PEAK

SECRETS FROM THE NEW SCIENCE OF EXPERTISE

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The Power of Purposeful Practice

IN JUST OUR FOURTH SESSION together, Steve was already beginning to sound discouraged. It was Thursday of the first week of an experiment that I had expected to last for two or three months, but from what Steve was telling me, it might not make much sense to go on. "There appears to be a limit for me somewhere around eight or nine digits," he told me, his words captured by the tape recorder that ran throughout each of our sessions. "With nine digits especially, it's very difficult to get regardless of what pattern I use — you know, my own kind of strategies. It really doesn't matter what I use — it seems very difficult to get."

Steve, an undergraduate at Carnegie Mellon University, where I was teaching at the time, had been hired to come in several times a week and work on a simple task: memorizing strings of numbers. I would read him a series of digits at a rate of about one per second — "Seven . . . four . . . zero . . . one . . . one . . . nine . . ." and so on — and Steve would try to remember them all and repeat them back to me once I was done. One goal was simply to see how much Steve could improve with practice. Now, after four of the hour-long sessions, he could reliably recall seven-digit strings — the length of a local phone number — and he usually got the eight-digit strings right, but nine digits was hit or miss, and he had never managed to remember a ten-digit string at all. And at this point, given his frustrating experience over the first few sessions, he was pretty sure that he wasn't going to get any better.

What Steve didn't know — but I did — was that pretty much all of psychological science at the time indicated that he was right. Decades of research had shown that there is a strict limit to the number of items that a person can retain in short-term memory, which is the type of memory the brain uses to hold on to small amounts of information for a brief period of time. If a friend gives you his address, it is your short-term memory that holds on to it just long enough to write it down. Or if you're multiplying a couple of two-digit numbers in your head, your short-term memory is where you keep track of all the intermediate pieces: "Let's see: 14 times 27 . . . First, 4 times 7 is 28, so keep the 8 and carry the 2, then 4 times 2 is 8 . . ." and so on. And there's a reason it's called "short-term." You're not going to remember that address or those intermediate numbers five minutes later unless you spend the time repeating them to yourself over and over again — and thus transfer them into your long-term memory.

The problem with short-term memory — and the problem that Steve was coming face-to-face with — is that the brain has strict limits on how many items it can hold in short-term memory at once. For some it is six items, for others it may be seven or eight, but the limit is generally about seven items — enough to hold on to a local phone number but not a Social Security number. Long-term memory doesn't have the same limitations — in fact, no one has ever found the upper limits of long-term memory — but it takes much longer to deploy. Given enough time to work on it, you can memorize dozens or even hundreds of phone numbers, but the test I was giving Steve was designed to present digits so fast that he was forced to use only his

short-term memory. I was reading the digits at a rate of one per second — too fast for him to transfer the digits into his long-term memory — so it was no surprise that he was running into a wall at numbers that were about eight or nine digits long.

Still, I hoped he might be able to do a little better. The idea for the study had come from an obscure paper I had discovered while searching through old scientific studies, a paper published in a 1929 issue of the *American Journal of Psychology* by Pauline Martin and Samuel Fernberger, two psychologists at the University of Pennsylvania. Martin and Fernberger reported that two undergraduate subjects had been able, with four months of practice, to increase the number of digits they could remember when given the digits at a rate of about one per second. One of the students had improved from an average of nine digits to thirteen, while the other had gone from eleven to fifteen.

This result had been overlooked or forgotten by the broader psychological research community, but it immediately captured my attention. Was this sort of improvement really even possible? And, if so, *how* was it possible? Martin and Fernberger had offered no details about how the students had improved their digit memory, but that was exactly the sort of question that most intrigued me. At the time, I was just out of graduate school, and my main area of interest was the mental processes that take place when someone is learning something or developing a skill. For my dissertation I had honed a psychological research tool called "the think-aloud protocol" that was designed specifically to study such mental processes. So in collaboration with Bill Chase, a well-known Carnegie Mellon psychology professor, I set out to redo the old Martin and Fernberger study, and this time I would be watching to see exactly how our subject improved his digit memory — if indeed he did.

The subject we had recruited was Steve Faloon, who was about as typical a Carnegie Mellon undergraduate as we could have hoped to find. He was a psychology major who was interested in early childhood development. He had just finished his junior year. His scores on achievement tests were similar to those of other Carnegie Mellon students, while his grades were somewhat higher than average. Tall and thin with thick, dark-blond hair, he was friendly, outgoing, and enthusiastic. And he was a serious runner — a fact that did not seem meaningful to us at the time but that would turn out to be crucial to our study.

On the first day that Steve showed up for the memory work, his performance was dead-on average. He could usually remember seven digits and sometimes eight but no more. It was the same sort of performance you would expect from any random person picked off the street. On Tuesday, Wednesday, and Thursday he was a little better — an average of just under nine digits — but still no better than normal. Steve said he thought that the main difference from the first day was that he knew what to expect from the memory test and thus was more comfortable. It was at the end of that Thursday's session that Steve explained to me why he thought he was unlikely to get any better.

Then on Friday something happened that would change everything. Steve found a way to break through. The training sessions went like this: I would start with a random five-digit string, and if Steve got it right (which he always did), I would go to six digits. If he got that right, we'd go to seven digits, and so on, increasing the length of the string by one each time he got it right. If he got it wrong, I would drop the length of the string by two and go again. In this way Steve was constantly challenged, but not too much. He was given strings of digits that were right at the boundary between what he could and couldn't do.

And on that Friday, Steve moved the boundary. Up to that point he had remembered a nine-digit string correctly only a handful of times, and he had never remembered a ten-digit string correctly, so he had never even had a chance to try strings of eleven digits or longer. But he began that fifth session on a roll. He got the first three

tries — five, six, and seven digits — right without a problem, missed the fourth one, then got back on track: six digits, right; seven digits, right; eight digits, right; nine digits, right. Then I read out a ten-digit number — 5718866610 — and he nailed that one as well. He missed the next string with eleven digits, but after he got another nine digits and another ten digits right, I read him a second eleven-digit string — 90756629867 — and this time he repeated the whole thing back to me without a hitch. It was two digits more than he had ever gotten right before, and although an additional two digits may not seem particularly impressive, it was actually a major accomplishment because the past several days had established that Steve had a "natural" ceiling — the number of digits he could comfortably hold in his short-term memory — of only eight or nine. He had found a way to push through that ceiling.

