IV

Before the Interview

Acing an interview starts well before the interview itself—years before, in fact. The following timeline outlines what you should be thinking about when.

If you're starting late into this process, don't worry. Do as much "catching up" as you can, and then focus on preparation. Good luck!

▸ Getting the Right Experience

Without a great resume, there's no interview. And without great experience, there's no great resume. Therefore, the first step in landing an interview is getting great experience. The further in advance you can think about this the better.

For current students, this may mean the following:

- *Take the Big Project Classes:* Seek out the classes with big coding projects. This is a great way to get somewhat practical experience before you have any formal work experience. The more relevant the project is to the real world, the better.
- *Get an Internship:* Do everything you can to land an internship early in school. It will pave the way for even better internships before you graduate. Many of the top tech companies have internship programs designed especially for freshman and sophomores. You can also look at startups, which might be more flexible.
- *Start Something:* Build a project on your own time, participate in hackathons, or contribute to an open source project. It doesn't matter too much what it is. The important thing is that you're coding. Not only will this develop your technical skills and practical experience, your initiative will impress companies.

Professionals, on the other hand, may already have the right experience to switch to their dream company. For instance, a Google dev probably already has sufficient experience to switch to Facebook. However, if you're trying to move from a lesser-known company to one of the "biggies," or from testing/IT into a dev role, the following advice will be useful:

- *Shift Work Responsibilities More Towards Coding:* Without revealing to your manager that you are thinking of leaving, you can discuss your eagerness to take on bigger coding challenges. As much as possible, try to ensure that these projects are "meaty," use relevant technologies, and lend themselves well to a resume bullet or two. It is these coding projects that will, ideally, form the bulk of your resume.
- *Use Your Nights and Weekends:* If you have some free time, use it to build a mobile app, a web app, or a piece of desktop software. Doing such projects is also a great way to get experience with new technologies, making you more relevant to today's companies. This project work should definitely be listed on your resume; few things are as impressive to an interviewer as a candidate who built something "just

for fun."

All of these boil down to the two big things that companies want to see: that you're smart and that you can code. If you can prove that, you can land your interview.

In addition, you should think in advance about where you want your career to go. If you want to move into management down the road, even though you're currently looking for a dev position, you should find ways now of developing leadership experience.

▸ Writing a Great Resume

Resume screeners look for the same things that interviewers do. They want to know that you're smart and that you can code.

That means you should prepare your resume to highlight those two things. Your love of tennis, traveling, or magic cards won't do much to show that. Think twice before cutting more technical lines in order to allow space for your non-technical hobbies.

Appropriate Resume Length

In the US, it is strongly advised to keep a resume to one page if you have less than ten years of experience. More experienced candidates can often justify 1.5 - 2 pages otherwise.

Think twice about a long resume. Shorter resumes are often more impressive.

- Recruiters only spend a fixed amount of time (about 10 seconds) looking at your resume. If you limit the content to the most impressive items, the recruiter is sure to see them. Adding additional items just distracts the recruiter from what you'd really like them to see.
- Some people just flat-out refuse to read long resumes. Do you really want to risk having your resume tossed for this reason?

If you are thinking right now that you have too much experience and can't fit it all on one or two pages, trust me, *you can*. Long resumes are not a reflection of having tons of experience; they're a reflection of not understanding how to prioritize content.

Employment History

Your resume does not—and should not—include a full history of every role you've ever had. Include only the relevant positions—the ones that make you a more impressive candidate.

Writing Strong Bullets

For each role, try to discuss your accomplishments with the following approach: "Accomplished X by implementing Y which led to Z." Here's an example:

- "Reduced object rendering time by 75% by implementing distributed caching, leading to a 10% reduction in log-in time."

Here's another example with an alternate wording:

- "Increased average match accuracy from 1.2 to 1.5 by implementing a new comparison algorithm based on windiff."

Not everything you did will fit into this approach, but the principle is the same: show what you did, how you did it, and what the results were. Ideally, you should try to make the results "measurable" somehow.

Projects

Developing the projects section on your resume is often the best way to present yourself as more experienced. This is especially true for college students or recent grads.

The projects should include your 2 - 4 most significant projects. State what the project was and which languages or technologies it employed. You may also want to consider including details such as whether the project was an individual or a team project, and whether it was completed for a course or independently. These details are not required, so only include them if they make you look better. Independent projects are generally preferred over course projects, as it shows initiative.

Do not add too many projects. Many candidates make the mistake of adding all 13 of their prior projects, cluttering their resume with small, non-impressive projects.

So what should you build? Honestly, it doesn't matter that much. Some employers really like open source projects (it offers experience contributing to a large code base), while others prefer independent projects (it's easier to understand your personal contributions). You could build a mobile app, a web app, or almost anything. The most important thing is that you're building something.

Programming Languages and Software

Software

Be conservative about what software you list, and understand what's appropriate for the company. Software like Microsoft Office can almost always be cut. Technical software like Visual Studio and Eclipse is somewhat more relevant, but many of the top tech companies won't even care about that. After all, is it really that hard to learn Visual Studio?

Of course, it won't hurt you to list all this software. It just takes up valuable space. You need to evaluate the trade-off of that.

Languages

Should you list everything you've ever worked with, or shorten the list to just the ones that you're most comfortable with?

Listing everything you've ever worked with is dangerous. Many interviewers consider anything on your resume to be "fair game" as far as the interview.

One alternative is to list most of the languages you've used, but add your experience level. This approach is shown below:

- Languages: Java (expert), C++ (proficient), JavaScript (prior experience).

Use whatever wording ("expert", "fluent", etc.) effectively communicates your skillset.

Some people list the number of years of experience they have with a particular language, but this can be really confusing. If you first learned Java 10 years ago, and have used it occasionally throughout that time, how many years of experience is this?

For this reason, the number of years of experience is a poor metric for resumes. It's better to just describe what you mean in plain English.

Advice for Non-Native English Speakers and Internationals

Some companies will throw out your resume just because of a typo. Please get at least one native English speaker to proofread your resume.

Additionally, for US positions, do *not* include age, marital status, or nationality. This sort of personal information is not appreciated by companies, as it creates a legal liability for them.

Beware of (Potential) Stigma

Certain languages have stigmas associated with them. Sometimes this is because of the language themselves, but often it's because of the places where this language is used. I'm not defending the stigma; I'm just letting you know of it.

A few stigmas you should be aware of:

- **Enterprise Languages:** Certain languages have a stigma associated with them, and those are often the ones that are used for enterprise development. Visual Basic is a good example of this. If you show yourself to be an expert with VB, it can cause people to assume that you're less skilled. Many of these same people will admit that, yes, VB.NET is actually perfectly capable of building sophisticated applications. But still, the kinds of applications that people tend to build with it are not very sophisticated. You would be unlikely to see a big name Silicon Valley using VB.

  In fact, the same argument (although less strong) applies to the whole .NET platform. If your primary focus is .NET and you're not applying for .NET roles, you'll have to do more to show that you're strong technically than if you were coming in with a different background.

- **Being Too Language Focused:** When recruiters at some of the top tech companies see resumes that list every flavor of Java on their resume, they make negative assumptions about the caliber of candidate. There is a belief in many circles that the best software engineers don't define themselves around a particular language. Thus, when they see a candidate seems to flaunt which specific versions of a language they know, recruiters will often bucket the candidate as "not our kind of person."

  Note that this does not mean that you should necessarily take this "language flaunting" off your resume. You need to understand what that company values. Some companies do value this.

- **Certifications:** Certifications for software engineers can be anything from a positive, to a neutral, to a negative. This goes hand-in-hand with being too language focused; the companies that are biased against candidates with a very lengthy list of technologies tend to also be biased against certifications. This means that in some cases, you should actually remove this sort of experience from your resume.

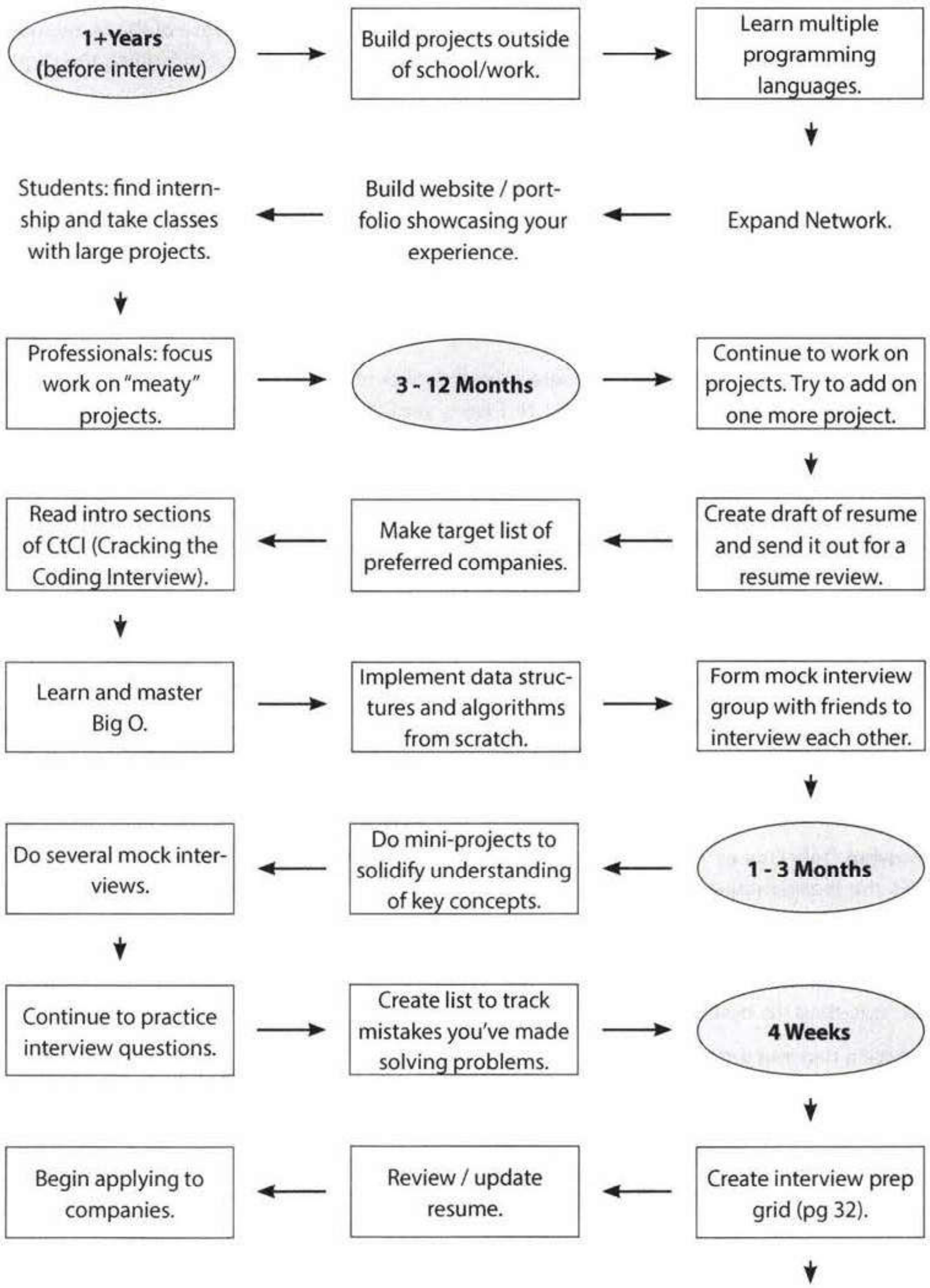
- **Knowing Only One or Two Languages:** The more time you've spent coding, the more things you've built, the more languages you will have tended to work with. The assumption then, when they see a resume with only one language, is that you haven't experienced very many problems. They also often worry that candidates with only one or two languages will have trouble learning new technologies (why hasn't the candidate learned more things?) or will just feel too tied with a specific technology (potentially not using the best language for the task).

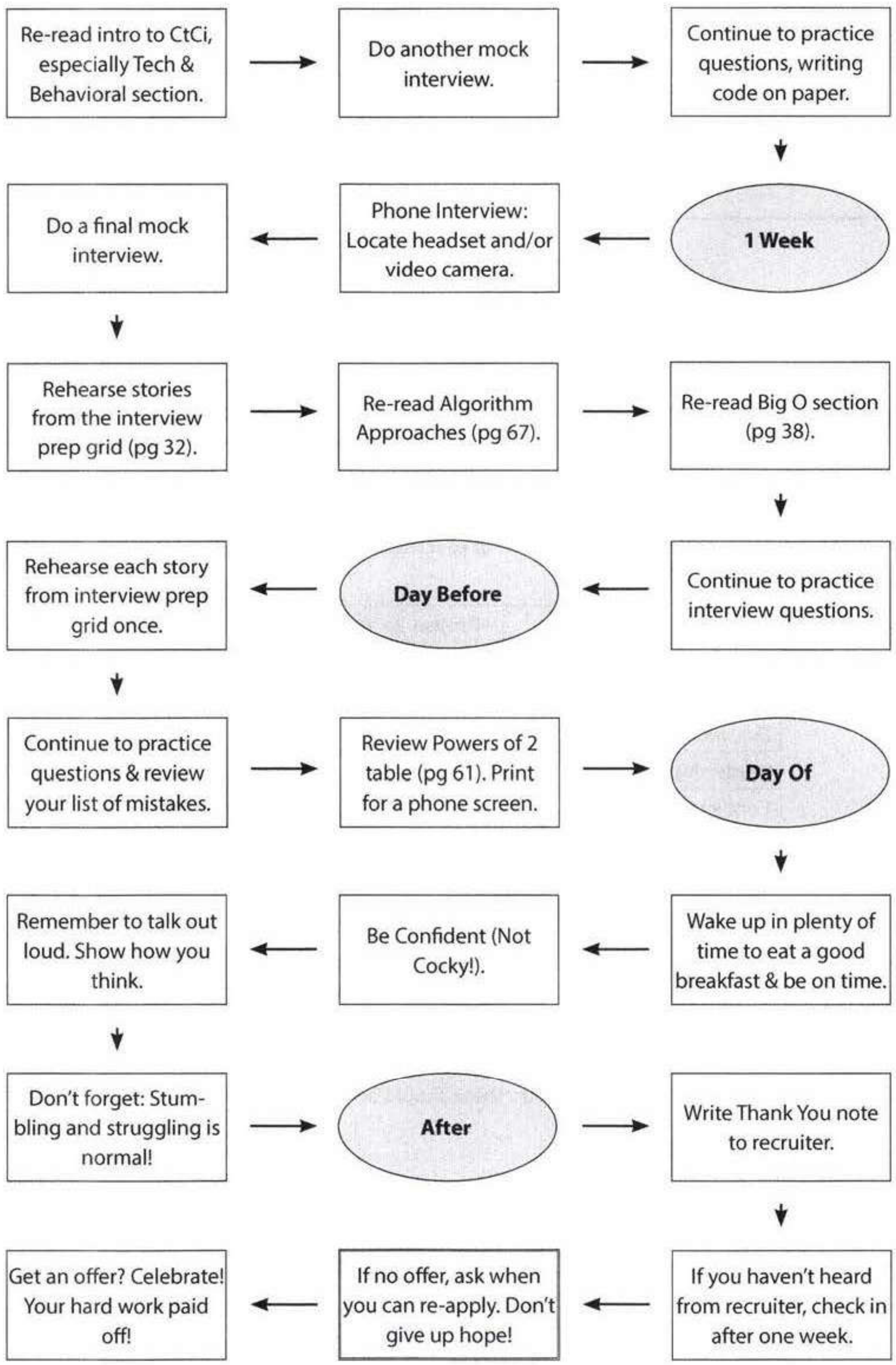
This advice is here not just to help you work on your resume, but also to help you develop the right experience. If your expertise is in C#.NET, try developing some projects in Python and JavaScript. If you only know one or two languages, build some applications in a different language.

