15-451 Algorithms

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Contents

Lecture 1

Introduction to Algorithms

1.1 Overview

The purpose of this lecture is to give a brief overview of the topic of Algorithms and the kind of thinking it involves: why we focus on the subjects that we do, and why we emphasize proving guarantees. We also go through examples of some problems that are easy to relate to (multiplying two numbers and multiplying two matrices) in which the straightforward approach is surprisingly not the fastest one. These examples leads naturally into the study of divide-and-conquer algorithms and provide a forward pointer to topics such as the FFT later on in the course.

Material in this lecture:

- Administrivia (see handouts)
- What is the study of Algorithms all about?
- Why do we care about specifications and proving guarantees?
- The Karatsuba multiplication algorithm.
- Strassen's matrix multiplication algorithm.

1.2 Introduction

This course is about the design and analysis of algorithms — how to design correct, efficient algorithms, and how to think clearly about analyzing correctness and running time.

What is an algorithm? At its most basic, an algorithm is a method for solving a computational problem. Along with an algorithm comes a specification that says what the algorithm's guarantees are. For example, we might be able to say that our algorithm indeed correctly solves the problem in question and runs in time at most $f(n)$ on any input of size n. This course is about the whole package: the design of efficient algorithms, *and* proving that they meet desired specifications. For each of these parts, we will examine important techniques that have been developed, and with practice we will build up our ability to think clearly about the key issues that arise.

The main goal of this course is to provide the intellectual tools for designing and analyzing your own algorithms for problems you need to solve in the future. Some tools we will discuss are Dynamic Programming, Divide-and-Conquer, Hashing and other Data Structures, Randomization, Network Flows, Linear Programming, and the Fast Fourier Transform. Some analytical tools we will discuss and use are Recurrences, Probabilistic Analysis, Amortized Analysis, and Potential Functions.

There is also a dual to algorithm design: Complexity Theory. Complexity Theory looks at the intrinsic difficulty of computational problems — what kinds of specifications can we expect *not* to be able to achieve? In this course, we will delve a bit into complexity theory, focusing on the somewhat surprising notion of NP-completeness. We will additionally discuss some approaches for dealing with NP-complete problems, including the notion of approximation algorithms.

Other problems may be challenging because they require decisions to be made without having full information, and we will discuss online algorithms and machine learning, which are two paradigms for problems of this nature.

1.3 On guarantees and specifications

One focus of this course is on proving correctness and running-time guarantees for algorithms. Why is having such a guarantee useful? Suppose we are talking about the problem of sorting a list of n numbers. It is pretty clear why we at least want to know that our algorithm is correct, so we don't have to worry about whether it has given us the right answer all the time. But, why analyze running time? Why not just code up our algorithm and test it on 100 random inputs and see what happens? Here are a few reasons that motivate our concern with this kind of analysis — you can probably think of more reasons too:

Composability. A guarantee on running time gives a "clean interface". It means that we can use the algorithm as a subroutine in some other algorithm, without needing to worry whether the kinds of inputs on which it is being used now necessarily match the kinds of inputs on which it was originally tested.

Scaling. The types of guarantees we will examine will tell us how the running time scales with the size of the problem instance. This is useful to know for a variety of reasons. For instance, it tells us roughly how large a problem size we can reasonably expect to handle given some amount of resources.

Designing better algorithms. Analyzing the asymptotic running time of algorithms is a useful way of thinking about algorithms that often leads to nonobvious improvements.

Understanding. An analysis can tell us what parts of an algorithm are crucial for what kinds of inputs, and why. If we later get a different but related task, we can often use our analysis to quickly tell us if a small modification to our existing algorithm can be expected to give similar performance to the new problem.

Complexity-theoretic motivation. In Complexity Theory, we want to know: "how hard is fundamental problem X really?" For instance, we might know that no algorithm can possibly run in time $o(n \log n)$ (growing more slowly than $n \log n$ in the limit) and we have an algorithm that runs in time $O(n^{3/2})$. This tells us how well we understand the problem, and also how much room for improvement we have.

It is often helpful when thinking about algorithms to imagine a game where one player is the algorithm designer, trying to come up with a good algorithm for the problem, and its opponent (the "adversary") is trying to come up with an input that will cause the algorithm to run slowly. An algorithm with good worst-case guarantees is one that performs well no matter what input the adversary chooses. We will return to this view in a more formal way when we discuss lower bounds and game theory.

1.4 An example: Karatsuba Multiplication

One thing that makes algorithm design "Computer Science" is that solving a problem in the most obvious way from its definitions is often not the best way to get a solution. A simple example of this is multiplication.

Say we want to multiply two n-bit numbers: for example, 41×42 (or, in binary, 101001×101010). According to the definition of what it means to multiply, what we are looking for is the result of adding 41 to itself 42 times (or vice versa). You could imagine actually computing the answer that way (i.e., performing 41 additions), which would be correct but not particularly efficient. If we used this approach to multiply two n-bit numbers, we would be making $\Theta(2^n)$ additions. This is exponential in n even without counting the number of steps needed to perform each addition. And, in general, exponential is bad.[1] A better way to multiply is to do what we learned in grade school:

```
        101001 = 41
x       101010 = 42
-------------
       1010010
     101001
+ 101001
-------------
  11010111010 = 1722
```

More formally, we scan the second number right to left, and every time we see a 1, we add a copy of the first number, shifted by the appropriate number of bits, to our total. Each addition takes $O(n)$ time, and we perform at most n additions, which means the total running time here is $O(n^2)$. So, this is a simple example where even though the problem is defined "algorithmically", using the definition is not the best way of solving the problem.

Is the above method the fastest way to multiply two numbers? It turns out it is not. Here is a faster method called Karatsuba Multiplication, discovered by Anatoli Karatsuba, in Russia, in 1962. In this approach, we take the two numbers X and Y and split them each into their most-significant half and their least-significant half:

$X = 2^{n/2}A + B$ | A | B |

$Y = 2^{n/2}C + D$ | C | D |

[1] This is reminiscent of an exponential-time sorting algorithm I once saw in Prolog. The code just contains the definition of what it means to sort the input — namely, to produce a permutation of the input in which all elements are in ascending order. When handed directly to the interpreter, it results in an algorithm that examines all $n!$ permutations of the given input list until it finds one that is in the right order.

