $\Omega(n \log n)$, then we have a $\log(n)$ “gap”: the maximum possible savings we could hope to achieve by improving our algorithm.

Often, we will prove lower bounds in restricted models of computation, that specify what types of operations may be performed on the input and at what cost. So, a lower bound in such a model means that if we want to do better, we would need somehow to do something outside the model.

Today we consider the class of comparison-based sorting algorithms. These are sorting algorithms that only operate on the input array by comparing pairs of elements and moving elements around based on the results of these comparisons. In particular, let us make the following definition.

Definition 5.1 *A comparison-based sorting algorithm takes as input an array $[a_1, a_2, \dots, a_n]$ of n items, and can only gain information about the items by comparing pairs of them. Each comparison (“is $a_i > a_j$?”) returns YES or NO and counts a 1 time-step. The algorithm may also for free*

reorder items based on the results of comparisons made. In the end, the algorithm must output a permutation of the input in which all items are in sorted order.

For instance, Quicksort, Mergesort, and Insertion-sort are all comparison-based sorting algorithms. What we will show is the following theorem.

Theorem 5.1 *Any deterministic comparison-based sorting algorithm must perform $\Omega(n \log n)$ comparisons to sort n elements in the worst case. Specifically, for any deterministic comparison-based sorting algorithm \mathcal{A} , for all $n \geq 2$ there exists an input I of size n such that \mathcal{A} makes at least $\log_2(n!) = \Omega(n \log n)$ comparisons to sort I .*

To prove this theorem, we cannot assume the sorting algorithm is going to necessarily choose a pivot as in Quicksort, or split the input as in Mergesort — we need to somehow analyze *any possible* (comparison-based) algorithm that might exist. The way we will do this is by showing that in order to sort its input, the sorting algorithm is implicitly playing a game of “20 questions” with the input, and an adversary by responding correctly can force the algorithm to ask many questions before it can tell what is the correct permutation to output.

Proof: Recall that the sorting algorithm must output a permutation of the input $[a_1, a_2, \dots, a_n]$. The key to the argument is that (a) there are $n!$ different possible permutations the algorithm might output, and (b) for each of these permutations, there exists an input for which that permutation is the only correct answer. For instance, the permutation $[a_3, a_1, a_4, a_2]$ is the only correct answer for sorting the input $[2, 4, 1, 3]$. In fact, if you fix a set of n distinct elements, then there will be a 1-1 correspondence between the different orderings the elements might be in and the permutations needed to sort them.

Given (a) and (b) above, this means we can fix some set of $n!$ inputs (e.g., all orderings of $\{1, 2, \dots, n\}$), one for each of the $n!$ output permutations.

let S be the set of these inputs that are consistent with the answers to all comparisons made so far (so, initially, $|S| = n!$). We can think of a new comparison as splitting S into two groups: those inputs for which the answer would be YES and those for which the answer would be NO. Now, suppose an adversary always gives the answer to each comparison corresponding to the larger group. Then, each comparison will cut down the size of S by at most a factor of 2. Since S initially has size $n!$, and by construction, the algorithm at the end must have reduced $|S|$ down to 1 in order to know which output to produce, the algorithm must make at least $\log_2(n!)$ comparisons before it can halt. We can then solve:

$$\begin{aligned} \log_2(n!) &= \log_2(n) + \log_2(n-1) + \dots + \log_2(2) \\ &= \Omega(n \log n). \quad \blacksquare \end{aligned}$$

Notice that our proof is like a game of 20 Questions in which the responder (the adversary) doesn’t actually decide what he is thinking of until there is only one option left. This is legitimate because we just need to show that there is *some* input that would cause the algorithm to take a long time. In other words, since the sorting algorithm is deterministic, we can take that final remaining option and then re-run the algorithm on that specific input, and the algorithm will make the same exact sequence of operations.

Let’s do an example with $n = 3$, and S as initially consisting of the 6 possible orderings of $\{1, 2, 3\}$:

$$(123), (132), (213), (231), (312), (321).$$

Suppose the sorting algorithm initially compares the first two elements a_1 and a_2 . Half of the possibilities have $a_1 > a_2$ and half have $a_2 > a_1$. So, the adversary can answer either way and let's say it answers that $a_2 > a_1$. This narrows down the input to the three possibilities:

$$(123), (132), (231).$$

Suppose the next comparison is between a_2 and a_3 . In this case, the most popular answer is that $a_2 > a_3$, so the adversary returns that answer which removes just one ordering, leaving the algorithm with:

$$(132), (231).$$

It now takes one more comparison to finally isolate the input ordering and determine the correct permutation to output.

Alternative view of the proof: Another way of looking at the proof we gave above is as follows. For a deterministic algorithm, the permutation it outputs is solely a function of the series of answers it receives (any two inputs producing the same series of answers will cause the same permutation to be output). So, if an algorithm always made at most $k < \lg(n!)$ comparisons, then there are at most $2^k < n!$ different permutations it can possibly output. In other words, there is some permutation it *can't* output. So, the algorithm will fail on any input for which that permutation is the only correct answer.

Question: Suppose we consider the problem: “order the input array so that the smallest $n/2$ come before the largest $n/2$ ”? Does our lower bound still hold for that problem, or where does it break down? How fast can you solve that problem?

Answer: No, the proof does not still hold. It breaks down because any given input can have multiple correct answers. E.g., for input [2 1 4 3], we could output any of $[a_1, a_2, a_3, a_4]$, $[a_2, a_1, a_3, a_4]$, $[a_1, a_2, a_4, a_3]$, or $[a_2, a_1, a_4, a_3]$. In fact, not only does the lower bound break down, but we can actually solve this problem in linear time: just run the linear-time median-finding algorithm and then make a second pass putting elements into the first half or second half based on how they compare to the median.