That was the beginning of what was to be the most surprising two years of my career. From this point on, Steve slowly but steadily improved his ability to remember strings of digits. By the sixtieth session he was able to consistently remember twenty digits — far more than Bill and I had imagined he ever could. After a little more than one hundred sessions, he was up to forty, which was more than anyone, even professional mnemonists, had ever achieved, and still he kept going. He worked with me for more than two hundred training sessions, and by the end he had reached eighty-two digits — eighty-two! If you think about that for a moment, you'll realize just how incredible this memory ability truly is. Here are eighty-two random digits:

0326443449602221328209301020391832373927788917267653245
037746120179094345510355530

Imagine hearing all of those read out to you at one per second and *being able to remember them all.* This is what Steve Faloon taught himself to do over the two years of our experiment — all without even knowing it was possible, just by continuing to work on it week after week.

THE RISE OF EXTRAORDINARY PERFORMERS

In 1908 Johnny Hayes won the Olympic marathon in what newspapers at the time described as "the greatest race of the century." Hayes's winning time, which set a world record for the marathon, was 2 hours, 55 minutes, and 18 seconds.

Today, barely more than a century later, the world record for a marathon is 2 hours, 2 minutes, and 57 seconds — nearly 30 percent faster than Hayes's record time — and if you're an eighteen- to thirty-four-year-old male, you aren't even allowed to enter the Boston Marathon unless you've run another marathon in less than 3 hours, 5 minutes. In short, Hayes's world-record time in 1908 would qualify him for today's Boston Marathon (which has about thirty thousand runners) but with not a lot to spare.

That same 1908 Summer Olympics saw a near disaster in the men's diving competition. One of the divers barely avoided serious injury while attempting a double somersault, and an official report released a few months later concluded that the dive was simply too dangerous and recommended that it be banned from future Olympic Games. Today the double somersault is an entry-level dive, with ten-year-olds nailing it in competitions, and by high school the best divers are doing four and a half somersaults. World-class competitors take it even further with dives such as "the Twister" — two and a half backward somersaults with two and a half twists added. It's difficult to imagine what those early-twentieth-century experts who found the double-somersault dive too dangerous would have thought about the Twister, but my guess is that they would have dismissed it as laughably impossible — assuming, that is, that someone would have had the imagination and the audacity to suggest it in the first place.

In the early 1930s Alfred Cortot was one of the best-known classical musicians in the world, and his recordings of Chopin's "24 Études" were considered the definitive interpretation. Today teachers offer

those same performances — sloppy and marred by missed notes — as an example of how *not* to play Chopin, with critics complaining about Cortot's careless technique, and any professional pianist is expected to be able to perform the études with far greater technical skill and élan than Cortot. Indeed, Anthony Tommasini, the music critic at the *New York Times*, once commented that musical ability has increased so much since Cortot's time that Cortot would probably not be admitted to Juilliard now.

In 1973 David Richard Spencer of Canada had memorized more digits of pi than any person before him: 511. Five years later, after a rapid-fire series of new records set by a handful of people competing to claim the memorization title, the record belonged to an American, David Sanker, who had committed 10,000 digits of pi to memory. In 2015, after another thirty-plus years of gains, the recognized title holder was Rajveer Meena of India, who had memorized the first 70,000 digits of pi — an accumulation that took him 24 hours and 4 minutes to recite — although Akira Haraguchi of Japan had claimed to have memorized an even more incredible 100,000 digits, or nearly two hundred times as many as anyone had memorized just forty-two years earlier.

These are not isolated examples. We live in a world full of people with extraordinary abilities — abilities that from the vantage point of almost any other time in human history would have been deemed impossible. Consider Roger Federer's magic with a tennis ball, or the astounding vault that McKayla Maroney nailed in the 2012 Summer Olympics: a round-off onto the springboard, a back handspring onto the vault, and then a high, arching flight with McKayla completing two and a half twists before she landed firmly and with complete control on the mat. There are chess grandmasters who can play several dozen different games simultaneously — while blindfolded — and a seemingly unending supply of young musical prodigies who can do things on the piano, the violin, the cello, or the flute that would have astonished aficionados a century ago.

But while the abilities are extraordinary, there is no mystery at all about how these people developed them. They practiced. A lot. The world-record time in the marathon wasn't cut by 30 percent over the course of a century because people were being born with a greater talent for running long distances. Nor did the second half of the twentieth century see some sudden surge in the births of people with a gift for playing Chopin or Rachmaninoff or for memorizing tens of thousands of random digits.

What the second half of the twentieth century did see was a steady increase in the amount of time that people in different areas devoted to training, combined with a growing sophistication of training techniques. This was true in a huge number of fields, particularly highly competitive fields such as musical performance and dance, individual and team sports, and chess and other competitive games. This increase in the amount and sophistication of practice resulted in a steady improvement in the abilities of the performers in these various fields — an improvement that was not always obvious from year to year but that is dramatic when viewed over the course of several decades.

One of the best, if sometimes bizarre, places to see the results of this sort of practice is in *Guinness World Records.* Flip through the pages of the book or visit the online version, and you will find such record holders as the American teacher Barbara Blackburn, who can type up to 212 words per minute; Marko Baloh of Slovenia, who once rode 562 miles on a bicycle in twenty-four hours; and Vikas Sharma of India, who in just one minute was able to calculate the roots of twelve large numbers, each with between twenty and fifty-one digits, with the roots ranging from the seventeenth to the fiftieth root. That last may be the most impressive of all of them because Sharma was able to perform twelve exceedingly difficult mental calculations in just sixty seconds — faster than many people could punch the numbers into a calculator and read off the answers.

I actually received an e-mail from one Guinness world record holder, Bob J. Fisher, who at one time held twelve different world records for basketball free-throw shooting. His records include such things as the most free throws accomplished in thirty seconds (33), the most in ten minutes (448), and the most in one hour (2,371). Bob wrote to tell me that he had read about my studies of the effects of practice and had applied what he had learned from those studies in developing his ability to shoot basketball free throws faster than anyone else.