We can now write the product of X and Y as

$$XY = 2^n AC + 2^{n/2}BC + 2^{n/2}AD + BD. \quad (1.1)$$

This does not yet seem so useful: if we use (1.1) as a recursive multiplication algorithm, we need to perform four $n/2$-bit multiplications, three shifts, and three $O(n)$-bit additions. If we use $T(n)$ to denote the running time to multiply two n-bit numbers by this method, this gives us a recurrence of

$$T(n) = 4T(n/2) + cn, \quad (1.2)$$

for some constant c. (The cn term reflects the time to perform the additions and shifts.) This recurrence solves to $O(n^2)$, so we do not seem to have made any progress. (In recitation we will review how to solve recurrences like this — see Appendix A.)

However, we can take the formula in (1.1) and rewrite it as follows:

$$(2^n - 2^{n/2})AC + 2^{n/2}(A+B)(C+D) + (1-2^{n/2})BD. \quad (1.3)$$

It is not hard to see — you just need to multiply it out — that the formula in (1.3) is equivalent to the expression in (1.1). The new formula looks more complicated, but, it results in only *three* multiplications of size $n/2$, plus a constant number of shifts and additions. So, the resulting recurrence is

$$T(n) = 3T(n/2) + c'n, \quad (1.4)$$

for some constant c'. This recurrence solves to $O(n^{\log_2 3}) \approx O(n^{1.585})$.

Is *this* method the fastest possible? Again it turns out that one can do better. In fact, Karp discovered a way to use the Fast Fourier Transform to multiply two n-bit numbers in time $O(n \log^2 n)$. Schönhage and Strassen in 1971 improved this to $O(n \log n \log\log n)$, which was until very recently the asymptotically fastest algorithm known.[2] We will discuss the FFT later on in this course.

Actually, the kind of analysis we have been doing really is meaningful only for very large numbers. On a computer, if you are multiplying numbers that fit into the word size, you would do this in hardware that has gates working in parallel. So instead of looking at sequential running time, in this case we would want to examine the size and depth of the circuit used, for instance. This points out that, in fact, there are different kinds of specifications that can be important in different settings.

1.5 Strassen's algorithm for matrix multiplication

It turns out the same basic divide-and-conquer approach of Karatsuba's algorithm can be used to speed up matrix multiplication as well. To be clear, we will now be considering a computational model where individual elements in the matrices are viewed as "small" and can be added or multiplied in constant time. In particular, to multiply two n-by-n matrices in the usual way (we take the

[2] Fürer in 2007 improved this by replacing the $\log\log n$ term with $2^{O(\log^* n)}$, where $\log^* n$ is a very slowly growing function discussed in Lecture 6. It remains unknown whether eliminating it completely and achieving running time $O(n \log n)$ is possible.

ith row of the first matrix and compute its dot-product with the jth column of the second matrix in order to produce the entry ij in the output) takes time $O(n^3)$. If one breaks down each n by n matrix into four $n/2$ by $n/2$ matrices, then the standard method can be thought of as performing eight $n/2$-by-$n/2$ multiplications and four additions as follows:

$$\begin{array}{|c|c|}\hline A & B \\ \hline C & D \\ \hline \end{array} \times \begin{array}{|c|c|}\hline E & F \\ \hline G & H \\ \hline \end{array} = \begin{array}{|c|c|}\hline AE+BG & AF+BH \\ \hline CE+DG & CF+DH \\ \hline \end{array}$$

Strassen noticed that, as in Karatsuba's algorithm, one can cleverly rearrange the computation to involve only *seven* $n/2$-by-$n/2$ multiplications (and 14 additions).[3] Since adding two n-by-n matrices takes time $O(n^2)$, this results in a recurrence of

$$T(n) \quad = \quad 7T(n/2) + cn^2. \tag{1.5}$$

This recurrence solves to a running time of just $O(n^{\log_2 7}) \approx O(n^{2.81})$ for Strassen's algorithm.[4]

Matrix multiplication is especially important in scientific computation. Strassen's algorithm has more overhead than standard method, but it is the preferred method on many modern computers for even modestly large matrices. Asymptotically, the best matrix multiply algorithm known is by Coppersmith and Winograd and has time $O(n^{2.376})$, but is not practical. Nobody knows if it is possible to do better — the FFT approach doesn't seem to carry over.

[3] In particular, the quantities that one computes recursively are $q_1 = (A+D)(E+H)$, $q_2 = D(G-E)$, $q_3 = (B-D)(G+H)$, $q_4 = (A+B)H$, $q_5 = (C+D)E$, $q_6 = A(F-H)$, and $q_7 = (C-A)(E+F)$. The upper-left quadrant of the solution is $q_1 + q_2 + q_3 - q_4$, the upper-right is $q_4 + q_6$, the lower-left is $q_2 + q_5$, and the lower right is $q_1 - q_5 + q_6 + q_7$. (feel free to check!)

[4] According to Manuel Blum, Strassen said that when coming up with his algorithm, he first tried to solve the problem mod 2. Solving mod 2 makes the problem easier because you only need to keep track of the parity of each entry, and in particular, addition is the same as subtraction. One he figured out the solution mod 2, he was then able to make it work in general.

Lecture 2

Selection (deterministic & randomized): finding the median in linear time

2.1 Overview

Given an unsorted array, how quickly can one find the median element? Can one do it more quickly than by sorting? This was an open question for some time, solved affirmatively in 1972 by (Manuel) Blum, Floyd, Pratt, Rivest, and Tarjan. In this lecture we describe two linear-time algorithms for this problem: one randomized and one deterministic. More generally, we solve the problem of finding the kth smallest out of an unsorted array of n elements.

2.2 The problem and a randomized solution

Consider the problem of finding the kth smallest element in an unsorted array of size n. (Let's say all elements are distinct to avoid the question of what we mean by the kth smallest when we have equalities). One way to solve this problem is to sort and then output the kth element. We can do this in time $O(n \log n)$ if we sort using Mergesort, Quicksort, or Heapsort. Is there something faster – a linear-time algorithm? The answer is yes. We will explore both a simple randomized solution and a more complicated deterministic one.

The idea for the randomized algorithm is to start with the Randomized-Quicksort algorithm (choose a random element as "pivot", partition the array into two sets LESS and GREATER consisting of those elements less than and greater than the pivot respectively, and then recursively sort LESS and GREATER). Then notice that there is a simple speedup we can make if we just need to find the kth smallest element. In particular, after the partitioning step we can tell which of LESS or GREATER has the item we are looking for, just by looking at their sizes. So, we only need to recursively examine one of them, not both. For instance, if we are looking for the 87th-smallest element in our array, and suppose that after choosing the pivot and partitioning we find that LESS has 200 elements, then we just need to find the 87th smallest element in LESS. On the other hand, if we find LESS has 40 elements, then we just need to find the $87 - 40 - 1 = 46$th smallest element in GREATER. (And if LESS has size exactly 86 then we can just return the pivot). One might

at first think that allowing the algorithm to only recurse on one subset rather than both would just cut down time by a factor of 2. However, since this is occuring recursively, it compounds the savings and we end up with $\Theta(n)$ rather than $\Theta(n \log n)$ time. This algorithm is often called Randomized-Select, or QuickSelect.