Where possible, try to truly diversify. The languages in the cluster of {Python, Ruby, and JavaScript} are somewhat similar to each other. It's better if you can learn languages that are more different, like Python, C++, and Java.

▸ Preparation Map

The following map should give you an idea of how to tackle the interview preparation process. One of the key takeaways here is that it's not just about interview questions. Do projects and write code, too!




Re-read intro to CtCi, especially Tech & Behavioral section.
Do another mock interview.
Continue to practice questions, writing code on paper.
1 Week
Phone Interview: Locate headset and/or video camera.
Do a final mock interview.
Rehearse stories from the interview prep grid (pg 32).
Re-read Algorithm Approaches (pg 67).
Re-read Big O section (pg 38).
Continue to practice interview questions.
Day Before
Rehearse each story from interview prep grid once.
Continue to practice questions & review your list of mistakes.
Review Powers of 2 table (pg 61). Print for a phone screen.
Day Of
Wake up in plenty of time to eat a good breakfast & be on time.
Be Confident (Not Cocky!).
Remember to talk out loud. Show how you think.
Don't forget: Stumbling and struggling is normal!
After
Write Thank You note to recruiter.
If you haven't heard from recruiter, check in after one week.
If no offer, ask when you can re-apply. Don't give up hope!
Get an offer? Celebrate! Your hard work paid off!

V

Behavioral Questions

Behavioral questions are asked to get to know your personality, to understand your resume more deeply, and just to ease you into an interview. They are important questions and can be prepared for.

▸ Interview Preparation Grid

Go through each of the projects or components of your resume and ensure that you can talk about them in detail. Filling out a grid like this may help:

Common Questions	**Project 1**	**Project 2**	**Project 3**
Challenges			
Mistakes/Failures			
Enjoyed			
Leadership			
Conflicts			
What You'd Do Differently			

Along the top, as columns, you should list all the major aspects of your resume, including each project, job, or activity. Along the side, as rows, you should list the common behavioral questions.

Study this grid before your interview. Reducing each story to just a couple of keywords may make the grid easier to study and recall. You can also more easily have this grid in front of you during an interview without it being a distraction.

In addition, ensure that you have one to three projects that you can talk about in detail. You should be able to discuss the technical components in depth. These should be projects where you played a central role.

What are your weaknesses?

When asked about your weaknesses, give a real weakness! Answers like "My greatest weakness is that I work too hard" tell your interviewer that you're arrogant and/or won't admit to your faults. A good answer conveys a real, legitimate weakness but emphasizes how you work to overcome it.

For example:

> "Sometimes, I don't have a very good attention to detail. While that's good because it lets me execute quickly, it also means that I sometimes make careless mistakes. Because of that, I make sure to always have someone else double check my work."

What questions should you ask the interviewer?

Most interviewers will give you a chance to ask them questions. The quality of your questions will be a factor, whether subconsciously or consciously, in their decisions. Walk into the interview with some questions in mind.

You can think about three general types of questions.

Genuine Questions

These are the questions you actually want to know the answers to. Here are a few ideas of questions that are valuable to many candidates:

1. "What is the ratio of testers to developers to program managers? What is the interaction like? How does project planning happen on the team?"
2. "What brought you to this company? What has been most challenging for you?"

These questions will give you a good feel for what the day-to-day life is like at the company.

Insightful Questions

These questions demonstrate your knowledge or understanding of technology.

1. "I noticed that you use technology X. How do you handle problem Y?"
2. "Why did the product choose to use the X protocol over the Y protocol? I know it has benefits like A, B, C, but many companies choose not to use it because of issue D."

Asking such questions will typically require advance research about the company.

Passion Questions

These questions are designed to demonstrate your passion for technology. They show that you're interested in learning and will be a strong contributor to the company.

1. "I'm very interested in scalability, and I'd love to learn more about it. What opportunities are there at this company to learn about this?"
2. "I'm not familiar with technology X, but it sounds like a very interesting solution. Could you tell me a bit more about how it works?"

▸ Know Your Technical Projects

As part of your preparation, you should focus on two or three technical projects that you should deeply master. Select projects that ideally fit the following criteria:

- The project had challenging components (beyond just "learning a lot").
- You played a central role (ideally on the challenging components).
- You can talk at technical depth.

For those projects, and all your projects, be able to talk about the challenges, mistakes, technical decisions, choices of technologies (and tradeoffs of these), and the things you would do differently.

You can also think about follow-up questions, like how you would scale the application.

Responding to Behavioral Questions

Behavioral questions allow your interviewer to get to know you and your prior experience better. Remember the following advice when responding to questions.

Be Specific, Not Arrogant

Arrogance is a red flag, but you still want to make yourself sound impressive. So how do you make yourself sound good without being arrogant? By being specific!

Specificity means giving just the facts and letting the interviewer derive an interpretation. For example, rather than saying that you "did all the hard parts," you can instead describe the specific bits you did that were challenging.

Limit Details

When a candidate blabbers on about a problem, it's hard for an interviewer who isn't well versed in the subject or project to understand it.

Stay light on details and just state the key points. When possible, try to translate it or at least explain the impact. You can always offer the interviewer the opportunity to drill in further.

> "By examining the most common user behavior and applying the Rabin-Karp algorithm, I designed a new algorithm to reduce search from `O(n)` to `O(log n)` in 90% of cases. I can go into more details if you'd like."

This demonstrates the key points while letting your interviewer ask for more details if he wants to.

Focus on Yourself, Not Your Team

Interviews are fundamentally an individual assessment. Unfortunately, when you listen to many candidates (especially those in leadership roles), their answers are about "we", "us", and "the team." The interviewer walks away having little idea what the candidate's actual impact was and might conclude that the candidate did little.

Pay attention to your answers. Listen for how much you say "we" versus "I." Assume that every question is about your role, and speak to that.

Give Structured Answers

There are two common ways to think about structuring responses to a behavioral question: nugget first and S.A.R. These techniques can be used separately or together.

Nugget First

Nugget First means starting your response with a "nugget" that succinctly describes what your response will be about.

For example:

- Interviewer: "Tell me about a time you had to persuade a group of people to make a big change."
- Candidate: "Sure, let me tell you about the time when I convinced my school to let undergraduates teach their own courses. Initially, my school had a rule where..."

This technique grabs your interviewer's attention and makes it very clear what your story will be about. It also helps you be more focused in your communication, since you've made it very clear to yourself what the gist of your response is.

S.A.R. (Situation, Action, Result)

The S.A.R. approach means that you start off outlining the situation, then explaining the actions you took, and lastly, describing the result.

Example: "Tell me about a challenging interaction with a teammate."

- **Situation:** On my operating systems project, I was assigned to work with three other people. While two were great, the third team member didn't contribute much. He stayed quiet during meetings, rarely chipped in during email discussions, and struggled to complete his components. This was an issue not only because it shifted more work onto us, but also because we didn't know if we could count on him.
- **Action:** I didn't want to write him off completely yet, so I tried to resolve the situation. I did three things.

  First, I wanted to understand why he was acting like this. Was it laziness? Was he busy with something else? I struck up a conversation with him and then asked him open-ended questions about how he felt it was going. Interestingly, basically out of nowhere, he said that he wanted to take on the writeup, which is one of the most time intensive parts. This showed me that it wasn't laziness; it was that he didn't feel like he was good enough to write code.

  Second, now that I understand the cause, I tried to make it clear that he shouldn't fear messing up. I told him about some of the bigger mistakes that I made and admitted that I wasn't clear about a lot of parts of the project either.

  Third and finally, I asked him to help me with breaking out some of the components of the project. We sat down together and designed a thorough spec for one of the big component, in much more detail than we had before. Once he could see all the pieces, it helped show him that the project wasn't as scary as he'd assumed.
- **Result:** With his confidence raised, he now offered to take on a bunch of the smaller coding work, and then eventually some of the biggest parts. He finished all his work on time, and he contributed more in discussions. We were happy to work with him on a future project.

The situation and the result should be succinct. Your interviewer generally does not need many details to understand what happened and, in fact, may be confused by them.

By using the S.A.R. model with clear situations, actions and results, the interviewer will be able to easily identify how you made an impact and why it mattered.

Consider putting your stories into the following grid:

	Nugget	Situation	Action(s)	Result	What It Says
Story 1			1. ... 2. ... 3. ...		
Story 2					

Explore the Action

In almost all cases, the "action" is the most important part of the story. Unfortunately, far too many people talk on and on about the situation, but then just breeze through the action.

Instead, dive into the action. Where possible, break down the action into multiple parts. For example: "I did three things. First, I..." This will encourage sufficient depth.

Think About What It Says

Re-read the story on page 35. What personality attributes has the candidate demonstrated?

- **Initiative/Leadership:** The candidate tried to resolve the situation by addressing it head-on.
- **Empathy:** The candidate tried to understand what was happening to the person. The candidate also showed empathy in knowing what would resolve the teammate's insecurity.
- **Compassion:** Although the teammate was harming the team, the candidate wasn't angry at the teammate. His empathy led him to compassion.
- **Humility:** The candidate was able to admit to his own flaws (not only to the teammate, but also to the interviewer).
- **Teamwork/Helpfulness:** The candidate worked with the teammate to break down the project into manageable chunks.

You should think about your stories from this perspective. Analyze the actions you took and how you reacted. What personality attributes does your reaction demonstrate?

In many cases, the answer is "none." That usually means you need to rework how you communicate the story to make the attribute clearer. You don't want to explicitly say, "I did X because I have empathy," but you can go one step away from that. For example:

- **Less Clear Attribute:** "I called up the client and told him what happened."
- **More Clear Attribute (Empathy and Courage):** "I made sure to call the client myself, because I knew that he would appreciate hearing it directly from me."

If you still can't make the personality attributes clear, then you might need to come up with a new story entirely.

▸ So, tell me about yourself...

Many interviewers kick off the session by asking you to tell them a bit about yourself, or asking you to walk through your resume. This is essentially a "pitch". It's your interviewer's first impression of you, so you want to be sure to nail this.

Structure

A typical structure that works well for many people is essentially chronological, with the opening sentence describing their current job and the conclusion discussing their relevant and interesting hobbies outside of work (if any).

1. **Current Role [Headline Only]:** "I'm a software engineer at Microworks, where I've been leading the Android team for the last five years."
2. **College:** My background is in computer science. I did my undergrad at Berkeley and spent a few summers working at startups, including one where I attempted to launch my own business.
3. **Post College & Onwards:** After college, I wanted to get some exposure to larger corporations so I joined Amazon as a developer. It was a great experience. I learned a ton about large system design and I got to really drive the launch of a key part of AWS. That actually showed me that I really wanted to be in a more

entrepreneurial environment.

4. **Current Role [Details]:** One of my old managers from Amazon recruited me out to join her startup, which was what brought me to Microworks. Here, I did the initial system architecture, which has scaled pretty well with our rapid growth. I then took an opportunity to lead the Android team. I do manage a team of three, but my role is primarily with technical leadership: architecture, coding, etc.
5. **Outside of Work:** Outside of work, I've been participating in some hackathons—mostly doing iOS development there as a way to learn it more deeply. I'm also active as a moderator on online forums around Android development.
6. **Wrap Up:** I'm looking now for something new, and your company caught my eye. I've always loved the connection with the user, and I really want to get back to a smaller environment too.

This structure works well for about 95% of candidates. For candidate with more experience, you might condense part of it. Ten years from now, the candidate's initial statements might become just: "After my CS degree from Berkeley, I spent a few years at Amazon and then joined a startup where I led the Android team."

Hobbies

Think carefully about your hobbies. You may or may not want to discuss them.

Often they're just fluff. If your hobby is just generic activities like skiing or playing with your dog, you can probably skip it.

Sometimes though, hobbies can be useful. This often happens when:

- The hobby is extremely unique (e.g., fire breathing). It may strike up a bit of a conversation and kick off the interview on a more amiable note.
- The hobby is technical. This not only boosts your actual skillset, but it also shows passion for technology.
- The hobby demonstrates a positive personality attribute. A hobby like "remodeling your house yourself" shows a drive to learn new things, take some risks, and get your hands dirty (literally and figuratively).

It would rarely hurt to mention hobbies, so when in doubt, you might as well.

Think about how to best frame your hobby though. Do you have any successes or specific work to show from it (e.g., landing a part in a play)? Is there a personality attribute this hobby demonstrates?

Sprinkle in Shows of Successes

In the above pitch, the candidate has casually dropped in some highlights of his background.

- He specifically mentioned that he was recruited out of Microworks by his old manager, which shows that he was successful at Amazon.
- He also mentions wanting to be in a smaller environment, which shows some element of culture fit (assuming this is a startup he's applying for).
- He mentions some successes he's had, such as launching a key part of AWS and architecting a scalable system.
- He mentions his hobbies, both of which show a drive to learn.

When you think about your pitch, think about what different aspects of your background say about you. Can you can drop in shows of successes (awards, promotions, being recruited out by someone you worked with, launches, etc.)? What do you want to communicate about yourself?

VI

Big O

This is such an important concept that we are dedicating an entire (long!) chapter to it.

Big O time is the language and metric we use to describe the efficiency of algorithms. Not understanding it thoroughly can really hurt you in developing an algorithm. Not only might you be judged harshly for not really understanding big O, but you will also struggle to judge when your algorithm is getting faster or slower.

Master this concept.

▸ An Analogy

Imagine the following scenario: You've got a file on a hard drive and you need to send it to your friend who lives across the country. You need to get the file to your friend as fast as possible. How should you send it?

Most people's first thought would be email, FTP, or some other means of electronic transfer. That thought is reasonable, but only half correct.