Those studies all have their roots in the work that I did with Steve Faloon in the late 1970s. Since that time I have devoted my career to understanding exactly how practice works to create new and expanded capabilities, with a particular focus on those people who have used practice to become among the best in the world at what they do. And after several decades of studying these best of the best — these "expert performers," to use the technical term — I have found that no matter what field you study, music or sports or chess or something else, the most effective types of practice all follow the same set of general principles.

There is no obvious reason why this should be the case. Why should the teaching techniques used to turn aspiring musicians into concert pianists have anything to do with the training that a dancer must go through to become a prima ballerina or the study that a chess player must undertake to become a grandmaster? The answer is that the most effective and most powerful types of practice in any field work by harnessing the adaptability of the human body and brain to create, step by step, the ability to do things that were previously not possible. If you wish to develop a truly effective training method for anything — creating world-class gymnasts, for instance, or even something like teaching doctors to perform laparoscopic surgery — that method will need to take into account what works and what doesn't in driving changes in the body and brain. Thus, all truly effective practice techniques work in essentially the same way.

These insights are all relatively new and weren't available to all the teachers, coaches, and performers who produced the incredible improvements in performance that have occurred over the past century. Instead, these advances were all accomplished through trial and error, with the people involved having essentially no idea why a particular training method might be effective. Furthermore, the practitioners in the various fields built their bodies of knowledge in isolation, with no sense that all of this was interconnected — that the ice-skater who was working on a triple axel was following the same set of general principles as, say, the pianist working to perfect a Mozart sonata. So imagine what might be possible with efforts that are inspired and directed by a clear scientific understanding of the best ways to build expertise. And imagine what might be possible if we applied the techniques that have proved to be so effective in sports and music and chess to all the different types of learning that people do, from the education of schoolchildren to the training of doctors, engineers, pilots, businesspeople, and workers of every sort. I believe that the dramatic improvements we have seen in those few fields over the past hundred years are achievable in pretty much every field if we apply the lessons that can be learned from studying the principles of effective practice.

There are various sorts of practice that can be effective to one degree or another, but one particular form — which I named "deliberate practice" back in the early 1990s — is the gold standard. It is the most effective and powerful form of practice that we know of, and applying the principles of deliberate practice is the best way to design practice methods in any area. We will devote most of the rest of this book to exploring what deliberate practice is, why it is so effective, and how best to apply it in various situations. But before we delve into the details of deliberate practice, it will be best if we spend a little time understanding some more basic types of practice — the sorts of practice that most people have already experienced in one way or another.

THE USUAL APPROACH

Let's begin by looking at the way people typically learn a new skill — driving a car, playing the piano, performing long division, drawing a human figure, writing code, or pretty much anything, really. For the sake of having a specific example, let's suppose you are learning to play tennis.

You've seen tennis matches played on television, and it looks like fun, or maybe you have some friends who play tennis and want you to join them. So you buy a couple of tennis outfits, court shoes, maybe a sweatband, and a racket and some balls. Now you're committed, but you don't know the first thing about actually playing tennis — you don't even know how to hold the racket — so you pay for some lessons from a tennis coach or maybe you just ask one of your friends to show you the basics. After those initial lessons you know enough to go out on your own and practice. You'll probably spend some time working on your serve, and you practice hitting the ball against a wall over and over again until you're pretty sure you can hold your own in a game against a wall. After that you go back to your coach or your friend for another lesson, and then you practice some more, and then another lesson, more practice, and after a while you've reached the point where you feel competent enough to play against other people. You're still not very good, but your friends are patient, and everyone has a good time. You keep practicing on your own and getting a lesson every now and then, and over time the really embarrassing mistakes — like swinging and missing the ball completely or hitting the ball very solidly straight into your doubles partner's back — become more and more rare. You get better with the various strokes, even the backhand, and occasionally, when everything comes together just so, you even end up hitting the ball like a pro (or so you tell yourself). You have reached a comfort level at which you can just go out and have fun playing the game. You pretty much know what you're doing, and the strokes have become automatic. You don't have to think too much about any of it. So you play weekend after weekend with your friends, enjoying the game and the exercise. You have become a tennis player. That is, you have "learned" tennis in the traditional sense, where the goal is to reach a point at which everything becomes automatic and an acceptable performance is possible with relatively little thought, so that you can just relax and enjoy the game.

At this point, even if you're not completely satisfied with your level of play, your improvement stalls. You have mastered the easy stuff.

But, as you quickly discover, you still have weaknesses that don't disappear no matter how often you play with your friends. Perhaps, for example, every time you use a backstroke to hit a ball that is coming in chest-high with a bit of spin, you miss the shot. You know this, and the cagier of your opponents have noticed this too, so it is frustrating. However, because it doesn't happen very often and you never know when it's coming, you never get a chance to consciously work on it, so you keep missing the shot in exactly the same way as you manage to hit other shots — automatically.

We all follow pretty much the same pattern with any skill we learn, from baking a pie to writing a descriptive paragraph. We start off with a general idea of what we want to do, get some instruction from a teacher or a coach or a book or a website, practice until we reach an acceptable level, and then let it become automatic. And there's nothing wrong with that. For much of what we do in life, it's perfectly fine to reach a middling level of performance and just leave it like that. If all you want to do is to safely drive your car from point A to point B or to play the piano well enough to plink out "Für Elise," then this approach to learning is all you need.

But there is one very important thing to understand here: once you have reached this satisfactory skill level and automated your performance — your driving, your tennis playing, your baking of pies — you have stopped improving. People often misunderstand this because they assume that the continued driving or tennis playing or pie baking is a form of practice and that if they keep doing it they are bound to get better at it, slowly perhaps, but better nonetheless. They assume that someone who has been driving for twenty years must be a better driver than someone who has been driving for five, that a doctor who has been practicing medicine for twenty years must be a better doctor than one who has been practicing for five, that a teacher who has been teaching for twenty years must be better than one who has been teaching for five.