QuickSelect: Given array A of size n and integer $k \leq n$,

1. Pick a pivot element p at random from A.
2. Split A into subarrays LESS and GREATER by comparing each element to p as in Quicksort. While we are at it, count the number L of elements going in to LESS.
3. (a) If $L = k-1$, then output p.
   (b) If $L > k-1$, output QuickSelect(LESS, k).
   (c) If $L < k-1$, output QuickSelect(GREATER, $k-L-1$)

Theorem 2.1 *The expected number of comparisons for QuickSelect is $O(n)$.*

Before giving a formal proof, let's first get some intuition. If we split a candy bar at random into two pieces, then the expected size of the larger piece is 3/4 of the bar. If the size of the larger subarray after our partition was always 3/4 of the array, then we would have a recurrence $T(n) \leq (n-1) + T(3n/4)$ which solves to $T(n) < 4n$. Now, this is not quite the case for our algorithm because $3n/4$ is only the *expected* size of the larger piece. That is, if i is the size of the larger piece, our expected cost to go is really $\mathbf{E}[T(i)]$ rather than $T(\mathbf{E}[i])$. However, because the answer is linear in n, the average of the $T(i)$'s turns out to be the same as T(average of the i's). Let's now see this a bit more formally.

Proof (Theorem 2.1): Let $T(n,k)$ denote the expected time to find the kth smallest in an array of size n, and let $T(n) = \max_k T(n,k)$. We will show that $T(n) < 4n$.

First of all, it takes $n-1$ comparisons to split into the array into two pieces in Step 2. These pieces are equally likely to have size 0 and $n-1$, or 1 and $n-2$, or 2 and $n-3$, and so on up to $n-1$ and 0. The piece we recurse on will depend on k, but since we are only giving an upper bound, we can imagine that we always recurse on the larger piece. Therefore we have:

$$\begin{aligned} T(n) &\leq (n-1) + \frac{2}{n}\sum_{i=n/2}^{n-1} T(i) \\ &= (n-1) + \text{avg}\left[T(n/2), \ldots, T(n-1)\right]. \end{aligned}$$

We can solve this using the "guess and check" method based on our intuition above. Assume inductively that $T(i) \leq 4i$ for $i < n$. Then,

$$\begin{aligned} T(n) &\leq (n-1) + \text{avg}\left[4(n/2), 4(n/2+1), \ldots, 4(n-1)\right] \\ &\leq (n-1) + 4(3n/4) \\ &< 4n, \end{aligned}$$

and we have verified our guess. ■

2.3 A deterministic linear-time algorithm

What about a deterministic linear-time algorithm? For a long time it was thought this was impossible – that there was no method faster than first sorting the array. In the process of trying to prove this claim it was discovered that this thinking was incorrect, and in 1972 a deterministic linear time algorithm was developed.

The idea of the algorithm is that one would like to pick a pivot deterministically in a way that produces a good split. Ideally, we would like the pivot to be the median element so that the two sides are the same size. But, this is the same problem we are trying to solve in the first place! So, instead, we will give ourselves leeway by allowing the pivot to be any element that is "roughly" in the middle: at least 3/10 of the array below the pivot and at least 3/10 of the array above. The algorithm is as follows:

DeterministicSelect: Given array A of size n and integer $k \leq n$,

1. Group the array into $n/5$ groups of size 5 and find the median of each group. (For simplicity, we will ignore integrality issues.)
2. Recursively, find the true median of the medians. Call this p.
3. Use p as a pivot to split the array into subarrays LESS and GREATER.
4. Recurse on the appropriate piece.

Theorem 2.2 *DeterministicSelect makes $O(n)$ comparisons to find the kth smallest in an array of size n.*

Proof: Let $T(n,k)$ denote the worst-case time to find the kth smallest out of n, and $T(n) = \max_k T(n,k)$ as before.

Step 1 takes time $O(n)$, since it takes just constant time to find the median of 5 elements. Step 2 takes time at most $T(n/5)$. Step 3 again takes time $O(n)$. Now, we claim that at least 3/10 of the array is $\leq p$, and at least 3/10 of the array is $\geq p$. Assuming for the moment that this claim is true, Step 4 takes time at most $T(7n/10)$, and we have the recurrence:

$$T(n) \quad \leq \quad cn + T(n/5) + T(7n/10), \tag{2.1}$$

for some constant c. Before solving this recurrence, lets prove the claim we made that the pivot will be roughly near the middle of the array. So, the question is: how bad can the median of medians be?

Let's first do an example. Suppose the array has 15 elements and breaks down into three groups of 5 like this:

$$\{1,2,3,10,11\}, \quad \{4,5,6,12,13\}, \quad \{7,8,9,14,15\}.$$

In this case, the medians are 3, 6, and 9, and the median of the medians p is 6. There are five elements less than p and nine elements greater.

In general, what is the worst case? If there are $g = n/5$ groups, then we know that in at least $\lceil g/2 \rceil$ of them (those groups whose median is $\leq p$) at least three of the five elements are $\leq p$. Therefore, the total number of elements $\leq p$ is at least $3\lceil g/2 \rceil \geq 3n/10$. Similarly, the total number of elements $\geq p$ is also at least $3\lceil g/2 \rceil \geq 3n/10$.

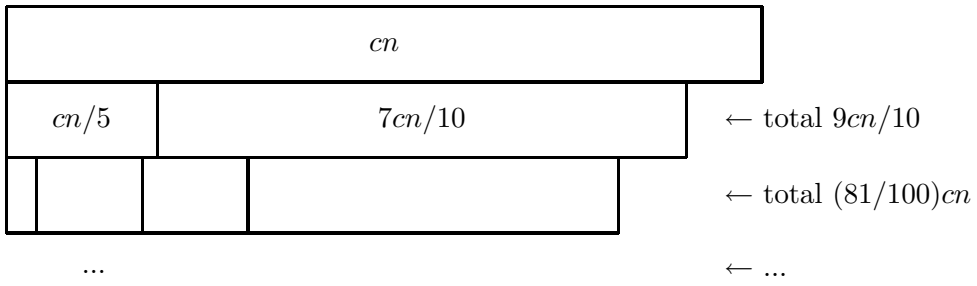


Figure 2.1: Stack of bricks view of recursions tree for recurrence 2.1.