If it's a small file, you're certainly right. It would take 5 - 10 hours to get to an airport, hop on a flight, and then deliver it to your friend.

But what if the file were really, really large? Is it possible that it's faster to physically deliver it via plane?

Yes, actually it is. A one-terabyte (1 TB) file could take more than a day to transfer electronically. It would be much faster to just fly it across the country. If your file is that urgent (and cost isn't an issue), you might just want to do that.

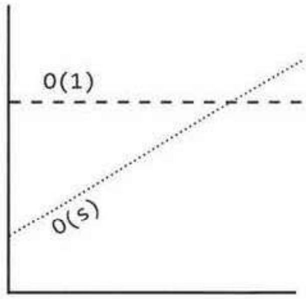
What if there were no flights, and instead you had to drive across the country? Even then, for a really huge file, it would be faster to drive.

▸ Time Complexity

This is what the concept of asymptotic runtime, or big O time, means. We could describe the data transfer "algorithm" runtime as:

- Electronic Transfer: `O(s)`, where `s` is the size of the file. This means that the time to transfer the file increases linearly with the size of the file. (Yes, this is a bit of a simplification, but that's okay for these purposes.)
- Airplane Transfer: `O(1)` with respect to the size of the file. As the size of the file increases, it won't take any longer to get the file to your friend. The time is constant.

No matter how big the constant is and how slow the linear increase is, linear will at some point surpass constant.



There are many more runtimes than this. Some of the most common ones are O(log N), O(N log N), O(N), O(N^2) and O(2^N). There's no fixed list of possible runtimes, though.

You can also have multiple variables in your runtime. For example, the time to paint a fence that's w meters wide and h meters high could be described as O(wh). If you needed p layers of paint, then you could say that the time is O(whp).

Big O, Big Theta, and Big Omega

If you've never covered big O in an academic setting, you can probably skip this subsection. It might confuse you more than it helps. This "FYI" is mostly here to clear up ambiguity in wording for people who have learned big O before, so that they don't say, "But I thought big O meant..."

Academics use big O, big Θ (theta), and big Ω (omega) to describe runtimes.

- **O (big O):** In academia, big O describes an upper bound on the time. An algorithm that prints all the values in an array could be described as O(N), but it could also be described as O(N^2), O(N^3), or O(2^N) (or many other big O times). The algorithm is at least as fast as each of these; therefore they are upper bounds on the runtime. This is similar to a less-than-or-equal-to relationship. If Bob is X years old (I'll assume no one lives past age 130), then you could say X ≤ 130. It would also be correct to say that X ≤ 1,000 or X ≤ 1,000,000. It's technically true (although not terribly useful). Likewise, a simple algorithm to print the values in an array is O(N) as well as O(N^3) or any runtime bigger than O(N).
- **Ω (big omega):** In academia, Ω is the equivalent concept but for lower bound. Printing the values in an array is Ω(N) as well as Ω(log N) and Ω(1). After all, you know that it won't be *faster* than those runtimes.
- **Θ (big theta):** In academia, Θ means both O and Ω. That is, an algorithm is Θ(N) if it is both O(N) and Ω(N). Θ gives a tight bound on runtime.

In industry (and therefore in interviews), people seem to have merged Θ and O together. Industry's meaning of big O is closer to what academics mean by Θ, in that it would be seen as incorrect to describe printing an array as O(N^2). Industry would just say this is O(N).

For this book, we will use big O in the way that industry tends to use it: By always trying to offer the tightest description of the runtime.

Best Case, Worst Case, and Expected Case

We can actually describe our runtime for an algorithm in three different ways.

Let's look at this from the perspective of quick sort. Quick sort picks a random element as a "pivot" and then swaps values in the array such that the elements less than pivot appear before elements greater than pivot. This gives a "partial sort." Then it recursively sorts the left and right sides using a similar process.

- **Best Case:** If all elements are equal, then quick sort will, on average, just traverse through the array once. This is `O(N)`. (This actually depends slightly on the implementation of quick sort. There are implementations, though, that will run very quickly on a sorted array.)
- **Worst Case:** What if we get really unlucky and the pivot is repeatedly the biggest element in the array? (Actually, this can easily happen. If the pivot is chosen to be the first element in the subarray and the array is sorted in reverse order, we'll have this situation.) In this case, our recursion doesn't divide the array in half and recurse on each half. It just shrinks the subarray by one element. This will degenerate to an $O(N^2)$ runtime.
- **Expected Case:** Usually, though, these wonderful or terrible situations won't happen. Sure, sometimes the pivot will be very low or very high, but it won't happen over and over again. We can expect a runtime of `O(N log N)`.

We rarely ever discuss best case time complexity, because it's not a very useful concept. After all, we could take essentially any algorithm, special case some input, and then get an `O(1)` time in the best case.

For many—probably most—algorithms, the worst case and the expected case are the same. Sometimes they're different, though, and we need to describe both of the runtimes.

What is the relationship between best/worst/expected case and big O/theta/omega?

It's easy for candidates to muddle these concepts (probably because both have some concepts of "higher", "lower" and "exactly right"), but there is no particular relationship between the concepts.

Best, worst, and expected cases describe the big O (or big theta) time for particular inputs or scenarios.

Big O, big omega, and big theta describe the upper, lower, and tight bounds for the runtime.

Space Complexity

Time is not the only thing that matters in an algorithm. We might also care about the amount of memory—or space—required by an algorithm.

Space complexity is a parallel concept to time complexity. If we need to create an array of size n, this will require `O(n)` space. If we need a two-dimensional array of size nxn, this will require $O(n^2)$ space.

Stack space in recursive calls counts, too. For example, code like this would take `O(n)` time and `O(n)` space.

```
int sum(int n) { /* Ex 1.*/
  if (n <= 0) {
    return 0;
  }
  return n + sum(n-1);
}
```

Each call adds a level to the stack.

```
sum(4)
  -> sum(3)
    -> sum(2)
      -> sum(1)
        -> sum(0)
```

Each of these calls is added to the call stack and takes up actual memory.

However, just because you have n calls total doesn't mean it takes O(n) space. Consider the below function, which adds adjacent elements between 0 and n:

```
int pairSumSequence(int n) { /* Ex 2.*/
  int sum = 0;
  for (int i = 0; i < n; i++) {
    sum += pairSum(i, i + 1);
  }
  return sum;
}

int pairSum(int a, int b) {
  return a + b;
}
```

There will be roughly O(n) calls to `pairSum`. However, those calls do not exist simultaneously on the call stack, so you only need O(1) space.

▸ Drop the Constants

It is very possible for O(N) code to run faster than O(1) code for specific inputs. Big O just describes the rate of increase.

For this reason, we drop the constants in runtime. An algorithm that one might have described as O(2N) is actually O(N).

Many people resist doing this. They will see code that has two (non-nested) for loops and continue this O(2N). They think they're being more "precise." They're not.

Consider the below code:

Min and Max 1

```
int min = Integer.MAX_VALUE;
int max = Integer.MIN_VALUE;
for (int x : array) {
  if (x < min) min = x;
  if (x > max) max = x;
}
```

Min and Max 2

```
int min = Integer.MAX_VALUE;
int max = Integer.MIN_VALUE;
for (int x : array) {
  if (x < min) min = x;
}
for (int x : array) {
  if (x > max) max = x;
}
```

Which one is faster? The first one does one for loop and the other one does two for loops. But then, the first solution has two lines of code per for loop rather than one.

If you're going to count the number of instructions, then you'd have to go to the assembly level and take into account that multiplication requires more instructions than addition, how the compiler would optimize something, and all sorts of other details.

This would be horrendously complicated, so don't even start going down this road. Big O allows us to express how the runtime scales. We just need to accept that it doesn't mean that O(N) is always better than O(N^2).

Drop the Non-Dominant Terms

What do you do about an expression such as `O(N² + N)`? That second N isn't exactly a constant. But it's not especially important.

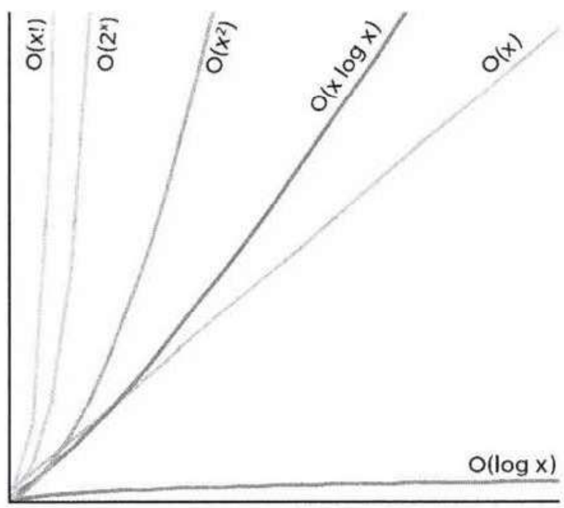
We already said that we drop constants. Therefore, $O(N^2 + N^2)$ would be $O(N^2)$. If we don't care about that latter N^2 term, why would we care about N? We don't.

You should drop the non-dominant terms.

- $O(N^2 + N)$ becomes $O(N^2)$.
- $O(N + \log N)$ becomes $O(N)$.
- $O(5*2^N + 1000N^{100})$ becomes $O(2^N)$.

We might still have a sum in a runtime. For example, the expression $O(B^2 + A)$ cannot be reduced (without some special knowledge of A and B).

The following graph depicts the rate of increase for some of the common big O times.



As you can see, $O(x^2)$ is much worse than $O(x)$, but it's not nearly as bad as $O(2^x)$ or $O(x!)$. There are lots of runtimes worse than $O(x!)$ too, such as $O(x^x)$ or $O(2^x * x!)$.

Multi-Part Algorithms: Add vs. Multiply

Suppose you have an algorithm that has two steps. When do you multiply the runtimes and when do you add them?

This is a common source of confusion for candidates.

Add the Runtimes: O(A + B)

```
for (int a : arrA) {
  print(a);
}

for (int b : arrB) {
  print(b);
}
```

Multiply the Runtimes: O(A*B)

```
for (int a : arrA) {
  for (int b : arrB) {
    print(a + "," + b);
  }
}
```

In the example on the left, we do A chunks of work then B chunks of work. Therefore, the total amount of work is `O(A + B)`.

In the example on the right, we do B chunks of work for each element in A. Therefore, the total amount of work is `O(A * B)`.

In other words:

- If your algorithm is in the form "do this, then, when you're all done, do that" then you add the runtimes.
- If your algorithm is in the form "do this for each time you do that" then you multiply the runtimes.

It's very easy to mess this up in an interview, so be careful.

▸ Amortized Time

An `ArrayList`, or a dynamically resizing array, allows you to have the benefits of an array while offering flexibility in size. You won't run out of space in the `ArrayList` since its capacity will grow as you insert elements.

An ArrayList is implemented with an array. When the array hits capacity, the `ArrayList` class will create a new array with double the capacity and copy all the elements over to the new array.

How do you describe the runtime of insertion? This is a tricky question.

The array could be full. If the array contains N elements, then inserting a new element will take `O(N)` time. You will have to create a new array of size 2N and then copy N elements over. This insertion will take `O(N)` time.

However, we also know that this doesn't happen very often. The vast majority of the time insertion will be in `O(1)` time.

We need a concept that takes both into account. This is what amortized time does. It allows us to describe that, yes, this worst case happens every once in a while. But once it happens, it won't happen again for so long that the cost is "amortized."

In this case, what is the amortized time?

As we insert elements, we double the capacity when the size of the array is a power of 2. So after X elements, we double the capacity at array sizes 1, 2, 4, 8, 16, ..., X. That doubling takes, respectively, 1, 2, 4, 8, 16, 32, 64, ..., X copies.

What is the sum of 1 + 2 + 4 + 8 + 16 + ... + X? If you read this sum left to right, it starts with 1 and doubles until it gets to X. If you read right to left, it starts with X and halves until it gets to 1.

What then is the sum of $X + \frac{X}{2} + \frac{X}{4} + \frac{X}{8} + \ldots + 1$? This is roughly 2X.

Therefore, X insertions take `O(2X)` time. The amortized time for each insertion is `O(1)`.

Log N Runtimes

We commonly see `O(log N)` in runtimes. Where does this come from?

Let's look at binary search as an example. In binary search, we are looking for an example x in an N-element sorted array. We first compare x to the midpoint of the array. If `x == middle`, then we return. If `x < middle`, then we search on the left side of the array. If `x > middle`, then we search on the right side of the array.

```
search 9 within {1, 5, 8, 9, 11, 13, 15, 19, 21}
    compare 9 to 11 -> smaller.
    search 9 within {1, 5, 8, 9, 11}
        compare 9 to 8 -> bigger
        search 9 within {9, 11}
            compare 9 to 9
            return
```

We start off with an N-element array to search. Then, after a single step, we're down to $N/2$ elements. One more step, and we're down to $N/4$ elements. We stop when we either find the value or we're down to just one element.

The total runtime is then a matter of how many steps (dividing N by 2 each time) we can take until N becomes 1.

```
N = 16
N = 8       /* divide by 2 */
N = 4       /* divide by 2 */
N = 2       /* divide by 2 */
N = 1       /* divide by 2 */
```

We could look at this in reverse (going from 1 to 16 instead of 16 to 1). How many times we can multiply 1 by 2 until we get N?

```
N = 1
N = 2       /* multiply by 2 */
N = 4       /* multiply by 2 */
N = 8       /* multiply by 2 */
N = 16      /* multiply by 2 */
```

What is k in the expression $2^k = N$? This is exactly what `log` expresses.

$2^4 = 16 \rightarrow \log_2 16 = 4$
$\log_2 N = k \rightarrow 2^k = N$

This is a good takeaway for you to have. When you see a problem where the number of elements in the problem space gets halved each time, that will likely be a `O(log N)` runtime.

This is the same reason why finding an element in a balanced binary search tree is `O(log N)`. With each comparison, we go either left or right. Half the nodes are on each side, so we cut the problem space in half each time.

> What's the base of the log? That's an excellent question! The short answer is that it doesn't matter for the purposes of big O. The longer explanation can be found at "Bases of Logs" on page 630.

Recursive Runtimes

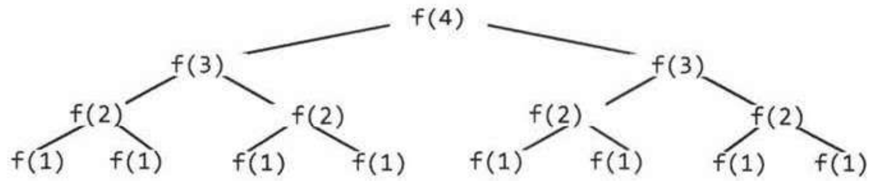
Here's a tricky one. What's the runtime of this code?

```
int f(int n) {
```

```
    if (n <= 1) {
      return 1;
    }
    return f(n - 1) + f(n - 1);
}
```

A lot of people will, for some reason, see the two calls to `f` and jump to $O(N^2)$. This is completely incorrect.