But no. Research has shown that, generally speaking, once a person reaches that level of "acceptable" performance and automaticity, the additional years of "practice" don't lead to improvement. If anything, the doctor or the teacher or the driver who's been at it for twenty years is likely to be a bit worse than the one who's been doing it for only five, and the reason is that these automated abilities gradually deteriorate in the absence of deliberate efforts to improve.

So what do you do if you're not satisfied with this automated level of performance? What if you are a teacher with ten years in the classroom and you want to do something to better engage your students and get your lessons across more effectively? A weekend golfer and you would like to move beyond your eighteen handicap? An advertising copywriter and you want to add a little wow to your words?

This is the same situation that Steve Faloon found himself in after just a couple of sessions. At that point he had become comfortable with the task of hearing a string of digits, holding them in his memory, and repeating them back to me, and he was performing about as well as could be expected, given what is known about the limitations of short-term memory. He could have just kept doing what he was doing and maxing out at eight or nine digits, session after session. But he didn't, because he was participating in an experiment in which he was constantly being challenged to remember just one more digit than the last time, and because he was naturally the sort of guy who liked this sort of challenge, Steve pushed himself to get better.

The approach that he took, which we will call "purposeful practice," turned out to be incredibly successful for him. It isn't always so successful, as we shall see, but it is more effective than the usual just-enough method—and it is a step toward deliberate practice, which is our ultimate goal.

PURPOSEFUL PRACTICE

Purposeful practice has several characteristics that set it apart from what we might call "naive practice," which is essentially just doing something repeatedly, and expecting that the repetition alone will improve one's performance.

Steve Oare, a specialist in music education at Wichita State University, once offered the following imaginary conversation between a music instructor and a young music student. It's the sort of conversation about practice that music instructors have all the time. In this case a teacher is trying to figure out why a young student has not been improving:

TEACHER: Your practice sheet says that you practice an hour a day, but your playing test was only a C. Can you explain why?
STUDENT: I don't know what happened! I could play the test last night!
TEACHER: How many times did you play it?
STUDENT: Ten or twenty.
TEACHER: How many times did you play it correctly?
STUDENT: Umm, I dunno . . . Once or twice . . .
TEACHER: Hmm . . . How did you practice it?
STUDENT: I dunno. I just played it.

This is naive practice in a nutshell: I just played it. I just swung the bat and tried to hit the ball. I just listened to the numbers and tried to remember them. I just read the math problems and tried to solve them.

Purposeful practice is, as the term implies, much more purposeful, thoughtful, and focused than this sort of naive practice. In particular, it has the following characteristics:

Purposeful practice has well-defined, specific goals. Our hypothetical music student would have been much more successful with a practice goal something like this: "Play the piece all the way through at the proper speed without a mistake three times in a row." Without such a goal, there was no way to judge whether the practice session had been a success.

In Steve's case there was no long-range goal because none of us knew how many digits one could possibly memorize, but he had a very specific short-term goal: to remember more digits than he had the previous session. As a distance runner, Steve was very competitive, even if he was only competing with himself, and he brought that attitude to the experiment. From the very beginning Steve was pushing each day to increase the number of digits he could remember.

Purposeful practice is all about putting a bunch of baby steps together to reach a longer-term goal. If you're a weekend golfer and you want to decrease your handicap by five strokes, that's fine for an overall purpose, but it is not a well-defined, specific goal that can be used effectively for your practice. Break it down and make a plan: What exactly do you need to do to slice five strokes off your handicap? One goal might be to increase the number of drives landing in the fairway. That's a reasonably specific goal, but you need to break it down even more: What exactly will you do to increase the number of successful drives? You will need to figure out why so many of your drives are not landing in the fairway and address that by, for instance, working to reduce your tendency to hook the ball. How do you do that? An instructor can give you advice on how to change your swing motion in specific ways. And so on. The key thing is to take that general goal—get better—and turn it into something specific that you can work on with a realistic expectation of improvement.

Purposeful practice is focused. Unlike the music student that Oare described, Steve Faloon was focused on his task from the very beginning, and his focus grew as the experiment went along and he was memorizing longer and longer strings of digits. You can get a sense of this focus by listening to the tape of session 115, which came about halfway through the study. Steve had regularly been remembering strings of close to forty digits, but forty itself was not something he could yet do with any consistency, and he really wanted to reach forty regularly on this day. We began with thirty-five digits, which was easy for him, and he started pumping himself up as the strings increased in length. Before I read the thirty-nine-digit string, he gave himself an excited pep talk, seemingly conscious of nothing but the approaching task: "We have a big day here! . . . I haven't missed one yet, have I? No! . . . This will be a banner day!" He was silent during the forty seconds it took me to read out the numbers, but then, as he carefully went over the digits in his head, remembering various groups of them and the order in which they appeared, he could barely contain himself. He hit the table loudly a number of times, and he clapped a lot, apparently in celebration of remembering this or that group of digits or where they went in the string. Once he blurted out, "Absolutely right! I'm certain!" And when he finally spit the digits back at me, he was indeed right, so we moved on to forty. Again, the pep talk: "Now this is the big one! If I get past this one, it's all over! I have to get past this one!" Again the silence as I read the digits, and then the excited noises and exclamations as he cogitated. "Wow! . . . Come on now! . . . All right! . . . Go!" He got that one right as well, and the session indeed became one in which he regularly hit forty digits, although no more.

Now, not everyone will focus by hollering and pounding on a table, but Steve's performance illustrates a key insight from the study of effective practice: You seldom improve much without giving the task your full attention.

Purposeful practice involves feedback. You have to know whether you are doing something right and, if not, how you're going wrong. In Oare's example the music student got belated feedback at school with

a C on the performance test, but there seems to have been no feedback during practice — no one listening and pointing out mistakes, with the student seemingly clueless about whether there were errors in the practice. ("How many times did you play it correctly?" "Umm, I dunno . . . Once or twice . . .")

In our memory study, Steve got simple, direct feedback after every attempt — correct or incorrect, success or failure. He always knew where he stood. But perhaps the more important feedback was something that he did himself. He paid close attention to which aspects of a string of digits caused him problems. If he'd gotten the string wrong, he usually knew exactly why and which digits he had messed up on. Even if he got the string correct, he could report to me afterward which digits had given him trouble and which had been no problem. By recognizing where his weaknesses were, he could switch his focus appropriately and come up with new memorization techniques that would address those weaknesses.