Now, finally, let's solve the recurrence. We have been solving a lot of recurrences by the "guess and check" method, which works here too, but how could we just stare at this and *know* that the answer is linear in n? One way to do that is to consider the "stack of bricks" view of the recursion tree discussed in Appendix A.

In particular, let's build the recursion tree for the recurrence (2.1), making each node as wide as the quantity inside it:

Notice that even if this stack-of-bricks continues downward forever, the total sum is at most

$$cn(1 + (9/10) + (9/10)^2 + (9/10)^3 + \ldots),$$

which is at most $10cn$. This proves the theorem. ■

Notice that in our analysis of the recurrence (2.1) the key property we used was that $n/5+7n/10 < n$. More generally, we see here that if we have a problem of size n that we can solve by performing recursive calls on pieces whose total size is at most $(1-\epsilon)n$ for some constant $\epsilon > 0$ (plus some additional $O(n)$ work), then the total time spent will be just linear in n. This gives us a nice extension to our "Master theorem" from Appendix A.

Theorem 2.3 *For constants c and $a_1, \ldots, a_k$ such that $a_1 + \ldots a_k < 1$, the recurrence*

$$T(n) \quad \leq \quad T(a_1 n) + T(a_2 n) + \ldots T(a_k n) + cn$$

solves to $T(n) = O(n)$.

Lecture 3

Concrete models and tight upper/lower bounds

3.1 Overview

In this lecture, we will examine some simple, concrete models of computation, each with a precise definition of what counts as a step, and try to get tight upper and lower bounds for a number of problems. Specific models and problems examined in this lecture include:

- The number of comparisons needed to sort an array.
- The number of exchanges needed to sort an array.
- The number of comparisons needed to find the largest and second-largest elements in an array.
- The number of probes into a graph needed to determine if the graph is connected (the evasiveness of connectivity).

3.2 Terminology and setup

In this lecture, we will look at (worst-case) upper and lower bounds for a number of problems in several different concrete models. Each model will specify exactly what operations may be performed on the input, and how much they cost. Typically, each model will have some operations that cost 1 step (like performing a comparison, or swapping a pair of elements), some that are free, and some that are not allowed at all.

By an *upper bound* of $f(n)$ for some problem, we mean that there exists an algorithm that takes at most $f(n)$ steps on any input of size n. By a *lower bound* of $g(n)$, we mean that for any algorithm there exists an input on which it takes at least $g(n)$ steps. The reason for this terminology is that if we think of our goal as being to understand the "true complexity" of each problem, measured in terms of the best possible worst-case guarantee achievable by any algorithm, then an upper bound of $f(n)$ and lower bound of $g(n)$ means that the true complexity is somewhere between $g(n)$ and $f(n)$.

3.3 Sorting in the comparison model

One natural model for examining problems like sorting is what is known as the comparison model.

Definition 3.1 *In the* comparison model*, we have an input consisting of n items (typically in some initial order). An algorithm may compare two items (asking is $a_i > a_j$?) at a cost of 1. Moving the items around is free. No other operations on the items are allowed (such as using them as indices, XORing them, etc).*

For the problem of *sorting* in the comparison model, the input is an array $a = [a_1, a_2, \ldots, a_n]$ and the output is a permutation of the input $\pi(a) = [a_{\pi(1)}, a_{\pi(2)}, \ldots, a_{\pi(n)}]$ in which the elements are in increasing order. We begin this lecture by showing the following lower bound for comparison-based sorting.

Theorem 3.1 *Any deterministic comparison-based sorting algorithm must perform at least* $\lg(n!)$ *comparisons to sort n elements in the worst case.*[1] *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* $\lg(n!) = \Omega(n \log n)$ *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. We now present the proof, which uses a very nice information-theoretic argument. (This proof is deceptively short: it's worth thinking through each line and each assertion.)

Proof: First of all, for a deterministic algorithm, the permutation it outputs (e.g., $[a_3, a_1, a_4, a_2]$) is solely a function of the sequence of answers it receives to its comparisons. In particular, any two different input arrays that yield the same sequence of answers will cause the same permutation to be produced as output. So, if an algorithm always made at most k comparisons, then there would be at most 2^k different permutations of the input array that it can possibly output, since each comparison has a YES or NO answer. This implies that if $k < \lg(n!)$, so $2^k < n!$, then there would be some permutation π of the input array that it *can't* output. Let's assume for contradiction that such a permutation exists. All that remains is to show that for any such permutation π, there is some input array for which π is the *only correct answer*. This is easy. For example, the permutation $[a_3, a_1, a_4, a_2]$ is the only correct answer for sorting the input $[2, 4, 1, 3]$, and more generally, permutation π is the only correct answer for the input $[\pi^{-1}(1), \pi^{-1}(2), \ldots, \pi^{-1}(n)]$. Thus we have our desired contradiction. ■

The above is often called an "information theoretic" argument because we are in essence saying that we need at least $\lg_2(n!)$ bits of information about the input before we can correctly decide what output we need to produce. More generally, if we have some problem with M different outputs the algorithm might be required to produce, then we have a worst-case lower bound of $\lg M$.

What does $\lg(n!)$ look like? We have: $\lg(n!) = \lg(n) + \lg(n-1) + \lg(n-2) + ... + \lg(1) < n \lg(n) = O(n \log n)$ and $\lg(n!) = \lg(n) + \lg(n-1) + \lg(n-2) + ... + \lg(1) > (n/2) \lg(n/2) = \Omega(n \log n)$. So, $\lg(n!) = \Theta(n \log n)$.

[1] As is common in CS, we will use "lg" to mean "$\log_2$".

However, since today's theme is tight bounds, let's be a little more precise. We can in particular use the fact that $n! \in [(n/e)^n, n^n]$ to get:

$$\begin{array}{rcccl} n\lg n - n\lg e & < & \lg(n!) & < & n\lg n \\ n\lg n - 1.443n & < & \lg(n!) & < & n\lg n. \end{array}$$

Since $1.433n$ is a low-order term, sometimes people will write this fact this as: $\lg(n!) = (n\lg n)(1 - o(1))$, meaning that the ratio between $\lg(n!)$ and $n\lg n$ goes to 1 as n goes to infinity.

Assume n is a power of 2 — in fact, let's assume this for the entire rest of today's lecture. Can you think of an algorithm that makes at most $n\lg n$ comparisons, and so is tight in the leading term? In fact, there are several algorithms, including:

Binary insertion sort If we perform insertion-sort, using binary search to insert each new element, then the number of comparisons made is at most $\sum_{k=2}^{n} \lceil \lg k \rceil \leq n\lg n$. Note that insertion-sort spends a lot in moving items in the array to make room for each new element, and so is not especially efficient if we count movement cost as well, but it does well in terms of comparisons.