Rather than making assumptions, let's derive the runtime by walking through the code. Suppose we call `f(4)`. This calls `f(3)` twice. Each of those calls to `f(3)` calls `f(2)`, until we get down to `f(1)`.



How many calls are in this tree? (Don't count!)

The tree will have depth N. Each node (i.e., function call) has two children. Therefore, each level will have twice as many calls as the one above it. The number of nodes on each level is:

Level	# Nodes	Also expressed as...	Or...
0	1		2^0
1	2	2 * previous level = 2	2^1
2	4	2 * previous level = $2 * 2^1 = 2^2$	2^2
3	8	2 * previous level = $2 * 2^2 = 2^3$	2^3
4	16	2 * previous level = $2 * 2^3 = 2^4$	2^4

Therefore, there will be $2^0 + 2^1 + 2^2 + 2^3 + 2^4 + ... + 2^N$ (which is $2^{N+1} - 1$) nodes. (See "Sum of Powers of 2" on page 630.)

Try to remember this pattern. When you have a recursive function that makes multiple calls, the runtime will often (but not always) look like $O(branches^{depth})$, where branches is the number of times each recursive call branches. In this case, this gives us $O(2^N)$.

> As you may recall, the base of a log doesn't matter for big O since logs of different bases are only different by a constant factor. However, this does not apply to exponents. The base of an exponent does matter. Compare 2^n and 8^n. If you expand 8^n, you get $(2^3)^n$, which equals 2^{3n}, which equals $2^{2n} * 2^n$. As you can see, 8^n and 2^n are different by a factor of 2^{2n}. That is very much not a constant factor!

The space complexity of this algorithm will be $O(N)$. Although we have $O(2^N)$ nodes in the tree total, only $O(N)$ exist at any given time. Therefore, we would only need to have $O(N)$ memory available.

Examples and Exercises

Big O time is a difficult concept at first. However, once it "clicks," it gets fairly easy. The same patterns come up again and again, and the rest you can derive.

We'll start off easy and get progressively more difficult.

Example 1

What is the runtime of the below code?

```
void foo(int[] array) {
  int sum = 0;
  int product = 1;
  for (int i = 0; i < array.length; i++) {
    sum += array[i];
  }
  for (int i = 0; i < array.length; i++) {
    product *= array[i];
  }
  System.out.println(sum + “, ” + product);
}
```

This will take O(N) time. The fact that we iterate through the array twice doesn't matter.

Example 2

What is the runtime of the below code?

```
void printPairs(int[] array) {
  for (int i = 0; i < array.length; i++) {
    for (int j = 0; j < array.length; j++) {
      System.out.println(array[i] + “,” + array[j]);
    }
  }
}
```

The inner for loop has O(N) iterations and it is called N times. Therefore, the runtime is $O(N^2)$.

Another way we can see this is by inspecting what the "meaning" of the code is. It is printing all pairs (two-element sequences). There are $O(N^2)$ pairs; therefore, the runtime is $O(N^2)$.

Example 3

This is very similar code to the above example, but now the inner for loop starts at `i + 1`.

```
void printUnorderedPairs(int[] array) {
  for (int i = 0; i < array.length; i++) {
    for (int j = i + 1; j < array.length; j++) {
      System.out.println(array[i] + “,” + array[j]);
    }
  }
}
```

We can derive the runtime several ways.

> This pattern of for loop is very common. It's important that you know the runtime and that you deeply understand it. You can't rely on just memorizing common runtimes. Deep comprehension is important.

Counting the Iterations

The first time through `j` runs for N-1 steps. The second time, it's N-2 steps. Then N-3 steps. And so on.

Therefore, the number of steps total is:

```
(N-1) + (N-2) + (N-3) + ... + 2 + 1
```

```
= 1 + 2 + 3 + ... + N-1
= sum of 1 through N-1
```

The sum of 1 through N-1 is $\frac{N(N-1)}{2}$ (see "Sum of Integers 1 through N" on page 630), so the runtime will be $O(N^2)$.

What It Means

Alternatively, we can figure out the runtime by thinking about what the code "means." It iterates through each pair of values for `(i, j)` where `j` is bigger than `i`.

There are N^2 total pairs. Roughly half of those will have `i < j` and the remaining half will have `i > j`. This code goes through roughly $N^2/2$ pairs so it does $O(N^2)$ work.

Visualizing What It Does

The code iterates through the following `(i, j)` pairs when `N = 8`:

```
(0, 1) (0, 2) (0, 3) (0, 4) (0, 5) (0, 6) (0, 7)
       (1, 2) (1, 3) (1, 4) (1, 5) (1, 6) (1, 7)
              (2, 3) (2, 4) (2, 5) (2, 6) (2, 7)
                     (3, 4) (3, 5) (3, 6) (3, 7)
                            (4, 5) (4, 6) (4, 7)
                                   (5, 6) (5, 7)
                                          (6, 7)
```

This looks like half of an NxN matrix, which has size (roughly) $N^2/2$. Therefore, it takes $O(N^2)$ time.

Average Work

We know that the outer loop runs N times. How much work does the inner loop do? It varies across iterations, but we can think about the average iteration.

What is the average value of `1, 2, 3, 4, 5, 6, 7, 8, 9, 10`? The average value will be in the middle, so it will be *roughly* 5. (We could give a more precise answer, of course, but we don't need to for big O.)

What about for `1, 2, 3, ..., N`? The average value in this sequence is N/2.

Therefore, since the inner loop does $N/2$ work on average and it is run N times, the total work is $N^2/2$ which is $O(N^2)$.

Example 4

This is similar to the above, but now we have two different arrays.

```
void printUnorderedPairs(int[] arrayA, int[] arrayB) {
  for (int i = 0; i < arrayA.length; i++) {
    for (int j = 0; j < arrayB.length; j++) {
      if (arrayA[i] < arrayB[j]) {
        System.out.println(arrayA[i] + "," + arrayB[j]);
      }
    }
  }
}
```

We can break up this analysis. The if-statement within `j`'s for loop is $O(1)$ time since it's just a sequence of constant-time statements.

We now have this:

```
void printUnorderedPairs(int[] arrayA, int[] arrayB) {
```

```
    for (int i = 0; i < arrayA.length; i++) {
        for (int j = 0; j < arrayB.length; j++) {
            /* O(1) work */
        }
    }
}
```

For each element of `arrayA`, the inner for loop goes through b iterations, where `b = arrayB.length`. If `a = arrayA.length`, then the runtime is `O(ab)`.

If you said $O(N^2)$, then remember your mistake for the future. It's not $O(N^2)$ because there are two different inputs. Both matter. This is an extremely common mistake.

Example 5

What about this strange bit of code?

```
void printUnorderedPairs(int[] arrayA, int[] arrayB) {
    for (int i = 0; i < arrayA.length; i++) {
        for (int j = 0; j < arrayB.length; j++) {
            for (int k = 0; k < 100000; k++) {
                System.out.println(arrayA[i] + "," + arrayB[j]);
            }
        }
    }
}
```

Nothing has really changed here. 100,000 units of work is still constant, so the runtime is `O(ab)`.

Example 6

The following code reverses an array. What is its runtime?

```
void reverse(int[] array) {
    for (int i = 0; i < array.length / 2; i++) {
        int other = array.length - i - 1;
        int temp = array[i];
        array[i] = array[other];
        array[other] = temp;
    }
}
```

This algorithm runs in `O(N)` time. The fact that it only goes through half of the array (in terms of iterations) does not impact the big O time.

Example 7

Which of the following are equivalent to `O(N)`? Why?

- `O(N + P)`, where $P < {}^{N}/_{2}$
- `O(2N)`
- `O(N + log N)`
- `O(N + M)`

Let's go through these.

- If $P < {}^{N}/_{2}$, then we know that N is the dominant term so we can drop the `O(P)`.
- `O(2N)` is `O(N)` since we drop constants.

- O(N) dominates O(log N), so we can drop the O(log N).
- There is no established relationship between N and M, so we have to keep both variables in there.

Therefore, all but the last one are equivalent to O(N).

Example 8

Suppose we had an algorithm that took in an array of strings, sorted each string, and then sorted the full array. What would the runtime be?

Many candidates will reason the following: sorting each string is O(N log N) and we have to do this for each string, so that's O(N*N log N). We also have to sort this array, so that's an additional O(N log N) work. Therefore, the total runtime is $O(N^2 \log N + N \log N)$, which is just $O(N^2 \log N)$.

This is completely incorrect. Did you catch the error?

The problem is that we used N in two different ways. In one case, it's the length of the string (which string?). And in another case, it's the length of the array.

In your interviews, you can prevent this error by either not using the variable "N" at all, or by only using it when there is no ambiguity as to what N could represent.

In fact, I wouldn't even use a and b here, or m and n. It's too easy to forget which is which and mix them up. An $O(a^2)$ runtime is completely different from an O(a*b) runtime.

Let's define new terms—and use names that are logical.

- Let s be the length of the longest string.
- Let a be the length of the array.

Now we can work through this in parts:

- Sorting each string is O(s log s).
- We have to do this for every string (and there are a strings), so that's O(a*s log s).
- Now we have to sort all the strings. There are a strings, so you'll may be inclined to say that this takes O(a log a) time. This is what most candidates would say. You should also take into account that you need to compare the strings. Each string comparison takes O(s) time. There are O(a log a) comparisons, therefore this will take O(a*s log a) time.

If you add up these two parts, you get O(a*s(log a + log s)).

This is it. There is no way to reduce it further.

Example 9

The following simple code sums the values of all the nodes in a balanced binary search tree. What is its runtime?

```
int sum(Node node) {
   if (node == null) {
      return 0;
   }
   return sum(node.left) + node.value + sum(node.right);
}
```

Just because it's a binary search tree doesn't mean that there is a log in it!

We can look at this two ways.

What It Means

The most straightforward way is to think about what this means. This code touches each node in the tree once and does a constant time amount of work with each "touch" (excluding the recursive calls).

Therefore, the runtime will be linear in terms of the number of nodes. If there are N nodes, then the runtime is $O(N)$.

Recursive Pattern

On page 44, we discussed a pattern for the runtime of recursive functions that have multiple branches. Let's try that approach here.

We said that the runtime of a recursive function with multiple branches is typically $O(branches^{depth})$. There are two branches at each call, so we're looking at $O(2^{depth})$.

At this point many people might assume that something went wrong since we have an exponential algorithm—that something in our logic is flawed or that we've inadvertently created an exponential time algorithm (yikes!).

The second statement is correct. We do have an exponential time algorithm, but it's not as bad as one might think. Consider what variable it's exponential with respect to.

What is `depth`? The tree is a balanced binary search tree. Therefore, if there are N total nodes, then `depth` is roughly `log N`.

By the equation above, we get $O(2^{\log N})$.

Recall what $\log_2$ means:

$$2^P = Q \rightarrow \log_2 Q = P$$

What is $2^{\log N}$? There is a relationship between 2 and log, so we should be able to simplify this.

Let $P = 2^{\log N}$. By the definition of $\log_2$, we can write this as $\log_2 P = \log_2 N$. This means that $P = N$.

$$\begin{aligned} &\text{Let } P = 2^{\log N} \\ &\quad \rightarrow \log_2 P = \log_2 N \\ &\quad \rightarrow P = N \\ &\quad \rightarrow 2^{\log N} = N \end{aligned}$$

Therefore, the runtime of this code is $O(N)$, where N is the number of nodes.

Example 10

The following method checks if a number is prime by checking for divisibility on numbers less than it. It only needs to go up to the square root of n because if n is divisible by a number greater than its square root then it's divisible by something smaller than it.

For example, while 33 is divisible by 11 (which is greater than the square root of 33), the "counterpart" to 11 is 3 (3 * 11 = 33). 33 will have already been eliminated as a prime number by 3.

What is the time complexity of this function?

```
boolean isPrime(int n) {
  for (int x = 2; x * x <= n; x++) {
    if (n % x == 0) {
      return false;
    }
  }
  return true;
```

```
}
```

Many people get this question wrong. If you're careful about your logic, it's fairly easy.

The work inside the for loop is constant. Therefore, we just need to know how many iterations the for loop goes through in the worst case.

The for loop will start when `x = 2` and end when `x*x = n`. Or, in other words, it stops when $x = \sqrt{n}$ (when x equals the square root of n).

This for loop is really something like this:

```
boolean isPrime(int n) {
  for (int x = 2; x <= sqrt(n); x++) {
    if (n % x == 0) {
      return false;
    }
  }
  return true;
}
```

This runs in $O(\sqrt{n})$ time.

Example 11

The following code computes `n!` (n factorial). What is its time complexity?

```
int factorial(int n) {
  if (n < 0) {
    return -1;
  } else if (n == 0) {
    return 1;
  } else {
    return n * factorial(n - 1);
  }
}
```

This is just a straight recursion from n to `n-1` to `n-2` down to `1`. It will take `O(n)` time.

Example 12

This code counts all permutations of a string.

```
void permutation(String str) {
  permutation(str, “”);
}

void permutation(String str, String prefix) {
  if (str.length() == 0) {
    System.out.println(prefix);
  } else {
    for (int i = 0; i < str.length(); i++) {
      String rem = str.substring(0, i) + str.substring(i + 1);
      permutation(rem, prefix + str.charAt(i));
    }
  }
}
```

This is a (very!) tricky one. We can think about this by looking at how many times `permutation` gets called and how long each call takes. We'll aim for getting as tight of an upper bound as possible.

How many times does permutation get called in its base case?

If we were to generate a permutation, then we would need to pick characters for each "slot." Suppose we had 7 characters in the string. In the first slot, we have 7 choices. Once we pick the letter there, we have 6 choices for the next slot. (Note that this is 6 choices *for each* of the 7 choices earlier.) Then 5 choices for the next slot, and so on.

Therefore, the total number of options is 7 * 6 * 5 * 4 * 3 * 2 * 1, which is also expressed as 7! (7 factorial).

This tells us that there are n! permutations. Therefore, `permutation` is called `n!` times in its base case (when `prefix` is the full permutation).

How many times does permutation get called before its base case?

But, of course, we also need to consider how many times lines 9 through 12 are hit. Picture a large call tree representing all the calls. There are `n!` leaves, as shown above. Each leaf is attached to a path of length n. Therefore, we know there will be no more than `n * n!` nodes (function calls) in this tree.

How long does each function call take?

Executing line 7 takes `O(n)` time since each character needs to be printed.