Generally speaking, no matter what you're trying to do, you need feedback to identify exactly where and how you are falling short. Without feedback — either from yourself or from outside observers — you cannot figure out what you need to improve on or how close you are to achieving your goals.

Purposeful practice requires getting out of one's comfort zone. This is perhaps the most important part of purposeful practice. Oare's music student shows no sign of ever pushing himself beyond what was familiar and comfortable. Instead, the student's words seem to imply a rather desultory attempt at practice, with no effort to do more than what was already easy for him. That approach just doesn't work.

Our memory experiment was set up to keep Steve from getting too comfortable. As he increased his memory capacity, I would challenge him with longer and longer strings of digits so that he was always close to his capacity. In particular, by increasing the number of digits each time he got a string right, and decreasing the number when he got it wrong, I kept the number of digits right around what he was capable of doing while always pushing him to remember just one more digit.

This is a fundamental truth about any sort of practice: If you never push yourself beyond your comfort zone, you will never improve. The amateur pianist who took half a dozen years of lessons when he was a teenager but who for the past thirty years has been playing the same set of songs in exactly the same way over and over again may have accumulated ten thousand hours of "practice" during that time, but he is no better at playing the piano than he was thirty years ago. Indeed, he's probably gotten worse.

We have especially strong evidence of this phenomenon as it applies to physicians. Research on many specialties shows that doctors who have been in practice for twenty or thirty years do worse on certain objective measures of performance than those who are just two or three years out of medical school. It turns out that most of what doctors do in their day-to-day practice does nothing to improve or even maintain their abilities; little of it challenges them or pushes them out of their comfort zones. For that reason, I participated in a consensus conference in 2015 to identify new types of continuing medical education that will challenge doctors and help them maintain and improve their skills. We will discuss this in detail in chapter 5.

Perhaps my favorite example of this lesson is the case of Ben Franklin's chess skills. Franklin was America's first famous genius. He was a scientist who made his reputation with his studies of electricity, a popular writer and publisher of *Poor Richard's Almanack,* the founder of the first public lending library in America, an accomplished diplomat, and the inventor of, among other things, bifocals, the lightning rod, and the Franklin stove. But his greatest passion was chess. He was one of the first chess players in America, and he was a participant in the earliest game of chess known to have been played here. He played chess for more than fifty years, and as he got older he spent more and more time on it. While in Europe he played with François-André Danican Philidor, the best chess player of the time. And despite his well-

known advice to be early to bed and early to rise, Franklin regularly played from around 6:00 p.m. until sunrise.

So Ben Franklin was brilliant, and he spent thousands of hours playing chess, sometimes against the best players of the time. Did that make him a great chess player? No. He was above average, but he never got good enough to compare with Europe's better players, much less the best. This failing was a source of great frustration to him, but he had no idea why he couldn't get any better. Today we understand: he never pushed himself, never got out of his comfort zone, never put in the hours of purposeful practice it would take to improve. He was like the pianist playing the same songs the same way for thirty years. That is a recipe for stagnation, not improvement.

Getting out of your comfort zone means trying to do something that you couldn't do before. Sometimes you may find it relatively easy to accomplish that new thing, and then you keep pushing on. But sometimes you run into something that stops you cold and it seems like you'll never be able to do it. Finding ways around these barriers is one of the hidden keys to purposeful practice.

Generally the solution is not "try harder" but rather "try differently." It is a technique issue, in other words. In Steve's case, one barrier came when he hit twenty-two digits. He was grouping them into four four-digit groups, which he used various mnemonic tricks to remember, plus a six-digit rehearsal group at the end that he would repeat over and over to himself until he could remember it by the sound of the numbers. But he couldn't figure out how to get past twenty-two digits, because when he tried to hold five four-digit groups in his head, he became confused about their order. He eventually hit upon the idea of using both three-digit groups and four-digit groups, a breakthrough that eventually allowed him to work up to using four four-digit groups, four three-digit groups, and a six-digit rehearsal group, for a maximum of thirty-four digits. Then, once he reached that limit, he had to develop another technique. This was a regular pattern throughout the entire memory study: Steve would improve up to a point, get stuck, look around for a different approach that could help him get past the barrier, find it, and then improve steadily until another barrier arose.

The best way to get past any barrier is to come at it from a different direction, which is one reason it is useful to work with a teacher or coach. Someone who is already familiar with the sorts of obstacles you're likely to encounter can suggest ways to overcome them.

And sometimes it turns out that a barrier is more psychological than anything else. The famous violin teacher Dorothy DeLay once described the time that one of her students came to her to help increase his speed on a particular piece that he was scheduled to play at a music festival. He could not play it fast enough, he told her. How fast, she asked, would you like to play it? He answered that he wanted to play it as fast as Itzhak Perlman, the world-famous violinist. So DeLay first got a recording of Perlman playing the piece and timed it. Then she set a metronome to a slow speed and had her student play the piece at that pace, which was well within his abilities. She had him play it again and again, each time speeding up the metronome a bit. And each time he nailed it. Finally, after he had gone through the piece flawlessly once more, she showed him the setting on the metronome: He had actually played it faster than Perlman.

Bill Chase and I used a similar technique with Steve a couple of times when he had hit a barrier and thought he might not be able to improve further. Once, I slowed down the rate at which I read the digits just a bit, and the extra time made it possible for Steve to remember significantly more digits. This convinced him that the problem was not the number of digits but rather how quickly he was encoding the digits — that is, coming up with mnemonics for the various groups of digits that made up the entire string — and that he could improve his performance if he could just speed up the time he took to commit the digits to long-term memory.

Another time, I gave Steve strings that were ten digits longer than any of the ones he had managed to remember up to that point. He surprised himself by remembering most of the digits in those strings — and, in particular, remembering more total digits than he had ever done before, even though he wasn't perfect. This convinced him that it was indeed possible to remember longer strings of digits. He realized his problem was not that he had reached the limit of his memory, but rather that he was messing up on one or two groups of digits in the entire string. He decided that the key to moving on was to encode the small groups of digits more carefully, and he began improving again.