Mergesort Merging two lists of $n/2$ elements each requires at most $n-1$ comparisons. So, unrolling the recurrence we get $(n-1) + 2(n/2-1) + 4(n/4-1) + \ldots + n/2(2-1) = n\lg n - (n-1) < n\lg n$.

3.4 Sorting in the exchange model

Consider a shelf containing n unordered books to be arranged alphabetically. In each step, we can swap any pair of books we like. How many swaps do we need to sort all the books? Formally, we are considering the problem of *sorting* in the *exchange model*.

Definition 3.2 *In the* **exchange model**, *an input consists of an array of n items, and the only operation allowed on the items is to swap a pair of them at a cost of 1 step. All other (planning) work is free: in particular, the items can be examined and compared to each other at no cost.*

Question: how many exchanges are necessary (lower bound) and sufficient (upper bound) in the exchange model to sort an array of n items in the worst case?

Claim 3.2 (Upper bound) *$n-1$ exchanges is sufficient.*

Proof: For this we just need to give an algorithm. For instance, consider the algorithm that in step 1 puts the smallest item in location 1, swapping it with whatever was originally there. Then in step 2 it swaps the second-smallest item with whatever is currently in location 2, and so on (if in step k, the kth-smallest item is already in the correct position then we just do a no-op). No step ever undoes any of the previous work, so after $n-1$ steps, the first $n-1$ items are in the correct position. This means the nth item must be in the correct position too. ■

But are $n-1$ exchanges necessary in the worst-case? If n is even, and no book is in its correct location, then $n/2$ exchanges are clearly necessary to "touch" all books. But can we show a better lower bound than that?

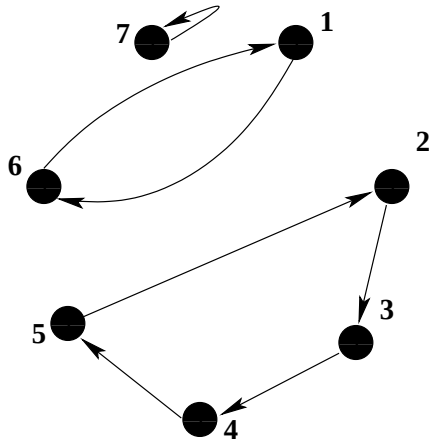


Figure 3.1: Graph for input `[f c d e b a g]`

Claim 3.3 (Lower bound) *In fact, $n-1$ exchanges are necessary, in the worst case.*

Proof: Here is how we can see it. Create a graph in which a directed edge (i, j) means that that the book in location i must end up at location j. For instance, consider the example in Figure 3.1. Note that this is a special kind of directed graph: it is a permutation — a set of cycles. In particular, every book points to *some* location, perhaps its own location, and every location is pointed to by exactly one book. Now consider the following points:

1. What is the effect of exchanging any two elements (books) that are in the same cycle?

   Answer: Suppose the graph had edges (i_1, j_1) and (i_2, j_2) and we swap the elements in locations i_1 and i_2. Then this causes those two edges to be replaced by edges (i_2, j_1) and (i_1, j_2) because now it is the element in location i_2 that needs to go to j_1 and the element in i_1 that needs to go to j_2. This means that if i_1 and i_2 were in the same cycle, that cycle now becomes two disjoint cycles.

2. What is the effect of exchanging any two elements that are in different cycles?

   Answer: If we swap elements i_1 and i_2 that are in different cycles, then the same argument as above shows that this merges those two cycles into one cycle.

3. How many cycles are in the final sorted array?

   Answer: The final sorted array has n cycles.

Putting the above 3 points together, suppose we begin with an array consisting of a single cycle, such as $[n, 1, 2, 3, 4, \ldots, n-1]$. Each operation at best increases the number of cycles by 1 and in the end we need to have n cycles. So, this input requires $n-1$ operations. ■

3.5 The comparison model revisited

3.5.1 Finding the maximum of n elements

How many comparisons are necessary and sufficient to find the maximum of n elements, in the comparison model of computation?

Claim 3.4 (Upper bound) *$n-1$ comparisons are sufficient to find the maximum of n elements.*

Proof: Just scan left to right, keeping track of the largest element so far. This makes at most $n-1$ comparisons. ■

Now, let's try for a lower bound. One simple lower bound is that since there are n possible answers for the location of the minimum element, our previous argument gives a lower bound of $\lg n$. But clearly this is not at all tight. In fact, we can give a better lower bound of $n-1$.

Claim 3.5 (Lower bound) *$n-1$ comparisons are needed in the worst-case to find the maximum of n elements.*

Proof: Suppose some algorithm $\mathcal{A}$ claims to find the maximum of n elements using less than $n-1$ comparisons. Consider an arbitrary input of n distinct elements, and construct a graph in which we join two elements by an edge if they are compared by $\mathcal{A}$. If fewer than $n-1$ comparisons are made, then this graph must have at least two components. Suppose now that algorithm $\mathcal{A}$ outputs some element u as the maximum, where u is in some component C_1. In that case, pick a different component C_2 and add a large positive number (e.g., the value of u) to every element in C_2. This process does not change the result of any comparison made by $\mathcal{A}$, so on this new set of elements, algorithm $\mathcal{A}$ would still output u. Yet this now ensures that u is not the maximum, so $\mathcal{A}$ must be incorrect. ■

Since the upper and lower bounds are equal, these bounds are tight.

3.5.2 Finding the second-largest of n elements

How many comparisons are necessary (lower bound) and sufficient (upper bound) to find the second largest of n elements? Again, let us assume that all elements are distinct.

Claim 3.6 (Lower bound) *$n-1$ comparisons are needed in the worst-case to find the second-largest of n elements.*

Proof: The same argument used in the lower bound for finding the maximum still holds. ■

Let us now work on finding an upper bound. Here is a simple one to start with.