Line 10 and line 11 will also take `O(n)` time combined, due to the string concatenation. Observe that the sum of the lengths of `rem`, `prefix`, and `str.charAt(i)` will always be n.

Each node in our call tree therefore corresponds to `O(n)` work.

What is the total runtime?

Since we are calling `permutation` `O(n * n!)` times (as an upper bound), and each one takes `O(n)` time, the total runtime will not exceed $O(n^2 * n!)$.

Through more complex mathematics, we can derive a tighter runtime equation (though not necessarily a nice closed-form expression). This would almost certainly be beyond the scope of any normal interview.

Example 13

The following code computes the Nth Fibonacci number.

```
int fib(int n) {
  if (n <= 0) return 0;
  else if (n == 1) return 1;
  return fib(n - 1) + fib(n - 2);
}
```

We can use the earlier pattern we'd established for recursive calls: $O(branches^{depth})$.

There are 2 branches per call, and we go as deep as N, therefore the runtime is $O(2^N)$.

> Through some very complicated math, we can actually get a tighter runtime. The time is indeed exponential, but it's actually closer to $O(1.6^N)$. The reason that it's not exactly $O(2^N)$ is that, at the bottom of the call stack, there is sometimes only one call. It turns out that a lot of the nodes are at the bottom (as is true in most trees), so this single versus double call actually makes a big difference. Saying $O(2^N)$ would suffice for the scope of an interview, though (and is still technically correct, if you read the note about big theta on page 39). You might get "bonus points" if you can recognize that it'll actually be less than that.

Generally speaking, when you see an algorithm with multiple recursive calls, you're looking at exponential runtime.

Example 14

The following code prints all Fibonacci numbers from 0 to n. What is its time complexity?

```
void allFib(int n) {
  for (int i = 0; i < n; i++) {
    System.out.println(i + ": " + fib(i));
  }
}

int fib(int n) {
  if (n <= 0) return 0;
  else if (n == 1) return 1;
  return fib(n - 1) + fib(n - 2);
}
```

Many people will rush to concluding that since `fib(n)` takes $O(2^n)$ time and it's called n times, then it's $O(n2^n)$.

Not so fast. Can you find the error in the logic?

The error is that the n is changing. Yes, `fib(n)` takes $O(2^n)$ time, but it matters what that value of n is.

Instead, let's walk through each call.

```
fib(1) -> 2^1 steps
fib(2) -> 2^2 steps
fib(3) -> 2^3 steps
fib(4) -> 2^4 steps
...
fib(n) -> 2^n steps
```

Therefore, the total amount of work is:

$$2^1 + 2^2 + 2^3 + 2^4 + \ldots + 2^n$$

As we showed on page 44, this is 2^{n+1}. Therefore, the runtime to compute the first n Fibonacci numbers (using this terrible algorithm) is still $O(2^n)$.

Example 15

The following code prints all Fibonacci numbers from 0 to n. However, this time, it stores (i.e., caches) previously computed values in an integer array. If it has already been computed, it just returns the cache. What is its runtime?

```
void allFib(int n) {
  int[] memo = new int[n + 1];
  for (int i = 0; i < n; i++) {
    System.out.println(i + ": " + fib(i, memo));
  }
}

int fib(int n, int[] memo) {
  if (n <= 0) return 0;
  else if (n == 1) return 1;
  else if (memo[n] > 0) return memo[n];

  memo[n] = fib(n - 1, memo) + fib(n - 2, memo);
```

```
    return memo[n];
}
```

Let's walk through what this algorithm does.

```
fib(1) -> return 1
fib(2)
    fib(1) -> return 1
    fib(0) -> return 0
    store 1 at memo[2]
fib(3)
    fib(2) -> lookup memo[2] -> return 1
    fib(1) -> return 1
    store 2 at memo[3]
fib(4)
    fib(3) -> lookup memo[3] -> return 2
    fib(2) -> lookup memo[2] -> return 1
    store 3 at memo[4]
fib(5)
    fib(4) -> lookup memo[4] -> return 3
    fib(3) -> lookup memo[3] -> return 2
    store 5 at memo[5]
...
```

At each call to `fib(i)`, we have already computed and stored the values for `fib(i-1)` and `fib(i-2)`. We just look up those values, sum them, store the new result, and return. This takes a constant amount of time.

We're doing a constant amount of work N times, so this is `O(n)` time.

This technique, called memoization, is a very common one to optimize exponential time recursive algorithms.

Example 16

The following function prints the powers of 2 from 1 through n (inclusive). For example, if n is 4, it would print 1, 2, and 4. What is its runtime?

```
int powersOf2(int n) {
  if (n < 1) {
     return 0;
  } else if (n == 1) {
     System.out.println(1);
     return 1;
  } else {
     int prev = powersOf2(n / 2);
     int curr = prev * 2;
     System.out.println(curr);
     return curr;
  }
}
```

There are several ways we could compute this runtime.

What It Does

Let's walk through a call like `powersOf2(50)`.

```
powersOf2(50)
    -> powersOf2(25)
```

```
        -> powersOf2(12)
            -> powersOf2(6)
                -> powersOf2(3)
                    -> powersOf2(1)
                        -> print & return 1
                    print & return 2
                print & return 4
            print & return 8
        print & return 16
    print & return 32
```

The runtime, then, is the number of times we can divide 50 (or n) by 2 until we get down to the base case (1). As we discussed on page 44, the number of times we can halve n until we get 1 is O(log n).

What It Means

We can also approach the runtime by thinking about what the code is supposed to be doing. It's supposed to be computing the powers of 2 from 1 through n.

Each call to powersOf2 results in exactly one number being printed and returned (excluding what happens in the recursive calls). So if the algorithm prints 13 values at the end, then powersOf2 was called 13 times.

In this case, we are told that it prints all the powers of 2 between 1 and n. Therefore, the number of times the function is called (which will be its runtime) must equal the number of powers of 2 between 1 and n.

There are log N powers of 2 between 1 and n. Therefore, the runtime is O(log n).

Rate of Increase

A final way to approach the runtime is to think about how the runtime changes as n gets bigger. After all, this is exactly what big O time means.

If N goes from P to P+1, the number of calls to powersOfTwo might not change at all. When will the number of calls to powersOfTwo increase? It will increase by 1 each time n doubles in size.

So, each time n doubles, the number of calls to powersOfTwo increases by 1. Therefore, the number of calls to powersOfTwo is the number of times you can double 1 until you get n. It is x in the equation $2^x = n$.

What is x? The value of x is log n. This is exactly what meant by x = log n.

Therefore, the runtime is O(log n).

Additional Problems

VI.1 The following code computes the product of a and b. What is its runtime?

```
int product(int a, int b) {
    int sum = 0;
    for (int i = 0; i < b; i++) {
        sum += a;
    }
    return sum;
}
```

VI.2 The following code computes a^b. What is its runtime?

```
int power(int a, int b) {
    if (b < 0) {
```

```
            return 0; // error
        } else if (b == 0) {
            return 1;
        } else {
            return a * power(a, b - 1);
        }
    }
```

VI.3 The following code computes a % b**. What is its runtime?**

```
    int mod(int a, int b) {
        if (b <= 0) {
            return -1;
        }
        int div = a / b;
        return a - div * b;
    }
```

VI.4 The following code performs integer division. What is its runtime (assume a and b are both positive)?

```
    int div(int a, int b) {
        int count = 0;
        int sum = b;
        while (sum <= a) {
            sum += b;
            count++;
        }
        return count;
    }
```

VI.5 The following code computes the [integer] square root of a number. If the number is not a perfect square (there is no integer square root), then it returns -1. It does this by successive guessing. If n is 100, it first guesses 50. Too high? Try something lower – halfway between 1 and 50. What is its runtime?

```
    int sqrt(int n) {
        return sqrt_helper(n, 1, n);
    }

    int sqrt_helper(int n, int min, int max) {
        if (max < min) return -1; // no square root

        int guess = (min + max) / 2;
        if (guess * guess == n) { // found it!
            return guess;
        } else if (guess * guess < n) { // too low
            return sqrt_helper(n, guess + 1, max); // try higher
        } else { // too high
            return sqrt_helper(n, min, guess - 1); // try lower
        }
    }
```

VI.6 The following code computes the [integer] square root of a number. If the number is not a perfect square (there is no integer square root), then it returns -1. It does this by trying increasingly large numbers until it finds the right value (or is too high). What is its runtime?

```
    int sqrt(int n) {
        for (int guess = 1; guess * guess <= n; guess++) {
            if (guess * guess == n) {
                return guess;
```

```
        }
    }
    return -1;
}
```

VI.7 **If a binary search tree is not balanced, how long might it take (worst case) to find an element in it?**

VI.8 **You are looking for a specific value in a binary tree, but the tree is not a binary search tree. What is the time complexity of this?**

VI.9 **The appendToNew method appends a value to an array by creating a new, longer array and returning this longer array. You've used the appendToNew method to create a copyArray function that repeatedly calls appendToNew. How long does copying an array take?**

```
int[] copyArray(int[] array) {
    int[] copy = new int[0];
    for (int value : array) {
        copy = appendToNew(copy, value);
    }
    return copy;
}

int[] appendToNew(int[] array, int value) {
    // copy all elements over to new array
    int[] bigger = new int[array.length + 1];
    for (int i = 0; i < array.length; i++) {
        bigger[i] = array[i];
    }

    // add new element
    bigger[bigger.length - 1] = value;
    return bigger;
}
```

VI.10 **The following code sums the digits in a number. What is its big O time?**

```
int sumDigits(int n) {
    int sum = 0;
    while (n > 0) {
        sum += n % 10;
        n /= 10;
    }
    return sum;
}
```

VI.11 **The following code prints all strings of length k where the characters are in sorted order. It does this by generating all strings of length k and then checking if each is sorted. What is its runtime?**

```
int numChars = 26;

void printSortedStrings(int remaining) {
    printSortedStrings(remaining, "");
}

void printSortedStrings(int remaining, String prefix) {
    if (remaining == 0) {
        if (isInOrder(prefix)) {
            System.out.println(prefix);
        }
```

```
    } else {
        for (int i = 0; i < numChars; i++) {
            char c = ithLetter(i);
            printSortedStrings(remaining - 1, prefix + c);
        }
    }
}

boolean isInOrder(String s) {
    for (int i = 1; i < s.length(); i++) {
        int prev = ithLetter(s.charAt(i - 1));
        int curr = ithLetter(s.charAt(i));
        if (prev > curr) {
            return false;
        }
    }
    return true;
}

char ithLetter(int i) {
    return (char) (((int) 'a') + i);
}
```

VI.12 The following code computes the intersection (the number of elements in common) of two arrays. It assumes that neither array has duplicates. It computes the intersection by sorting one array (array b) and then iterating through array a checking (via binary search) if each value is in b. What is its runtime?

```
int intersection(int[] a, int[] b) {
    mergesort(b);
    int intersect = 0;

    for (int x : a) {
        if (binarySearch(b, x) >= 0) {
            intersect++;
        }
    }

    return intersect;
}
```

Solutions

1. `O(b)`. The for loop just iterates through b.
2. `O(b)`. The recursive code iterates through b calls, since it subtracts one at each level.
3. `O(1)`. It does a constant amount of work.
4. $O(a/b)$. The variable `count` will eventually equal a/b. The while loop iterates count times. Therefore, it iterates a/b times.
5. `O(log n)`. This algorithm is essentially doing a binary search to find the square root. Therefore, the runtime is `O(log n)`.
6. `O(sqrt(n))`. This is just a straightforward loop that stops when `guess*guess > n` (or, in other words, when `guess > sqrt(n)`).

7. `O(n)`, where n is the number of nodes in the tree. The max time to find an element is the depth tree. The tree could be a straight list downwards and have depth n.
8. `O(n)`. Without any ordering property on the nodes, we might have to search through all the nodes.
9. $O(n^2)$, where n is the number of elements in the array. The first call to `appendToNew` takes 1 copy. The second call takes 2 copies. The third call takes 3 copies. And so on. The total time will be the sum of 1 through n, which is $O(n^2)$.
10. `O(log n)`. The runtime will be the number of digits in the number. A number with d digits can have a value up to 10^d. If $n = 10^d$, then `d = log n`. Therefore, the runtime is `O(log n)`.
11. $O(kc^k)$, where k is the length of the string and c is the number of characters in the alphabet. It takes $O(c^k)$ time to generate each string. Then, we need to check that each of these is sorted, which takes `O(k)` time.
12. `O(b log b + a log b)`. First, we have to sort array b, which takes `O(b log b)` time. Then, for each element in a, we do binary search in `O(log b)` time. The second part takes `O(a log b)` time.

VII

Technical Questions

Technical questions form the basis for how many of the top tech companies interview. Many candidates are intimidated by the difficulty of these questions, but there are logical ways to approach them.

▸ How to Prepare

Many candidates just read through problems and solutions. That's like trying to learn calculus by reading a problem and its answer. You need to practice solving problems. Memorizing solutions won't help you much.

For each problem in this book (and any other problem you might encounter), do the following:

1. *Try to solve the problem on your own.* Hints are provided at the back of this book, but push yourself to develop a solution with as little help as possible. Many questions are designed to be tough—that's okay! When you're solving a problem, make sure to think about the space and time efficiency.
2. *Write the code on paper.* Coding on a computer offers luxuries such as syntax highlighting, code completion, and quick debugging. Coding on paper does not. Get used to this—and to how slow it is to write and edit code—by coding on paper.
3. *Test your code—on paper.* This means testing the general cases, base cases, error cases, and so on. You'll need to do this during your interview, so it's best to practice this in advance.
4. *Type your paper code as-is into a computer.* You will probably make a bunch of mistakes. Start a list of all the errors you make so that you can keep these in mind during the actual interview.

In addition, try to do as many mock interviews as possible. You and a friend can take turns giving each other mock interviews. Though your friend may not be an expert interviewer, he or she may still be able to walk you through a coding or algorithm problem. You'll also learn a lot by experiencing what it's like to be an interviewer.

▸ What You Need To Know

The sorts of data structure and algorithm questions that many companies focus on are not knowledge tests. However, they do assume a baseline of knowledge.

Core Data Structures, Algorithms, and Concepts

Most interviewers won't ask about specific algorithms for binary tree balancing or other complex algorithms. Frankly, being several years out of school, they probably don't remember these algorithms either.

You're usually only expected to know the basics. Here's a list of the absolute, must-have knowledge:

Data Structures	Algorithms	Concepts
Linked Lists	Breadth-First Search	Bit Manipulation
Trees, Tries, & Graphs	Depth-First Search	Memory (Stack vs. Heap)
Stacks & Queues	Binary Search	Recursion
Heaps	Merge Sort	Dynamic Programming
Vectors / ArrayLists	Quick Sort	Big O Time & Space
Hash Tables		

For each of these topics, make sure you understand how to use and implement them and, where applicable, the space and time complexity.