Whenever you're trying to improve at something, you will run into such obstacles — points at which it seems impossible to progress, or at least where you have no idea what you should do in order to improve. This is natural. What is not natural is a true dead-stop obstacle, one that is impossible to get around, over, or through. In all of my years of research, I have found it is surprisingly rare to get clear evidence in any field that a person has reached some immutable limit on performance. Instead, I've found that people more often just give up and stop trying to improve.

One caveat here is that while it is always possible to keep going and keep improving, it is not always easy. Maintaining the focus and the effort required by purposeful practice is hard work, and it is generally not fun. So the issue of motivation inevitably comes up: Why do some people engage in this sort of practice? What keeps them going? We will return to these vital questions again and again throughout the book.

In Steve's case, there were several factors at work. First, he was getting paid. But he could have always shown up for the sessions and not tried particularly hard and still have gotten paid, so while that may have been part of his motivation, it was certainly not all of it. Why did he push himself so hard to improve? From talking to him, I believe that a large part of it was that once he started to see improvement after the first few sessions, he really enjoyed seeing his memory scores go up. It felt good, and he wanted to keep feeling that way. Also, after he reached a certain level in his memorization abilities, he became something of a celebrity; stories about him appeared in newspapers and magazines, and he made a number of appearances on television, including the *Today* show. This provided another type of positive feedback. Generally speaking, meaningful positive feedback is one of the crucial factors in maintaining motivation. It can be internal feedback, such as the satisfaction of seeing yourself improve at something, or external feedback provided by others, but it makes a huge difference in whether a person will be able to maintain the consistent effort necessary to improve through purposeful practice.

One other factor was that Steve liked to challenge himself. This was clear from his record as a cross-country and track runner. Everyone who knew him would tell you that he trained as hard as anyone but that his motivation was simply to improve his own performance, not necessarily to win races. Furthermore, from years of running he knew what it meant to train regularly, week after week, month after month, and it seems unlikely that the task of working on his memory three times a week for an hour each time seemed particularly daunting, given that he regularly went for three-hour runs. Later, after finishing the memory work with Steve and a couple of other students, I made it a point to recruit only subjects who had trained extensively as athletes, dancers, musicians, or singers. None of them ever quit on me.

So here we have purposeful practice in a nutshell: Get outside your comfort zone but do it in a focused way, with clear goals, a plan for reaching those goals, and a way to monitor your progress. Oh, and figure out a way to maintain your motivation.

This recipe is an excellent start for anyone who wishes to improve — but it is still just a start.

THE LIMITS OF PURPOSEFUL PRACTICE

While Bill Chase and I were still carrying out our two-year memory study with Steve Faloon — but after Steve had begun to set records

with his digit-span memory — we decided to look for another subject who would be willing to take on the same challenge. Neither of us believed that Steve had been born with some special gift for memorizing digits, but rather we assumed that the skills he developed could be attributed completely to the training that he went through, and the best way to prove that was to run the same study with another subject and see if we got the same result.

The first person to volunteer was a graduate student, Renée Elio. Before getting started she was told that her predecessor had dramatically increased the number of digits he could memorize, so she knew such improvement was possible — which was more than Steve had known when he started — but we told Renée nothing about how Steve had done it. She would have to come up with her own approach.

When she started out, she improved at a pace that was very similar to Steve's, and she was able to increase her digit-span memory to close to twenty digits after about fifty hours of practice sessions. However, unlike Steve, at this point she hit a wall that she just couldn't get past. After spending another fifty hours or so without improving, she decided to drop out of the training sessions. She had increased her memory for digits to the point that it was far better than any untrained person — and comparable with some mnemonists — but she fell far short of what Steve had accomplished.

What was the difference? Steve had succeeded by developing a collection of mental structures — various mnemonics, many of them based on running times, plus a system for keeping track of the order of the mnemonics — that allowed him to use his long-term memory to sidestep the usual limitations of short-term memory and remember long strings of digits. When he heard the digits 907, for instance, he conceptualized them as a pretty good two-mile time — 9:07, or 9 minutes, 7 seconds — and they were no longer random numbers that he had to commit to short-term memory but rather something he was already familiar with. As we shall see, the key to improved mental performance of almost any sort is the development of mental structures that make it possible to avoid the limitations of short-term memory and deal effectively with large amounts of information at once. Steve had done this.

Renée, not knowing how Steve had done it, had developed a completely different approach to memorizing the digits. Where Steve had memorized groups of three and four digits mainly in terms of running times, Renée employed an elaborate set of mnemonics that relied on such things as days, dates, and times of day. One key difference between Steve and Renée was that Steve had always decided ahead of time what pattern he would use in memorizing the digits, breaking the strings into three- and four-digit sets plus a group at the end with four to six digits that he would repeat to himself over and over until he had the sound of it in his memory. For twenty-seven digits, for instance, he would organize the digits into three sets of four digits each, three sets of three digits each, and then a six-digit group at the end. We referred to this pre-fixed pattern as a "retrieval structure," and it allowed Steve to focus on memorizing the three- and four-digit sets individually and then keep in mind where in the retrieval structure each of these individual sets fit. This proved to be a very powerful approach, as it allowed him to encode each set of three or four digits as a running time or some other mnemonic, put it in his long-term memory, and then not have to think about it again until he went back at the end to recall all of the digits in the string.

Renée, by contrast, devised her mnemonics on the fly, deciding according to the digits she heard what mnemonic she would use to remember them. For a string like 4778245 she might remember it as April 7, 1978 at 2:45, but if the string was 4778295, she would have to use April 7, 1978 and then start a new date: February 9 . . . Without the sort of consistency that Steve's approach offered, she could not master more than twenty digits.

After that experience Bill and I decided to look for another subject who would be as similar to Steve as possible in terms of the way he would memorize the digit strings. Thus we recruited another runner, Dario Donatelli, a member of the Carnegie Mellon long-distance team and one of Steve's training partners. Steve had told Dario that we were looking for someone who would commit to being a long-term participant in our memory-training study, and Dario agreed.