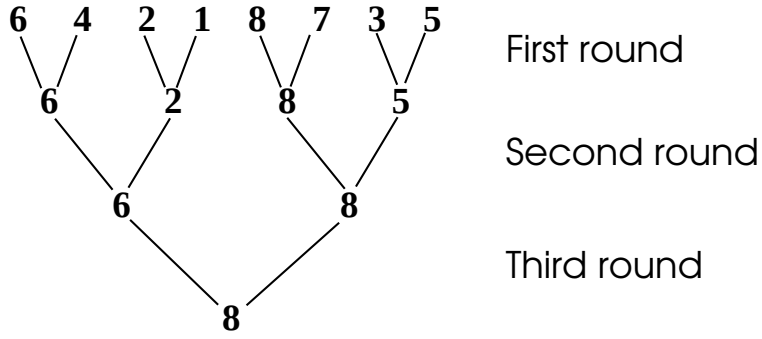
Claim 3.7 (Upper bound #1) *$2n-3$ comparisons are sufficient to find the second-largest of n elements.*

Proof: Just find the largest using $n-1$ comparisons, and then the largest of the remainder using $n-2$ comparisons, for a total of $2n-3$ comparisons. ■

We now have a gap: $n-1$ versus $2n-3$. It is not a huge gap: both are $\Theta(n)$, but remember today's theme is tight bounds. So, which do you think is closer to the truth? It turns out, we can reduce the upper bound quite a bit:

Claim 3.8 (Upper bound #2) *$n+\lg n-2$ comparisons are sufficient to find the second-largest of n elements.*

Proof: As a first step, let's find the maximum element using $n-1$ comparisons, but in a tennis-tournament or playoff structure. That is, we group elements into pairs, finding the maximum in each pair, and recurse on the maxima. E.g.,



Now, given just what we know from comparisons so far, what can we say about possible locations for the second-highest number (i.e., the second-best player)? The answer is that the second-best must have been directly compared to the best, and lost.[2] This means there are only $\lg n$ possibilities for the second-highest number, and we can find the maximum of them making only $\lg(n)-1$ more comparisons. ■

At this point, we have a lower bound of $n-1$ and an upper bound of $n+\lg(n)-2$, so they are nearly tight. It turns out that, in fact, the lower bound can be improved to exactly meet the upper bound.[3]

3.6 Query models, and the evasiveness of connectivity

To finish with something totally different, let's look at the query complexity of determining if a graph is connected. Assume we are given the adjacency matrix G for some n-node graph. That is, $G[i,j]=1$ if there is an edge between i and j, and $G[i,j]=0$ otherwise. We consider a model in which we can *query* any element of the matrix G in 1 step. All other computation is free. That is, imagine the graph matrix has values written on little slips of paper, face down. In one step we can turn over any slip of paper. How many slips of paper do we need to turn over to tell if G is connected?

[2] Apparently the first person to have pointed this out was Charles Dodgson (better known as Lewis Carroll!), writing about the proper way to award prizes in lawn tennis tournaments.

[3] First shown by Kislitsyn (1964).

Claim 3.9 (Easy upper bound) $n(n-1)/2$ *queries are sufficient to determine if* G *is connected.*

Proof: This just corresponds to querying every pair (i, j). Once we have done that, we know the entire graph and can just compute for free to see if it is connected. ■

Interestingly, it turns out the simple upper-bound of querying every edge is a lower bound too. Because of this, connectivity is called an "evasive" property of graphs.

Theorem 3.10 (Lower bound) $n(n-1)/2$ *queries are necessary to determine connectivity in the worst case.*

Proof: Here is the strategy for the adversary: when the algorithm asks us to flip over a slip of paper, we return the answer 0 *unless* that would force the graph to be disconnected, in which case we answer 1. (It is not important to the argument, but we can figure this out by imagining that all un-turned slips of paper are 1 and seeing if that graph is connected.) Now, here is the key claim:

> *Claim:* we maintain the invariant that for any un-asked pair (u, v), the graph revealed so far has no path from u to v.
>
> *Proof of claim:* If there was, consider the last edge (u', v') revealed on that path. We could have answered 0 for that and kept the same connectivity in the graph by having an edge (u, v). So, that contradicts the definition of our adversary strategy.

Now, to finish the proof: Suppose an algorithm halts without examining every pair. Consider some unasked pair (u, v). If the algorithm says "connected," we reveal all-zeros for the remaining unasked edges and then there is no path from u to v (by the key claim) so the algorithm is wrong. If the algorithm says "disconnected," we reveal all-ones for the remaining edges, and the algorithm is wrong by definition of our adversary strategy. So, the algorithm must ask for all edges. ■

Appendix A

Asymptotic Analysis and Recurrences

A.1 Overview

We discuss the notion of asymptotic analysis and introduce O, Ω, Θ, and o notation. We then turn to the topic of recurrences, discussing several methods for solving them. Recurrences will come up in many of the algorithms we study, so it is useful to get a good intuition for them right at the start. In particular, we focus on divide-and-conquer style recurrences, which are the most common ones we will see.

Material in this lecture:

- Asymptotic notation: O, Ω, Θ, and o.
- Recurrences and how to solve them.
  - Solving by unrolling.
  - Solving with a guess and inductive proof.
  - Solving using a recursion tree.
  - A master formula.

A.2 Asymptotic analysis

When we consider an algorithm for some problem, in addition to knowing that it produces a correct solution, we will be especially interested in analyzing its running time. There are several aspects of running time that one could focus on. Our focus will be primarily on the question: "how does the running time *scale* with the size of the input?" This is called *asymptotic analysis*, and the idea is that we will ignore low-order terms and constant factors, focusing instead on the shape of the running time curve. We will typically use n to denote the size of the input, and $T(n)$ to denote the running time of our algorithm on an input of size n.

We begin by presenting some convenient definitions for performing this kind of analysis.

Definition A.1 *$T(n) \in O(f(n))$ if there exist constants $c, n_0 > 0$ such that $T(n) \leq cf(n)$ for all $n > n_0$.*

Informally we can view this as "$T(n)$ is proportional to $f(n)$, or better, as n gets large." For example, $3n^2 + 17 \in O(n^2)$ and $3n^2 + 17 \in O(n^3)$. This notation is especially useful in discussing upper bounds on algorithms: for instance, we saw last time that Karatsuba multiplication took time $O(n^{\log_2 3})$.

Notice that $O(f(n))$ is a set of functions. Nonetheless, it is common practice to write $T(n) = O(f(n))$ to mean that $T(n) \in O(f(n))$: especially in conversation, it is more natural to say "$T(n)$ is $O(f(n))$" than to say "$T(n)$ is in $O(f(n))$". We will typically use this common practice, reverting to the correct set notation when this practice would cause confusion.

Definition A.2 *$T(n) \in \Omega(f(n))$ if there exist constants $c, n_0 > 0$ such that $T(n) \geq cf(n)$ for all $n > n_0$.*

Informally we can view this as "$T(n)$ is proportional to $f(n)$, or worse, as n gets large." For example, $3n^2 - 2n \in \Omega(n^2)$. This notation is especially useful for lower bounds. In Lecture 3, for instance, we will prove that any comparison-based sorting algorithm must take time $\Omega(n \log n)$ in the worst case.

Definition A.3 *$T(n) \in \Theta(f(n))$ if $T(n) \in O(f(n))$ and $T(n) \in \Omega(f(n))$.*

Informally we can view this as "$T(n)$ is proportional to $f(n)$ as n gets large."