Practicing implementing the data structures and algorithm (on paper, and then on a computer) is also a great exercise. It will help you learn how the internals of the data structures work, which is important for many interviews.

> Did you miss that paragraph above? It's important. If you don't feel very, very comfortable with each of the data structures and algorithms listed, practice implementing them from scratch.

In particular, hash tables are an extremely important topic. Make sure you are very comfortable with this data structure.

Powers of 2 Table

The table below is useful for many questions involving scalability or any sort of memory limitation. Memorizing this table isn't strictly required, but it can be useful. You should at least be comfortable deriving it.

Power of 2	Exact Value (X)	Approx. Value	X Bytes into MB, GB, etc.
7	128		
8	256		
10	1024	1 thousand	1 KB
16	65,536		64 KB
20	1,048,576	1 million	1 MB
30	1,073,741,824	1 billion	1 GB
32	4,294,967,296		4 GB
40	1,099,511,627,776	1 trillion	1 TB

For example, you could use this table to quickly compute that a bit vector mapping every 32-bit integer to a boolean value could fit in memory on a typical machine. There are 2^{32} such integers. Because each integer takes one bit in this bit vector, we need 2^{32} bits (or 2^{29} bytes) to store this mapping. That's about half a gigabyte of memory, which can be easily held in memory on a typical machine.

If you are doing a phone screen with a web-based company, it may be useful to have this table in front of you.

Walking Through a Problem

The below map/flowchart walks you through how to solve a problem. Use this in your practice. You can download this handout and more at CrackingTheCodingInterview.com.

A Problem-Solving Flowchart

Listen

Pay very close attention to any information in the problem description. You probably need it all for an optimal algorithm.

Example

Most examples are too small or are special cases. **Debug your example.** Is there any way it's a special case? Is it big enough?

Brute Force

Get a brute-force solution as soon as possible. Don't worry about developing an efficient algorithm yet. State a naive algorithm and its runtime, then optimize from there. Don't code yet though!

Optimize

Walk through your brute force with **BUD optimization** or try some of these ideas:

- Look for any unused info. You usually need all the information in a problem.
- Solve it manually on an example, then reverse engineer your thought process. How did you solve it?
- Solve it "incorrectly" and then think about why the algorithm fails. Can you fix those issues?
- Make a time vs. space tradeoff. Hash tables are especially useful!

BUD Optimization

Bottlenecks

Unnecessary Work

Duplicated Work

Walk Through

Now that you have an optimal solution, **walk through your approach in detail.** Make sure you understand each detail before you start coding.

Implement

Your goal is to **write beautiful code.** Modularize your code from the beginning and refactor to clean up anything that isn't beautiful.

Test

Test in this order:

1. Conceptual test. Walk through your code like you would for a detailed code review.
2. Unusual or non-standard code.
3. Hot spots, like arithmetic and null nodes.
4. Small test cases. It's much faster than a big test case and just as effective.
5. Special cases and edge cases.

And when you find bugs, **fix them carefully!**

Keep talking! Your interviewer wants to hear how you approach the problem.

We'll go through this flowchart in more detail.

What to Expect

Interviews are supposed to be difficult. If you don't get every—or any—answer immediately, that's okay! That's the normal experience, and it's not bad.

Listen for guidance from the interviewer. The interviewer might take a more active or less active role in your problem solving. The level of interviewer participation depends on your performance, the difficulty of the question, what the interviewer is looking for, and the interviewer's own personality.

When you're given a problem (or when you're practicing), work your way through it using the approach below.

1. Listen Carefully

You've likely heard this advice before, but I'm saying something a bit more than the standard "make sure you hear the problem correctly" advice.

Yes, you do want to listen to the problem and make sure you heard it correctly. You do want to ask questions about anything you're unsure about.

But I'm saying something more than that.

Listen carefully to the problem, and be sure that you've mentally recorded any *unique* information in the problem.

For example, suppose a question starts with one of the following lines. It's reasonable to assume that the information is there for a reason.

- "Given two arrays that are sorted, find ..."

  You probably need to know that the data is sorted. The optimal algorithm for the sorted situation is probably different than the optimal algorithm for the unsorted situation.

- "Design an algorithm to be run repeatedly on a server that ..."

  The server/to-be-run-repeatedly situation is different from the run-once situation. Perhaps this means that you cache data? Or perhaps it justifies some reasonable precomputation on the initial dataset?

It's unlikely (although not impossible) that your interviewer would give you this information if it didn't affect the algorithm.

Many candidates will hear the problem correctly. But ten minutes into developing an algorithm, some of the key details of the problem have been forgotten. Now they are in a situation where they actually can't solve the problem optimally.

Your first algorithm doesn't need to use the information. But if you find yourself stuck, or you're still working to develop something more optimal, ask yourself if you've used all the information in the problem.

You might even find it useful to write the pertinent information on the whiteboard.

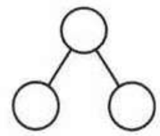
2. Draw an Example

An example can dramatically improve your ability to solve an interview question, and yet so many candidates just try to solve the question in their heads.

When you hear a question, get out of your chair, go to the whiteboard, and draw an example.

There's an art to drawing an example though. You want a good example.

Very typically, a candidate might draw something like this for an example of a binary search tree:



This is a bad example for several reasons. First, it's too small. You will have trouble finding a pattern in such a small example. Second, it's not specific. A binary search tree has values. What if the numbers tell you something about how to approach the problem? Third, it's actually a special case. It's not just a balanced tree, but it's also a beautiful, perfect tree where every node other than the leaves has two children. Special cases can be very deceiving.

Instead, you want to create an example that is:

- Specific. It should use real numbers or strings (if applicable to the problem).
- Sufficiently large. Most examples are too small, by about 50%.
- Not a special case. Be careful. It's very easy to inadvertently draw a special case. If there's any way your example is a special case (even if you think it probably won't be a big deal), you should fix it.

Try to make the best example you can. If it later turns out your example isn't quite right, you can and should fix it.

3. State a Brute Force

Once you have an example done (actually, you can switch the order of steps 2 and 3 in some problems), state a brute force. It's okay and expected that your initial algorithm won't be very optimal.

Some candidates don't state the brute force because they think it's both obvious and terrible. But here's the thing: Even if it's obvious for you, it's not necessarily obvious for all candidates. You don't want your interviewer to think that you're struggling to see even the easy solution.

It's okay that this initial solution is terrible. Explain what the space and time complexity is, and then dive into improvements.

Despite being possibly slow, a brute force algorithm is valuable to discuss. It's a starting point for optimizations, and it helps you wrap your head around the problem.

4. Optimize

Once you have a brute force algorithm, you should work on optimizing it. A few techniques that work well are:

1. Look for any unused information. Did your interviewer tell you that the array was sorted? How can you leverage that information?
2. Use a fresh example. Sometimes, just seeing a different example will unclog your mind or help you see a pattern in the problem.
3. Solve it "incorrectly." Just like having an inefficient solution can help you find an efficient solution, having an incorrect solution might help you find a correct solution. For example, if you're asked to generate a

random value from a set such that all values are equally likely, an incorrect solution might be one that returns a semi-random value: Any value could be returned, but some are more likely than others. You can then think about why that solution isn't perfectly random. Can you rebalance the probabilities?

4. Make time vs. space tradeoff. Sometimes storing extra state about the problem can help you optimize the runtime.
5. Precompute information. Is there a way that you can reorganize the data (sorting, etc.) or compute some values upfront that will help save time in the long run?
6. Use a hash table. Hash tables are widely used in interview questions and should be at the top of your mind.
7. Think about the best conceivable runtime (discussed on page 72).

Walk through the brute force with these ideas in mind and look for BUD (page 67).

5. Walk Through

After you've nailed down an optimal algorithm, don't just dive into coding. Take a moment to solidify your understanding of the algorithm.

Whiteboard coding is slow—very slow. So is testing your code and fixing it. As a result, you need to make sure that you get it as close to "perfect" in the beginning as possible.

Walk through your algorithm and get a feel for the structure of the code. Know what the variables are and when they change.

> What about pseudocode? You can write pseudocode if you'd like. Be careful about what you write. Basic steps ("(1) Search array. (2) Find biggest. (3) Insert in heap.") or brief logic ("if `p < q`, move `p`. else move `q`") can be valuable. But when your pseudocode starts having for loops that are written in plain English, then you're essentially just writing sloppy code. It'd probably be faster to just write the code.

If you don't understand exactly what you're about to write, you'll struggle to code it. It will take you longer to finish the code, and you're more likely to make major errors.

6. Implement

Now that you have an optimal algorithm and you know exactly what you're going to write, go ahead and implement it.

Start coding in the far top left corner of the whiteboard (you'll need the space). Avoid "line creep" (where each line of code is written an awkward slant). It makes your code look messy and can be very confusing when working in a whitespace-sensitive language, like Python.

Remember that you only have a short amount of code to demonstrate that you're a great developer. Everything counts. Write beautiful code.

Beautiful code means:

- Modularized code. This shows good coding style. It also makes things easier for you. If your algorithm uses a matrix initialized to `{{1, 2, 3}, {4, 5, 6}, ...}`, don't waste your time writing this initialization code. Just pretend you have a function `initIncrementalMatrix(int size)`. Fill in the details later if you need to.

- Error checks. Some interviewers care a lot about this, while others don't. A good compromise here is to add a `todo` and then just explain out loud what you'd like to test.
- Use other classes/structs where appropriate. If you need to return a list of start and end points from a function, you could do this as a two-dimensional array. It's better though to do this as a list of `StartEndPair` (or possibly `Range`) objects. You don't necessarily have to fill in the details for the class. Just pretend it exists and deal with the details later if you have time.
- Good variable names. Code that uses single-letter variables everywhere is difficult to read. That's not to say that there's anything wrong with using `i` and `j`, where appropriate (such as in a basic for-loop iterating through an array). However, be careful about where you do this. If you write something like `int i = startOfChild(array)`, there might be a better name for this variable, such as `startChild`.

  Long variable names can also be slow to write though. A good compromise that most interviewers will be okay with is to abbreviate it after the first usage. You can use `startChild` the first time, and then explain to your interviewer that you will abbreviate this as `sc` after this.

The specifics of what makes good code vary between interviewers and candidates, and the problem itself. Focus on writing beautiful code, whatever that means to you.

If you see something you can refactor later on, then explain this to your interviewer and decide whether or not it's worth the time to do so. Usually it is, but not always.

If you get confused (which is common), go back to your example and walk through it again.

7. Test

You wouldn't check in code in the real world without testing it, and you shouldn't "submit" code in an interview without testing it either.

There are smart and not-so-smart ways to test your code though.

What many candidates do is take their earlier example and test it against their code. That might discover bugs, but it'll take a really long time to do so. Hand testing is very slow. If you really did use a nice, big example to develop your algorithm, then it'll take you a very long time to find that little off-by-one error at the end of your code.

Instead, try this approach:

1. Start with a "conceptual" test. A conceptual test means just reading and analyzing what each line of code does. Think about it like you're explaining the lines of code for a code reviewer. Does the code do what you think it should do?
2. Weird looking code. Double check that line of code that says `x = length - 2`. Investigate that for loop that starts at `i = 1`. While you undoubtedly did this for a reason, it's really easy to get it just slightly wrong.
3. Hot spots. You've coded long enough to know what things are likely to cause problems. Base cases in recursive code. Integer division. Null nodes in binary trees. The start and end of iteration through a linked list. Double check that stuff.
4. Small test cases. This is the first time we use an actual, specific test case to test the code. Don't use that nice, big 8-element array from the algorithm part. Instead, use a 3 or 4 element array. It'll likely discover the same bugs, but it will be much faster to do so.
5. Special cases. Test your code against null or single element values, the extreme cases, and other special cases.

When you find bugs (and you probably will), you should of course fix them. But don't just make the first correction you think of. Instead, carefully analyze why the bug occurred and ensure that your fix is the best one.

▸ Optimize & Solve Technique #1: Look for BUD

This is perhaps the most useful approach I've found for optimizing problems. "BUD" is a silly acronym for:

- **B**ottlenecks
- **U**nnecessary work
- **D**uplicated work

These are three of the most common things that an algorithm can "waste" time doing. You can walk through your brute force looking for these things. When you find one of them, you can then focus on getting rid of it.

If it's still not optimal, you can repeat this approach on your current best algorithm.

Bottlenecks

A bottleneck is a part of your algorithm that slows down the overall runtime. There are two common ways this occurs:

- You have one-time work that slows down your algorithm. For example, suppose you have a two-step algorithm where you first sort the array and then you find elements with a particular property. The first step is `O(N log N)` and the second step is `O(N)`. Perhaps you could reduce the second step to `O(log N)` or `O(1)`, but would it matter? Not too much. It's certainly not a priority, as the `O(N log N)` is the bottleneck. Until you optimize the first step, your overall algorithm will be `O(N log N)`.
- You have a chunk of work that's done repeatedly, like searching. Perhaps you can reduce that from `O(N)` to `O(log N)` or even `O(1)`. That will greatly speed up your overall runtime.

Optimizing a bottleneck can make a big difference in your overall runtime.

> Example: Given an array of distinct integer values, count the number of pairs of integers that have difference k. For example, given the array `{1, 7, 5, 9, 2, 12, 3}` and the difference `k = 2`, there are four pairs with difference 2: `(1, 3), (3, 5), (5, 7), (7, 9)`.

A brute force algorithm is to go through the array, starting from the first element, and then search through the remaining elements (which will form the other side of the pair). For each pair, compute the difference. If the difference equals k, increment a counter of the difference.

The bottleneck here is the repeated search for the "other side" of the pair. It's therefore the main thing to focus on optimizing.

How can we more quickly find the right "other side"? Well, we actually know the other side of `(x, ?)`. It's `x + k` or `x - k`. If we sorted the array, we could find the other side for each of the N elements in `O(log N)` time by doing a binary search.

We now have a two-step algorithm, where both steps take `O(N log N)` time. Now, sorting is the new bottleneck. Optimizing the second step won't help because the first step is slowing us down anyway.

We just have to get rid of the first step entirely and operate on an unsorted array. How can we find things quickly in an unsorted array? With a hash table.

Throw everything in the array into the hash table. Then, to look up if `x + k` or `x - k` exist in the array, we just look it up in the hash table. We can do this in `O(N)` time.

Unnecessary Work

> Example: Print all positive integer solutions to the equation $a^3 + b^3 = c^3 + d^3$ where a, b, c, and d are integers between 1 and 1000.