This time, instead of letting Dario figure it out for himself, we had Steve teach Dario his method for encoding digits. With this head start, Dario was able to improve much more quickly than Steve had, at least initially. He got to twenty digits in significantly fewer training sessions, but he began to slow down after that, and once he reached thirty digits it seemed that he was no longer getting much benefit from following Steve's method, and his progress languished. At that point Dario began developing his own version of Steve's method. He came up with slightly different ways of encoding the strings of three and four digits, and, more importantly, he designed a significantly different retrieval structure that worked much better for him. Still, when we tested how Dario was memorizing the digits, we found that he was relying on mental processes that were very much like the ones that Steve had developed, using long-term memory to sidestep the limitations of short-term memory. After several years of training, Dario would eventually be able to remember more than one hundred digits, or about twenty more than Steve. At this point Dario had become, like Steve before him, the best at this particular skill that the world had ever known.

There is an important lesson here: Although it is generally possible to improve to a certain degree with focused practice and staying out of your comfort zone, that's not all there is to it. Trying hard isn't enough. Pushing yourself to your limits isn't enough. There are other, equally important aspects to practice and training that are often overlooked.

One particular approach to practice and training has proven to be the most powerful and effective way to improve one's abilities in every area that has been studied. This approach is deliberate practice, and we will describe it in detail shortly. But first we'll take a closer look at what is behind the amazing sorts of improvement that are possible with the right sort of practice.

2

Harnessing Adaptability

IF YOU'RE A BODYBUILDER or just someone lifting weights to add some muscle, it is easy to track the results as you challenge your biceps, triceps, quadriceps, pecs, delts, lats, traps, abs, glutes, calves, and hamstrings. A tape measure works, or you can simply look in the mirror and admire your progress. If you're running or biking or swimming to increase your endurance, you can track your progress by your heart rate, your breathing, and how long you can keep going until your muscles falter due to lactic acid buildup.

But if your challenge is mental — becoming proficient at calculus, say, or learning how to play a musical instrument or speak a new language — it's different. There is no easy way to observe the resulting changes in your brain as it adapts to the increasing demands being placed on it. There is no soreness in your cortex the day after a particularly tough training session. You don't have to go out and buy new hats because the old ones are now too small. You don't develop a six-pack on your forehead. And because you can't see any changes in your brain, it's easy to assume that there really isn't much going on.

That would be a mistake, however. There is a growing body of evidence that both the structure and the function of the brain change in response to various sorts of mental training, in much the same way as your muscles and cardiovascular system respond to physical training. With the help of such brain-imaging techniques as magnetic resonance imaging (MRI), neuroscientists have begun to study how the brains of people with particular skills differ from the brains of people without those skills and to explore which sorts of training produce which types of changes. Although there is still a tremendous amount to learn in this area, we already know enough to have a clear idea of how purposeful practice and deliberate practice work to increase both our physical and mental capabilities and make it possible to do things that we never could before.

Much of what we know about how the body adapts to training comes from studies of runners, weightlifters, and various other athletes. Interestingly enough, however, some of the best studies to date of how the brain changes in response to extended training were carried out not with musicians or chess players or mathematicians — some of the more traditional subjects in studies of the effects of practice on performance — but instead with taxi drivers.

THE BRAINS OF LONDON CABBIES

Few cities in the world can baffle a GPS system like London can. To start with, there is no grid of thoroughfares that can be used for orientation and routing as you will find in Manhattan or Paris or Tokyo. Instead the city's major streets are set at odd angles to each other. They curve and they squiggle. One-way streets abound, there are traffic circles and dead ends all over, and through the middle of everything runs the Thames River, spanned by a dozen bridges in central London, at least one of which — and sometimes more — will likely have to be crossed during a trip of any length through the city. And the erratic numbering system doesn't always tell you exactly where to find a particular address even when you've found the right street.

Thus the best advice for visitors is to forget about renting a car with a navigational system and instead rely on the city's cabbies. They're ubiquitous — some twenty-five thousand of them driving around in their big, black, boxy cars that are the automotive equivalent of sensible shoes — and they are astonishingly good at getting you from point A to point B in the most efficient way possible, taking into account not only the lengths of the various possible paths, but the time of day, the expected traffic, temporary roadwork and road closings, and any other details that might be relevant to the trip. Nor do points A and B have to be traditional street addresses. Suppose you'd like to revisit that funky little hat shop in Charing Cross whose name you don't quite recall — Lord's or Lear or something like that — but you do remember that there is a little shop next door that sells cupcakes. Well, that will be enough. Tell all that to your cabbie, and as soon as is automotively possible you will find yourself in front of Laird London, 23A New Row.

As you might imagine, given the challenges of finding one's way in London, not just anyone can be a cabbie. Indeed, to become a licensed London taxi driver one must pass a series of examinations that have been described as, collectively, the most difficult test in the world. The test is administered by Transport for London, and that agency describes "the Knowledge" — what a prospective driver must learn — as follows:

> To achieve the required standard to be licensed as an "All London" taxi driver you will need a thorough knowledge, primarily, of the area within a six-mile radius of Charing Cross. You will need to know: all the streets; housing estates; parks and open spaces; government offices and departments; financial and commercial centres; diplomatic premises; town halls; registry offices; hospitals; places of worship; sports stadiums and leisure centres; airline offices; stations; hotels; clubs; theatres; cinemas; museums; art galleries; schools; colleges and universities; police stations and headquarters buildings; civil, criminal and coroner's courts; prisons; and places of interest to tourists. In fact, anywhere a taxi passenger might ask to be taken.

That area within six miles of Charing Cross contains approximately twenty-five thousand streets. But a prospective cabbie must be familiar with more than just streets and buildings. Any landmark is fair game. According to a 2014 story about London taxi drivers in the *New York Times Magazine,* one prospective driver was asked about the location of a statue of two mice with a piece of cheese; the statue, on the façade of a building, was just one foot tall.