Definition A.4 *$T(n) \in o(f(n))$ if for all constants $c > 0$, there exists $n_0 > 0$ such that $T(n) < cf(n)$ for all $n > n_0$.*

For example, last time we saw that we could indeed multiply two n-bit numbers in time $o(n^2)$ by the Karatsuba algorithm. Very informally, O is like $\leq$, Ω is like $\geq$, Θ is like $=$, and o is like $<$. There is also a similar notation ω that corresponds to $>$.

In terms of computing whether or not $T(n)$ belongs to one of these sets with respect to $f(n)$, a convenient way is to compute the limit:

$$\lim_{n \to \infty} \frac{T(n)}{f(n)}. \tag{A.1}$$

If the limit exists, then we can make the following statements:

- If the limit is 0, then $T(n) = o(f(n))$ and $T(n) = O(f(n))$.
- If the limit is a number greater than 0 (e.g., 17) then $T(n) = \Theta(f(n))$ (and $T(n) = O(f(n))$ and $T(n) = \Omega(f(n))$)
- If the limit is infinity, then $T(n) = \omega(f(n))$ and $T(n) = \Omega(f(n))$.

For example, suppose $T(n) = 2n^3 + 100n^2 \log_2 n + 17$ and $f(n) = n^3$. The ratio of these is $2 + (100 \log_2 n)/n + 17/n^3$. In this limit, this goes to 2. Therefore, $T(n) = \Theta(f(n))$. Of course, it is possible that the limit doesn't exist — for instance if $T(n) = n(2 + \sin n)$ and $f(n) = n$ then the ratio oscillates between 1 and 3. In this case we would go back to the definitions to say that $T(n) = \Theta(n)$.

One convenient fact to know (which we just used in the paragraph above and you can prove by taking derivatives) is that for any constant k, $\lim_{n\to\infty}(\log n)^k/n = 0$. This implies, for instance, that $n\log n = o(n^{1.5})$ because $\lim_{n\to\infty}(n\log n)/n^{1.5} = \lim_{n\to\infty}(\log n)/\sqrt{n} = \lim_{n\to\infty}\sqrt{(\log n)^2/n} = 0$.

So, this notation gives us a language for talking about desired or achievable specifications. A typical use might be "we can prove that *any* algorithm for problem X must take $\Omega(n\log n)$ time in the worst case. My fancy algorithm takes time $O(n\log n)$. Therefore, my algorithm is asymptotically optimal."

A.3 Recurrences

We often are interested in algorithms expressed in a recursive way. When we analyze them, we get a recurrence: a description of the running time on an input of size n as a function of n *and* the running time on inputs of smaller sizes. Here are some examples:

Mergesort: To sort an array of size n, we sort the left half, sort right half, and then merge the two results. We can do the merge in linear time. So, if $T(n)$ denotes the running time on an input of size n, we end up with the recurrence $T(n) = 2T(n/2) + cn$.

Selection sort: In selection sort, we run through the array to find the smallest element. We put this in the leftmost position, and then recursively sort the remainder of the array. This gives us a recurrence $T(n) = cn + T(n-1)$.

Multiplication: Here we split each number into its left and right halves. We saw in the last lecture that the straightforward way to solve the subproblems gave us $T(n) = 4T(n/2) + cn$. However, rearranging terms in a clever way improved this to $T(n) = 3T(n/2) + cn$.

What about the base cases? In general, once the problem size gets down to a small constant, we can just use a brute force approach that takes some other constant amount of time. So, almost always we can say the base case is that $T(n) \le c$ for all $n \le n_0$, where n_0 is a constant we get to choose (like 17) and c is some other constant that depends on n_0.

What about the "integrality" issue? For instance, what if we want to use mergesort on an array with an odd number of elements — then the recurrence above is not technically correct. Luckily, this issue turns out almost never to matter, so we can ignore it. In the case of mergesort we can argue formally by using the fact that $T(n)$ is sandwiched between $T(n')$ and $T(n'')$ where n' is the next smaller power of 2 and n'' is the next larger power of 2, both of which differ by at most a constant factor from each other.

We now describe four methods for solving recurrences that are useful to know.

A.3.1 Solving by unrolling

Many times, the easiest way to solve a recurrence is to unroll it to get a summation. For example, unrolling the recurrence for selection sort gives us:

$$T(n) \quad = \quad cn + c(n-1) + c(n-2) + \ldots + c. \tag{A.2}$$

Since there are n terms and each one is at most cn, we can see that this summation is at most cn^2. Since the first $n/2$ terms are each at least $cn/2$, we can see that this summation is at least

$(n/2)(cn/2) = cn^2/4$. So, it is $\Theta(n^2)$. Similarly, a recurrence $T(n) = n^5 + T(n-1)$ unrolls to:

$$T(n) = n^5 + (n-1)^5 + (n-2)^5 + \ldots + 1^5, \tag{A.3}$$

which solves to $\Theta(n^6)$ using the same style of reasoning as before. In particular, there are n terms each of which is at most n^5 so the sum is *at most* n^6, and the top $n/2$ terms are each at least $(n/2)^5$ so the sum is *at least* $(n/2)^6$. Another convenient way to look at many summations of this form is to see them as approximations to an integral. E.g., in this last case, the sum is at least the integral of $f(x) = x^5$ evaluated from 0 to n, and at most the integral of $f(x) = x^5$ evaluated from 1 to $n+1$. So, the sum lies in the range $[\frac{1}{6}n^6, \frac{1}{6}(n+1)^6]$.

A.3.2 Solving by guess and inductive proof

Another good way to solve recurrences is to make a guess and then prove the guess correct inductively. Or if we get into trouble proving our guess correct (e.g., because it was wrong), often this will give us clues as to a better guess. For example, say we have the recurrence

$$T(n) = 7T(n/7) + n, \tag{A.4}$$
$$T(1) = 0. \tag{A.5}$$

We might first try a solution of $T(n) \leq cn$ for some $c > 0$. We would then assume it holds true inductively for $n' < n$ (the base case is obviously true) and plug in to our recurrence (using $n' = n/7$) to get:

$$\begin{aligned} T(n) &\leq 7(cn/7) + n \\ &= cn + n \\ &= (c+1)n. \end{aligned}$$

Unfortunately, this isn't what we wanted: our multiplier "c" went up by 1 when n went up by a factor of 7. In other words, our multiplier is acting like $\log_7(n)$. So, let's make a new guess using a multiplier of this form. So, we have a new guess of

$$T(n) \leq n \log_7(n). \tag{A.6}$$

If we assume this holds true inductively for $n' < n$, then we get:

$$\begin{aligned} T(n) &\leq 7[(n/7)\log_7(n/7)] + n \\ &= n\log_7(n/7) + n \\ &= n\log_7(n) - n + n \\ &= n\log_7(n). \end{aligned} \tag{A.7}$$

So, we have verified our guess.