A brute force solution will just have four nested for loops. Something like:

```
n = 1000
for a from 1 to n
  for b from 1 to n
    for c from 1 to n
      for d from 1 to n
        if a^3 + b^3 == c^3 + d^3
          print a, b, c, d
```

This algorithm iterates through all possible values of a, b, c, and d and checks if that combination happens to work.

It's unnecessary to continue checking for other possible values of d. Only one could work. We should at least break after we find a valid solution.

```
n = 1000
for a from 1 to n
  for b from 1 to n
    for c from 1 to n
      for d from 1 to n
        if a^3 + b^3 == c^3 + d^3
          print a, b, c, d
          break // break out of d's loop
```

This won't make a meaningful change to the runtime—our algorithm is still $O(N^4)$—but it's still a good, quick fix to make.

Is there anything else that is unnecessary? Yes. If there's only one valid d value for each (a, b, c), then we can just compute it. This is just simple math: $d = \sqrt[3]{a^3 + b^3 - c^3}$.

```
1  n = 1000
2  for a from 1 to n
3    for b from 1 to n
4      for c from 1 to n
5        d = pow(a^3 + b^3 - c^3, 1/3) // Will round to int
6        if a^3 + b^3 == c^3 + d^3 // Validate that the value works
7          print a, b, c, d
```

The `if` statement on line 6 is important. Line 5 will always find a value for d, but we need to check that it's the right integer value.

This will reduce our runtime from $O(N^4)$ to $O(N^3)$.

Duplicated Work

Using the same problem and brute force algorithm as above, let's look for duplicated work this time.

The algorithm operates by essentially iterating through all `(a, b)` pairs and then searching all `(c, d)` pairs to find if there are any matches to that `(a, b)` pair.

Why do we keep on computing all `(c, d)` pairs for each `(a, b)` pair? We should just create the list of `(c, d)` pairs once. Then, when we have an `(a, b)` pair, find the matches within the `(c, d)` list. We can quickly locate the matches by inserting each `(c, d)` pair into a hash table that maps from the sum to the pair (or, rather, the list of pairs that have that sum).

```
n = 1000
for c from 1 to n
  for d from 1 to n
    result = c^3 + d^3
    append (c, d) to list at value map[result]
for a from 1 to n
  for b from 1 to n
    result = a^3 + b^3
    list = map.get(result)
    for each pair in list
      print a, b, pair
```

Actually, once we have the map of all the `(c, d)` pairs, we can just use that directly. We don't need to generate the `(a, b)` pairs. Each `(a, b)` will already be in the map.

```
n = 1000
for c from 1 to n
  for d from 1 to n
    result = c^3 + d^3
    append (c, d) to list at value map[result]

for each result, list in map
  for each pair1 in list
    for each pair2 in list
      print pair1, pair2
```

This will take our runtime to $O(N^2)$.

▸ Optimize & Solve Technique #2: DIY (Do It Yourself)

The first time you heard about how to find an element in a sorted array (before being taught binary search), you probably didn't jump to, "Ah ha! We'll compare the target element to the midpoint and then recurse on the appropriate half."

And yet, you could give someone who has no knowledge of computer science an alphabetized pile of student papers and they'll likely implement something like binary search to locate a student's paper. They'll probably say, "Gosh, Peter Smith? He'll be somewhere in the bottom of the stack." They'll pick a random paper in the middle(ish), compare the name to "Peter Smith", and then continue this process on the remainder of the papers. Although they have no knowledge of binary search, they intuitively "get it."

Our brains are funny like this. Throw the phrase "Design an algorithm" in there and people often get all jumbled up. But give people an actual example—whether just of the data (e.g., an array) or of the real-life parallel (e.g., a pile of papers)—and their intuition gives them a very nice algorithm.

I've seen this come up countless times with candidates. Their computer algorithm is extraordinarily slow, but when asked to solve the same problem manually, they immediately do something quite fast. (And it's not too surprisingly, in some sense. Things that are slow for a computer are often slow by hand. Why would you put yourself through extra work?)

Therefore, when you get a question, try just working it through intuitively on a real example. Often a bigger example will be easier.

> Example: Given a smaller string s and a bigger string b, design an algorithm to find all permutations of the shorter string within the longer one. Print the location of each permutation.

Think for a moment about how you'd solve this problem. Note permutations are rearrangements of the string, so the characters in s can appear in any order in b. They must be contiguous though (not split by other characters).

If you're like most candidates, you probably thought of something like: Generate all permutations of s and then look for each in b. Since there are S! permutations, this will take `O(S! * B)` time, where S is the length of s and B is the length of b.

This works, but it's an extraordinarily slow algorithm. It's actually *worse* than an exponential algorithm. If s has 14 characters, that's over 87 billion permutations. Add one more character into s and we have 15 times more permutations. Ouch!

Approached a different way, you could develop a decent algorithm fairly easily. Give yourself a big example, like this one:

```
s: abbc
b: cbabadcbbabbcbabaabccbabc
```

Where are the permutations of s within b? Don't worry about how you're doing it. Just find them. Even a 12 year old could do this!

(No, really, go find them. I'll wait!)

I've underlined below each permutation.

```
s: abbc
b: cbabadcbbabbcbabaabccbabc
```

Did you find these? How?

Few people—even those who earlier came up with the `O(S! * B)` algorithm—actually generate all the permutations of `abbc` to locate those permutations in b. Almost everyone takes one of two (very similar) approaches:

1. Walk through b and look at sliding windows of 4 characters (since s has length 4). Check if each window is a permutation of s.
2. Walk through b. Every time you see a character in s, check if the next four (the length of s) characters are a permutation of s.

Depending on the exact implementation of the "is this a permutation" part, you'll probably get a runtime of either `O(B * S)`, `O(B * S log S)`, or $O(B * S^2)$. None of these are the most optimal algorithm (there is an `O(B)` algorithm), but it's a lot better than what we had before.

Try this approach when you're solving questions. Use a nice, big example and intuitively—manually, that is—solve it for the specific example. Then, afterwards, think hard about how you solved it. Reverse engineer your own approach.

Be particularly aware of any "optimizations" you intuitively or automatically made. For example, when you were doing this problem, you might have just skipped right over the sliding window with `"d"` in it, since `"d"` isn't in `abbc`. That's an optimization your brain made, and it's something you should at least be aware of in your algorithm.

▸ Optimize & Solve Technique #3: Simplify and Generalize

With Simplify and Generalize, we implement a multi-step approach. First, we simplify or tweak some constraint, such as the data type. Then, we solve this new simplified version of the problem. Finally, once we have an algorithm for the simplified problem, we try to adapt it for the more complex version.

> Example: A ransom note can be formed by cutting words out of a magazine to form a new sentence. How would you figure out if a ransom note (represented as a string) can be formed from a given magazine (string)?

To simplify the problem, we can modify it so that we are cutting *characters* out of a magazine instead of whole words.

We can solve the simplified ransom note problem with characters by simply creating an array and counting the characters. Each spot in the array corresponds to one letter. First, we count the number of times each character in the ransom note appears, and then we go through the magazine to see if we have all of those characters.

When we generalize the algorithm, we do a very similar thing. This time, rather than creating an array with character counts, we create a hash table that maps from a word to its frequency.

▸ Optimize & Solve Technique #4: Base Case and Build

With Base Case and Build, we solve the problem first for a base case (e.g., `n = 1`) and then try to build up from there. When we get to more complex/interesting cases (often n = 3 or n = 4), we try to build those using the prior solutions.

> Example: Design an algorithm to print all permutations of a string. For simplicity, assume all characters are unique.

Consider a test string `abcdefg`.

```
Case "a" --> {"a"}
Case "ab" --> {"ab", "ba"}
Case "abc" --> ?
```

This is the first "interesting" case. If we had the answer to `P("ab")`, how could we generate `P("abc")`? Well, the additional letter is "c," so we can just stick c in at every possible point. That is:

```
P("abc") = insert "c" into all locations of all strings in P("ab")
P("abc") = insert "c" into all locations of all strings in {"ab","ba"}
P("abc") = merge({"cab", "acb", "abc"}, {"cba", "bca", bac"})
P("abc") = {"cab", "acb", "abc", "cba", "bca", bac"}
```

Now that we understand the pattern, we can develop a general recursive algorithm. We generate all permutations of a string $s_1 \ldots s_n$ by "chopping off" the last character and generating all permutations of $s_1 \ldots s_{n-1}$. Once we have the list of all permutations of $s_1 \ldots s_{n-1}$, we iterate through this list. For each string in it, we insert s_n into every location of the string.

Base Case and Build algorithms often lead to natural recursive algorithms.

▸ Optimize & Solve Technique #5: Data Structure Brainstorm

This approach is certainly hacky, but it often works. We can simply run through a list of data structures and try to apply each one. This approach is useful because solving a problem may be trivial once it occurs to us to use, say, a tree.

> Example: Numbers are randomly generated and stored into an (expanding) array. How would you keep track of the median?

Our data structure brainstorm might look like the following:

- Linked list? Probably not. Linked lists tend not to do very well with accessing and sorting numbers.
- Array? Maybe, but you already have an array. Could you somehow keep the elements sorted? That's probably expensive. Let's hold off on this and return to it if it's needed.
- Binary tree? This is possible, since binary trees do fairly well with ordering. In fact, if the binary search tree is perfectly balanced, the top might be the median. But, be careful—if there's an even number of elements, the median is actually the average of the middle two elements. The middle two elements can't both be at the top. This is probably a workable algorithm, but let's come back to it.
- Heap? A heap is really good at basic ordering and keeping track of max and mins. This is actually interesting—if you had two heaps, you could keep track of the bigger half and the smaller half of the elements. The bigger half is kept in a min heap, such that the smallest element in the bigger half is at the root. The smaller half is kept in a max heap, such that the biggest element of the smaller half is at the root. Now, with these data structures, you have the potential median elements at the roots. If the heaps are no longer the same size, you can quickly "rebalance" the heaps by popping an element off the one heap and pushing it onto the other.

Note that the more problems you do, the more developed your instinct on which data structure to apply will be. You will also develop a more finely tuned instinct as to which of these approaches is the most useful.

▸ Best Conceivable Runtime (BCR)

Considering the best conceivable runtime can offer a useful hint for some problem.

The best conceivable runtime is, literally, the *best* runtime you could *conceive* of a solution to a problem having. You can easily prove that there is no way you could beat the BCR.

For example, suppose you want to compute the number of elements that two arrays (of length A and B) have in common. You immediately know that you can't do that in better than $O(A + B)$ time because you have to "touch" each element in each array. $O(A + B)$ is the BCR.

Or, suppose you want to print all pairs of values within an array. You know you can't do that in better than $O(N^2)$ time because there are N^2 pairs to print.

Be careful though! Suppose your interviewer asks you to find all pairs with sum k within an array (assuming all distinct elements). Some candidates who have not fully mastered the concept of BCR will say that the BCR is $O(N^2)$ because you have to look at N^2 pairs.

That's not true. Just because you want all pairs with a particular sum doesn't mean you have to look at *all* pairs. In fact, you don't.

> What's the relationship between the Best Conceivable Runtime and Best Case Runtime? Nothing at all! The Best Conceivable Runtime is for a *problem* and is largely a function of the inputs and outputs. It has no particular connection to a specific algorithm. In fact, if you compute the Best Conceivable Runtime by thinking about what *your* algorithm does, you're probably doing something wrong. The Best Case Runtime is for a specific algorithm (and is a mostly useless value).

Note that the best conceivable runtime is not necessarily achievable. It says only that you can't do *better* than it.

An Example of How to Use BCR

Question: Given two sorted arrays, find the number of elements in common. The arrays are the same length and each has all distinct elements.

Let's start with a good example. We'll underline the elements in common.

```
A: 13  27  35  40  49  55  59
B: 17  35  39  40  55  58  60
```

A brute force algorithm for this problem is to start with each element in A and search for it in B. This takes $O(N^2)$ time since for each of N elements in A, we need to do an $O(N)$ search in B.

The BCR is $O(N)$, because we know we will have to look at each element at least once and there are 2N total elements. (If we skipped an element, then the value of that element could change the result. For example, if we never looked at the last value in B, then that 60 could be a 59.)

Let's think about where we are right now. We have an $O(N^2)$ algorithm and we want to do better than that—potentially, but not necessarily, as fast as $O(N)$.

```
Brute Force:        O(N²)
Optimal Algorithm:  ?
BCR:                O(N)
```

What is between $O(N^2)$ and $O(N)$? Lots of things. Infinite things actually. We could theoretically have an algorithm that's $O(N \log(\log(\log(\log(N)))))$. However, both in interviews and in real life, that runtime doesn't come up a whole lot.

> Try to remember this for your interview because it throws a lot of people off. Runtime is not a multiple choice question. Yes, it's very common to have a runtime that's $O(\log N)$, $O(N)$, $O(N \log N)$, $O(N^2)$ or $O(2^N)$. But you shouldn't assume that something has a particular runtime by sheer process of elimination. In fact, those times when you're confused about the runtime and so you want to take a guess—those are the times when you're most likely to have a non-obvious and less common runtime. Maybe the runtime is $O(N^2K)$, where N is the size of the array and K is the number of pairs. Derive, don't guess.

Most likely, we're driving towards an $O(N)$ algorithm or an $O(N \log N)$ algorithm. What does that tell us?

If we imagine our current algorithm's runtime as $O(N \times N)$, then getting to $O(N)$ or $O(N \times \log N)$ might mean reducing that second $O(N)$ in the equation to $O(1)$ or $O(\log N)$.

> This is one way that BCR can be useful. We can use the runtimes to get a "hint" for what we need to reduce.

That second `O(N)` comes from searching. The array is sorted. Can we search in a sorted array in faster than `O(N)` time?

Why, yes. We can use binary search to find an element in a sorted array in `O(log N)` time.

We now have an improved algorithm: `O(N log N)`.

```
Brute Force:          O(N²)
Improved Algorithm: O(N log N)
Optimal Algorithm:  ?
BCR:                  O(N)
```

Can we do even better? Doing better likely means reducing that `O(log N)` to `O(1)`.

In general, we cannot search an array—even a sorted array—in better than `O(log N)` time. This is *not* the general case though. We're doing this search over and over again.

The BCR is telling us that we will never, ever have an algorithm that's faster than `O(N)`. Therefore, any work we do in `O(N)` time is a "freebie"—it won't impact our runtime.

Re-read the list of optimization tips on page 64. Is there anything that can help us?

One of the tips there suggests precomputing or doing upfront work. Any upfront work we do in `O(N)` time is a freebie. It won't impact our runtime.

> This is another place where BCR can be useful. Any work you do that's less than or equal to the BCR is "free," in the sense that it won't impact your runtime. You might want to eliminate it eventually, but it's not a top priority just yet.

Our focus is still on reducing search from `O(log N)` to `O(1)`. Any precomputation that's `O(N)` or less is "free."