5.3 Average-case lower bounds

In fact, we can generalize the above theorem to show that any comparison-based sorting algorithm must take $\Omega(n \log n)$ time *on average*, not just in the worst case.

Theorem 5.2 *For any deterministic comparison-based sorting algorithm \mathcal{A} , the average-case number of comparisons (the number of comparisons on average on a randomly chosen permutation of n distinct elements) is at least $\lceil \log_2(n!) \rceil$.*

Proof: Let S be the set of all $n!$ possible orderings of n distinct elements. As noted in the previous argument, these each require a different permutation to be produced as output. Let's now build out the entire decision tree for algorithm \mathcal{A} on S : the tree we get by looking at all the different question/answer paths we get by running algorithm \mathcal{A} on the inputs in S . This tree has $n!$ leaves, where the depth of a leaf is the number of comparisons performed by the sorting algorithm on

that input. Our goal is to show that the *average* depth of the leaves must be at least $\lfloor \log_2(n!) \rfloor$ (previously, we only cared about the *maximum* depth).

If the tree is completely balanced, then each leaf is at depth $\lceil \log_2(n!) \rceil$ or $\lfloor \log_2(n!) \rfloor$ and we are done.¹ To prove the theorem, we just need to show that out of all binary trees on a given number of leaves, the one that minimizes their average depth is a completely balanced tree. This is not too hard to see: given some unbalanced tree, we take two sibling leaves at largest depth and move them to be children of the leaf of smallest depth. Since the difference between the largest depth and the smallest depth is at least 2 (otherwise the tree would be balanced), this operation reduces the average depth of the leaves. Specifically, if the smaller depth is d and the larger depth is D , we have removed two leaves of depth D and one of depth d , and we have added two leaves of depth $d + 1$ and one of depth $D - 1$. Since any unbalanced tree can be modified to have a smaller average depth, such a tree cannot be one that *minimizes* average depth, and therefore the tree of smallest average depth must in fact be balanced. ■

In fact, if we are a bit more clever in the proof, we can get rid of the floor in the bound.

5.4 Lower bounds for randomized algorithms

Theorem 5.3 *The above bound holds for randomized algorithms too.*

Proof: The argument here is a bit subtle. The first step is to argue that with respect to counting comparisons, we can think of a randomized algorithm \mathcal{A} as a probability distribution over deterministic algorithms. In particular, we can think of a randomized algorithm \mathcal{A} as a deterministic algorithm with access to a special “random bit tape”: every time \mathcal{A} wants to flip a coin, it just pulls the next bit off that tape. In that case, for any *given* run of algorithm \mathcal{A} , say reading bit-string s from that tape, there is an equivalent deterministic algorithm \mathcal{A}_s with those bits hardwired in. Algorithm \mathcal{A} is then a probability distribution over all those deterministic algorithms \mathcal{A}_s .

This means that the expected number of comparisons made by randomized algorithm \mathcal{A} on some input I is just

$$\sum_s \Pr(s) (\text{Running time of } \mathcal{A}_s \text{ on } I).$$

If you recall the definition of expectation, the running time of the randomized algorithm is a random variable and the sequences s correspond to the elementary events.

So, the expected running time of the randomized algorithm is just an average over deterministic algorithms. Since each deterministic algorithm has average-case running time at least $\lfloor \log_2(n!) \rfloor$, any average over them must too. Formally, the average-case running time of the randomized algorithm is

$$\begin{aligned} \text{avg}_{\text{inputs } I} \sum_s [\Pr(s) (\text{Running time of } \mathcal{A}_s \text{ on } I)] &= \sum_s \text{avg}_I [\Pr(s) (\text{Running time of } \mathcal{A}_s \text{ on } I)] \\ &= \sum_s \Pr(s) \text{avg}_I (\text{Running time of } \mathcal{A}_s \text{ on } I) \end{aligned}$$

¹Let us define a tree to be completely balanced if the deepest leaf is at most one level deeper than the shallowest leaf. Everything would be easier if we could somehow assume $n!$ was a power of 2....

$$\begin{aligned} &\geq \sum_s \Pr(s) \lfloor \log_2(n!) \rfloor \\ &= \lfloor \log_2(n!) \rfloor. \quad \blacksquare \end{aligned}$$

One way to think of the kinds of bounds we have been proving is to think of a matrix with one row for every possible deterministic comparison-based sorting algorithm (there could be a lot of rows!) and one column for every possible permutation of n given input elements (there are a lot of columns too). Entry (i, j) in this matrix contains the running time of algorithm i on input j . The worst-case deterministic lower bound tells us that for each row i there exists a column j_i such that the entry (i, j_i) is large. The average-case deterministic lower bound tells us that for each row i , the average of the elements in the row is large. The randomized lower bound says “well, since the above statement holds for every row, it must also hold for any weighted average of the rows.” In the language of game-theory, one could think of this as a two-player game (much like rock-paper-scissors) between an “algorithm player” who gets to pick a row and an adversarial “input player” who gets to pick a column. Each player makes their choice and the entry in the matrix is the cost to the algorithm-player which we can think of as how much money the algorithm-player has to pay the input player. We have shown that there is a randomized strategy for the input player (namely, pick a column at random) that guarantees it an expected gain of $\Omega(n \log n)$ no matter what strategy the algorithm-player chooses.