It is important in this type of proof to be careful. For instance, one could be lulled into thinking that our initial guess of cn was correct by reasoning "we assumed $T(n/7)$ was $\Theta(n/7)$ and got $T(n) = \Theta(n)$". The problem is that the constants changed (c turned into $c+1$) so they really weren't constant after all!

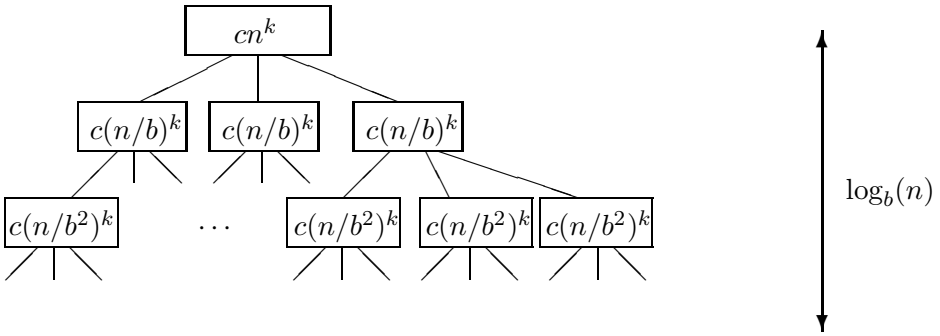
A.3.3 Recursion trees, stacking bricks, and a Master Formula

The final method we examine, which is especially good for divide-and-conquer style recurrences, is the use of a recursion tree. We will use this to method to produce a simple "master formula" that can be applied to many recurrences of this form.

Consider the following type of recurrence:

$$\begin{aligned} T(n) &= aT(n/b) + cn^k \\ T(1) &= c, \end{aligned} \tag{A.8}$$

for positive constants a, b, c, and k. This recurrence corresponds to the time spent by an algorithm that does cn^k work up front, and then divides the problem into a pieces of size n/b, solving each one recursively. For instance, mergesort, Karatsuba multiplication, and Strassen's algorithm all fit this mold. A *recursion tree* is just a tree that represents this process, where each node contains inside it the work done up front and then has one child for each recursive call. The leaves of the tree are the base cases of the recursion. A tree for the recurrence (A.8) is given below.[1]



To compute the result of the recurrence, we simply need to add up all the values in the tree. We can do this by adding them up level by level. The top level has value cn^k, the next level sums to $ca(n/b)^k$, the next level sums to $ca^2(n/b^2)^k$, and so on. The depth of the tree (the number of levels not including the root) is $\log_b(n)$. Therefore, we get a summation of:

$$cn^k \left[1 + a/b^k + (a/b^k)^2 + (a/b^k)^3 + ... + (a/b^k)^{\log_b n}\right] \tag{A.9}$$

To help us understand this, let's define $r = a/b^k$. Notice that r is a *constant*, since a, b, and k are constants. For instance, for Strassen's algorithm $r = 7/2^2$, and for mergesort $r = 2/2 = 1$. Using our definition of r, our summation simplifies to:

$$cn^k \left[1 + r + r^2 + r^3 + ... + r^{\log_b n}\right] \tag{A.10}$$

We can now evaluate three cases:

Case 1: $r < 1$. In this case, the sum is a convergent series. Even if we imagine the series going to infinity, we still get that the sum $1 + r + r^2 + \ldots = 1/(1-r)$. So, we can upper-bound formula (A.9) by $cn^k/(1-r)$, and lower bound it by just the first term cn^k. Since r and c are constants, this solves to $\Theta(n^k)$.

[1] This tree has branching factor a.

Case 2: $r = 1$. In this case, all terms in the summation (A.9) are equal to 1, so the result is $cn^k(\log_b n + 1) \in \Theta(n^k \log n)$.

Case 3: $r > 1$. In this case, the last term of the summation dominates. We can see this by pulling it out, giving us:

$$cn^k r^{\log_b n}\left[(1/r)^{\log_b n} + \ldots + 1/r + 1\right] \tag{A.11}$$

Since $1/r < 1$, we can now use the same reasoning as in Case 1: the summation is at most $1/(1 - 1/r)$ which is a constant. Therefore, we have

$$T(n) \quad \in \quad \Theta\left(n^k (a/b^k)^{\log_b n}\right).$$

We can simplify this formula by noticing that $b^{k \log_b n} = n^k$, so we are left with

$$T(n) \quad \in \quad \Theta\left(a^{\log_b n}\right). \tag{A.12}$$

We can simplify this further using $a^{\log_b n} = b^{(\log_b a)(\log_b n)} = n^{\log_b a}$ to get:

$$T(n) \quad \in \quad \Theta\left(n^{\log_b a}\right). \tag{A.13}$$

Note that Case 3 is what we used for Karatsuba multiplication ($a = 3, b = 2, k = 1$) and Strassen's algorithm ($a = 7, b = 2, k = 2$).

Combining the three cases above gives us the following "master theorem".

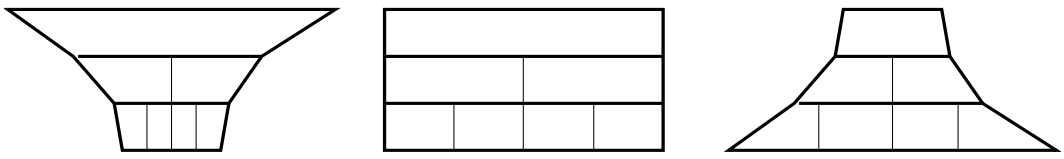
Theorem A.1 *The recurrence*

$$\begin{aligned} T(n) &= aT(n/b) + cn^k \\ T(1) &= c, \end{aligned}$$

where a, b, c, and k are all constants, solves to:

$$\begin{aligned} T(n) &\in \Theta(n^k) \text{ if } a < b^k \\ T(n) &\in \Theta(n^k \log n) \text{ if } a = b^k \\ T(n) &\in \Theta(n^{\log_b a}) \text{ if } a > b^k \end{aligned}$$

A nice intuitive way to think of the computation above is to think of each node in the recursion tree as a brick of height 1 and width equal to the value inside it. Our goal is now to compute the area of the stack. Depending on whether we are in Case 1, 2, or 3, the picture then looks like one of the following:



In the first case, the area is dominated by the top brick; in the second case, all levels provide an equal contribution, and in the last case, the area is dominated by the bottom level.