In this case, we can just throw everything in B into a hash table. This will take `O(N)` time. Then, we just go through A and look up each element in the hash table. This look up (or search) is `O(1)`, so our runtime is `O(N)`.

Suppose our interviewer hits us with a question that makes us cringe: Can we do better?

No, not in terms of runtime. We have achieved the fastest possible runtime, therefore we cannot optimize the big O time. We could potentially optimize the space complexity.

> This is another place where BCR is useful. It tells us that we're "done" in terms of optimizing the runtime, and we should therefore turn our efforts to the space complexity.

In fact, even without the interviewer prompting us, we should have a question mark with respect to our algorithm. We would have achieved the exact same runtime if the data wasn't sorted. So why did the interviewer give us sorted arrays? That's not unheard of, but it is a bit strange.

Let's turn back to our example.

```
A: 13  27  35  40  49  55  59
B: 17  35  39  40  55  58  60
```

We're now looking for an algorithm that:

- Operates in `O(1)` space (probably). We already have an `O(N)` space algorithm with optimal runtime. If we want to use less additional space, that probably means no additional space. Therefore, we need to drop the hash table.

- Operates in O(N) time (probably). We'll probably want to at least match the current best runtime, and we know we can't beat it.
- Uses the fact that the arrays are sorted.

Our best algorithm that doesn't use extra space was the binary search one. Let's think about optimizing that. We can try walking through the algorithm.

1. Do a binary search in B for A[0] = 13. Not found.
2. Do a binary search in B for A[1] = 27. Not found.
3. Do a binary search in B for A[2] = 35. Found at B[1].
4. Do a binary search in B for A[3] = 40. Found at B[5].
5. Do a binary search in B for A[4] = 49. Not found.
6. ...

Think about BUD. The bottleneck is the searching. Is there anything unnecessary or duplicated?

It's unnecessary that A[3] = 40 searched over all of B. We know that we just found 35 at B[1], so 40 certainly won't be before 35.

Each binary search should start where the last one left off.

In fact, we don't need to do a binary search at all now. We can just do a linear search. As long as the linear search in B is just picking up where the last one left off, we know that we're going to be operating in linear time.

1. Do a linear search in B for A[0] = 13. Start at B[0] = 17. Stop at B[0] = 17. Not found.
2. Do a linear search in B for A[1] = 27. Start at B[0] = 17. Stop at B[1] = 35. Not found.
3. Do a linear search in B for A[2] = 35. Start at B[1] = 35. Stop at B[1] = 35. Found.
4. Do a linear search in B for A[3] = 40. Start at B[2] = 39. Stop at B[3] = 40. Found.
5. Do a linear search in B for A[4] = 49. Start at B[3] = 40. Stop at B[4] = 55. Found.
6. ...

This algorithm is very similar to merging two sorted arrays. It operates in O(N) time and O(1) space.

We have now reached the BCR and have minimal space. We know that we cannot do better.

> This is another way we can use BCR. If you ever reach the BCR and have O(1) additional space, then you know that you can't optimize the big O time or space.

Best Conceivable Runtime is not a "real" algorithm concept, in that you won't find it in algorithm textbooks. But I have found it personally very useful, when solving problems myself, as well as while coaching people through problems.

If you're struggling to grasp it, make sure you understand big O time first (page 38). You need to master it. Once you do, figuring out the BCR of a problem should take literally seconds.

Handling Incorrect Answers

One of the most pervasive—and dangerous—rumors is that candidates need to get every question right. That's not quite true.

First, responses to interview questions shouldn't be thought of as "correct" or "incorrect." When I evaluate how someone performed in an interview, I never think, "How many questions did they get right?" It's not a binary evaluation. Rather, it's about how optimal their final solution was, how long it took them to get there, how much help they needed, and how clean was their code. There is a range of factors.

Second, your performance is evaluated *in comparison to other candidates*. For example, if you solve a question optimally in 15 minutes, and someone else solves an easier question in five minutes, did that person do better than you? Maybe, but maybe not. If you are asked really easy questions, then you might be expected to get optimal solutions really quickly. But if the questions are hard, then a number of mistakes are expected.

Third, many—possibly most—questions are too difficult to expect even a strong candidate to immediately spit out the optimal algorithm. The questions I tend to ask would take strong candidates typically 20 to 30 minutes to solve.

In evaluating thousands of hiring packets at Google, I have only once seen a candidate have a "flawless" set of interviews. Everyone else, including the hundreds who got offers, made mistakes.

When You've Heard a Question Before

If you've heard a question before, admit this to your interviewer. Your interviewer is asking you these questions in order to evaluate your problem-solving skills. If you already know the question, then you aren't giving them the opportunity to evaluate you.

Additionally, your interviewer may find it highly dishonest if you don't reveal that you know the question. (And, conversely, you'll get big honesty points if you do reveal this.)

The "Perfect" Language for Interviews

At many of the top companies, interviewers aren't picky about languages. They're more interested in how well you solve the problems than whether you know a specific language.

Other companies though are more tied to a language and are interested in seeing how well you can code in a particular language.

If you're given a choice of languages, then you should probably pick whatever language you're most comfortable with.

That said, if you have several good languages, you should keep in mind the following.

Prevalence

It's not required, but it is ideal for your interviewer to know the language you're coding in. A more widely known language can be better for this reason.

Language Readability

Even if your interviewer doesn't know your programming language, they should hopefully be able to basically understand it. Some languages are more naturally readable than others, due to their similarity to other languages.

For example, Java is fairly easy for people to understand, even if they haven't worked in it. Most people have worked in something with Java-like syntax, such as C and C++.

However, languages such as Scala or Objective C have fairly different syntax.

Potential Problems

Some languages just open you up to potential issues. For example, using C++ means that, in addition to all the usual bugs you can have in your code, you can have memory management and pointer issues.

Verbosity

Some languages are more verbose than others. Java for example is a fairly verbose language as compared with Python. Just compare the following code snippets.

Python:

```
dict = {"left": 1, "right": 2, "top": 3, "bottom": 4};
```

Java:

```
HashMap<String, Integer> dict = new HashMap<String, Integer>().
dict.put("left", 1);
dict.put("right", 2);
dict.put("top", 3);
dict.put("bottom", 4);
```

However, some of the verbosity of Java can be reduced by abbreviating code. I could imagine a candidate on a whiteboard writing something like this:

```
HM<S, I> dict = new HM<S, I>().
dict.put("left", 1);
...       "right", 2
...       "top", 3
...       "bottom", 4
```

The candidate would need to explain the abbreviations, but most interviewers wouldn't mind.

Ease of Use

Some operations are easier in some languages than others. For example, in Python, you can very easily return multiple values from a function. In Java, the same action would require a new class. This can be handy for certain problems.

Similar to the above though, this can be mitigated by just abbreviating code or presuming methods that you don't actually have. For example, if one language provides a function to transpose a matrix and another language doesn't, this doesn't necessarily make the first language much better to code in (for a problem that needs such a function). You could just assume that the other language has a similar method.

▸ What Good Coding Looks Like

You probably know by now that employers want to see that you write "good, clean" code. But what does this really mean, and how is this demonstrated in an interview?

Broadly speaking, good code has the following properties:

- **Correct:** The code should operate correctly on all expected and unexpected inputs.
- **Efficient:** The code should operate as efficiently as possible in terms of both time and space. This "efficiency" includes both the asymptotic (big O) efficiency and the practical, real-life efficiency. That is, a

constant factor might get dropped when you compute the big O time, but in real life, it can very much matter.

- **Simple:** If you can do something in 10 lines instead of 100, you should. Code should be as quick as possible for a developer to write.
- **Readable:** A different developer should be able to read your code and understand what it does and how it does it. Readable code has comments where necessary, but it implements things in an easily understandable way. That means that your fancy code that does a bunch of complex bit shifting is not necessarily *good* code.
- **Maintainable:** Code should be reasonably adaptable to changes during the life cycle of a product and should be easy to maintain by other developers, as well as the initial developer.

Striving for these aspects requires a balancing act. For example, it's often advisable to sacrifice some degree of efficiency to make code more maintainable, and vice versa.

You should think about these elements as you code during an interview. The following aspects of code are more specific ways to demonstrate the earlier list.

Use Data Structures Generously

Suppose you were asked to write a function to add two simple mathematical expressions which are of the form $Ax^a + Bx^b + \ldots$ (where the coefficients and exponents can be any positive or negative real number). That is, the expression is a sequence of terms, where each term is simply a constant times an exponent. The interviewer also adds that she doesn't want you to have to do string parsing, so you can use whatever data structure you'd like to hold the expressions.

There are a number of different ways you can implement this.

Bad Implementation

A bad implementation would be to store the expression as a single array of doubles, where the `k`th element corresponds to the coefficient of the x^k term in the expression. This structure is problematic because it could not support expressions with negative or non-integer exponents. It would also require an array of 1000 elements to store just the expression x^{1000}.

```
int[] sum(double[] expr1, double[] expr2) {
  ...
}
```

Less Bad Implementation

A slightly less bad implementation would be to store the expression as a set of two arrays, `coefficients` and `exponents`. Under this approach, the terms of the expression are stored in any order, but "matched" such that the `i`th term of the expression is represented by `coefficients[i] * x`$^{\texttt{exponents[i]}}$.

Under this implementation, if `coefficients[p] = k` and `exponents[p] = m`, then the pth term is kx^m. Although this doesn't have the same limitations as the earlier solution, it's still very messy. You need to keep track of two arrays for just one expression. Expressions could have "undefined" values if the arrays were of different lengths. And returning an expression is annoying because you need to return two arrays.

```
??? sum(double[] coeffs1, double[] expon1, double[] coeffs2, double[] expon2) {
  ...
}
```

Good Implementation

A good implementation for this problem is to design your own data structure for the expression.

```
class ExprTerm {
  double coefficient;
  double exponent;
}

ExprTerm[] sum(ExprTerm[] expr1, ExprTerm[] expr2) {
  ...
}
```

Some might (and have) argued that this is "over-optimizing." Perhaps so, perhaps not. Regardless of whether you think it's over-optimizing, the above code demonstrates that you think about how to design your code and don't just slop something together in the fastest way possible.

Appropriate Code Reuse

Suppose you were asked to write a function to check if the value of a binary number (passed as a string) equals the hexadecimal representation of a string.

An elegant implementation of this problem leverages code reuse.

```
boolean compareBinToHex(String binary, String hex) {
  int n1 = convertFromBase(binary, 2);
  int n2 = convertFromBase(hex, 16);
  if (n1 < 0 || n2 < 0) {
    return false;
  }
  return n1 == n2;
}

int convertFromBase(String number, int base) {
  if (base < 2 || (base > 10 && base != 16)) return -1;
  int value = 0;
  for (int i = number.length() - 1; i >= 0; i--) {
    int digit = digitToValue(number.charAt(i));
    if (digit < 0 || digit >= base) {
      return -1;
    }
    int exp = number.length() - 1 - i;
    value += digit * Math.pow(base, exp);
  }
  return value;
}

int digitToValue(char c) { ... }
```

We could have implemented separate code to convert a binary number and a hexadecimal code, but this just makes our code harder to write and harder to maintain. Instead, we reuse code by writing one `convertFromBase` method and one `digitToValue` method.

Modular

Writing modular code means separating isolated chunks of code out into their own methods. This helps keep the code more maintainable, readable, and testable.

Imagine you are writing code to swap the minimum and maximum element in an integer array. You could implement it all in one method like this:

```
void swapMinMax(int[] array) {
  int minIndex = 0;
  for (int i = 1; i < array.length; i++) {
    if (array[i] < array[minIndex]) {
      minIndex = i;
    }
  }

  int maxIndex = 0;
  for (int i = 1; i < array.length; i++) {
    if (array[i] > array[maxIndex]) {
      maxIndex = i;
    }
  }

  int temp = array[minIndex];
  array[minIndex] = array[maxIndex];
  array[maxIndex] = temp;
}
```

Or, you could implement in a more modular way by separating the relatively isolated chunks of code into their own methods.

```
void swapMinMaxBetter(int[] array) {
  int minIndex = getMinIndex(array);
  int maxIndex = getMaxIndex(array);
  swap(array, minIndex, maxIndex);
}

int getMinIndex(int[] array) { ... }
int getMaxIndex(int[] array) { ... }
void swap(int[] array, int m, int n) { ... }
```

While the non-modular code isn't particularly awful, the nice thing about the modular code is that it's easily testable because each component can be verified separately. As code gets more complex, it becomes increasingly important to write it in a modular way. This will make it easier to read and maintain. Your interviewer wants to see you demonstrate these skills in your interview.

Flexible and Robust

Just because your interviewer only asks you to write code to check if a normal tic-tac-toe board has a winner, doesn't mean you *must* assume that it's a 3x3 board. Why not write the code in a more general way that implements it for an NxN board?

Writing flexible, general-purpose code may also mean using variables instead of hard-coded values or using templates / generics to solve a problem. If we can write our code to solve a more general problem, we should.

Of course, there is a limit. If the solution is much more complex for the general case, and it seems unnecessary at this point in time, it may be better just to implement the simple, expected case.

Error Checking

One sign of a careful coder is that she doesn't make assumptions about the input. Instead, she validates that the input is what it should be, either through ASSERT statements or if-statements.

For example, recall the earlier code to convert a number from its base `i` (e.g., base 2 or base 16) representation to an `int`.

```
1  int convertToBase(String number, int base) {
2    if (base < 2 || (base > 10 && base != 16)) return -1;
3    int value = 0;
4    for (int i = number.length() - 1; i >= 0; i--) {
5      int digit = digitToValue(number.charAt(i));
6      if (digit < 0 || digit >= base) {
7        return -1;
8      }
9      int exp = number.length() - 1 - i;
10     value += digit * Math.pow(base, exp);
11   }
12   return value;
13 }
```

In line 2, we check to see that `base` is valid (we assume that bases greater than 10, other than base 16, have no standard representation in string form). In line 6, we do another error check: making sure that each digit falls within the allowable range.

Checks like these are critical in production code and, therefore, in interview code as well.

Of course, writing these error checks can be tedious and can waste precious time in an interview. The important thing is to point out that you *would* write the checks. If the error checks are much more than a quick if-statement, it may be best to leave some space where the error checks would go and indicate to your interviewer that you'll fill them in when you're finished with the rest of the code.

▸ Don't Give Up!

I know interview questions can be overwhelming, but that's part of what the interviewer is testing. Do you rise to a challenge, or do you shrink back in fear? It's important that you step up and eagerly meet a tricky problem head-on. After all, remember that interviews are supposed to be hard. It shouldn't be a surprise when you get a really tough problem.

For extra "points," show excitement about solving hard problems.