More to the point, prospective taxi drivers must demonstrate that they can get from one point in the city to another as efficiently as possible. Tests consist of a series of "runs" in which the examiner gives two points in London and the examinee must provide the precise location of each of the points and then describe the best route between them, turn by turn, naming each street in the sequence. Each run earns a numerical score based on its accuracy, and as the prospective driver accumulates points, the tests get harder and harder, with the endpoints becoming more obscure and the routes longer, more complicated, and more convoluted. Half or more of the prospective drivers end up dropping out, but those who stay with it and earn their licenses have internalized London to a degree that Google Maps, with its satellite images, camera cars, and unfathomable memory and processing power, can only vaguely approximate.

To master the Knowledge, prospective cabbies — who are known as "Knowledge boys" and, occasionally, "Knowledge girls" — spend years driving from place to place in London, making notes of what is where and how to get from here to there. The first step is to master a list of 320 runs in the guidebook provided to taxi-driver candidates. For a given run, a candidate will generally first figure out the shortest route by physically traveling the various possible routes, usually by motorbike, and then will explore the areas around the beginning and the end of the run. This means wandering around within a quarter mile or so of each of those places, taking notes on which buildings and which landmarks are in the vicinity. After having repeated this process 320 times, the prospective cabbie has accumulated a foundational set of 320 best routes around London and has also explored — and taken notes on — pretty much every bit of the core area within six miles of Charing Cross. It is a start, but successful candidates keep challenging themselves to determine the best routes for many other runs that are not on the list and to take note of buildings and landmarks that they might have missed before or that might have recently appeared. Indeed, even after passing all the tests and getting licensed, London taxi drivers continue to increase and hone their knowledge of London's streets.

The resulting memory and navigational skills are nothing short of astonishing, and so London taxi drivers have proved irresistible to psychologists interested in learning and, particularly, in the learning of navigational skills. By far the most in-depth studies of the cabbies — and the ones that have the most to tell us about how training affects the brain — have been carried out by Eleanor Maguire, a neuroscientist at University College London.

In one of her earliest works on the taxi drivers, published in 2000, Maguire used magnetic resonance imaging to look at the brains of sixteen male taxi drivers and compare them with the brains of fifty other males of similar ages who were not taxi drivers. She looked in particular at the hippocampus, that seahorse-shaped part of the brain involved in the development of memories. The hippocampus is particularly engaged by spatial navigation and in remembering the location of things in space. (Each person actually has two hippocampi, one on each side of the brain.) For instance, species of birds that store food in different places and thus must be able to remember the location of these various caches have relatively larger hippocampi than closely related birds that

don't store food in different places. More to the point, the size of the hippocampus is quite flexible in at least some species of birds and can grow by as much as 30 percent in response to a bird's food-storing experiences. But would the same thing be true in humans?

Maguire found that a particular part of the hippocampus — the posterior, or rear, part — was larger in the taxi drivers than in the other subjects. Furthermore, the more time that a person had spent as a taxi driver, the larger the posterior hippocampi were. In another study that Maguire carried out a few years later, she compared the brains of London taxi drivers with London bus drivers. Like the taxi drivers, the bus drivers spent their days driving around London; the difference between them was that the bus drivers repeated the same routes over and over and thus never had to figure out the best way to get from point A to point B. Maguire found that the posterior hippocampi of the taxi drivers were significantly larger than the same parts of the brain in the bus drivers. The clear implication was that whatever was responsible for the difference in the size of the posterior hippocampi was not related to the driving itself but rather was related specifically to the navigational skills that the job required.

That still left one loose end, however: perhaps the taxi drivers in the studies had started out with larger posterior hippocampi that gave them an advantage in finding their way around London, and the extensive testing they went through was nothing more than a weeding-out process that zeroed in on those prospective drivers who were naturally better equipped to be able to learn their way around the maze that is London.

Maguire addressed this issue quite simply and powerfully: she followed a group of prospective taxi drivers from the time they started training for their licenses until the point at which all of them had either passed the tests and become licensed cabbies or else had given up and gone on to do something else. In particular, she recruited seventy-nine prospective drivers — all of them male — who were just starting training, as well as another thirty-one males of similar ages to serve as controls. When she scanned all their brains, she found no difference in the sizes of the posterior hippocampi between the prospective drivers and the controls.

Four years later she revisited the two groups of subjects. By this time forty-one of the trainees had become licensed London taxi drivers, while thirty-eight had stopped training or failed their tests. So at this point there were three groups to compare: the new taxi drivers who had learned enough about London's streets to pass the series of tests, the trainees who had not learned enough to pass, and the group who had not ever trained at all. Once again Maguire scanned their brains and calculated the size of the posterior hippocampi in each.

What she found would have been no surprise if she had been measuring biceps in bodybuilders, but she wasn't — she was measuring the sizes of different parts of the brain — and so the result was startling. The volume of the posterior hippocampi had gotten significantly larger in the group of trainees who had continued their training and had become licensed taxi drivers. By contrast, there was no change in the size of the posterior hippocampi among the prospective taxi drivers who had failed to become licensed (either because they simply stopped training or because they could not pass the tests) or among the subjects who had never had anything to do with the taxi training program. The years spent mastering the Knowledge had enlarged precisely that part of the brain that is responsible for navigating from one place to another.

Maguire's study, which was published in 2011, is perhaps the most dramatic evidence we have that the human brain grows and changes in response to intense training. Furthermore, the clear implication of her study is that the extra neurons and other tissue in the posterior hippocampi of the licensed cabbies underlie their increased navigational capabilities. You can think about the posterior hippocampi of a London taxi driver as the neural equivalent of the massively developed arms and shoulders of a male gymnast. Years of work on the rings and pommel horse and parallel bars and floor exercises have built muscles that

are exquisitely suited for the sorts of movements he performs on those different pieces of apparatus — and, indeed, that make it possible for him to do all sorts of gymnastics moves that were simply not within his reach when he began training. The posterior hippocampi of the taxi drivers are equally "bulked up," but with brain tissue, not muscle fiber.

ADAPTABILITY

Until the first decade of the twenty-first century, most scientists would have flat out denied that something like what Maguire has seen in the brains of London cabbies was even possible. The general belief was that once a person reached adulthood, the wiring of his or her brain was pretty much fixed. Sure, everyone understood that there had to be tweaks here and there when you learned something new, but these were thought to be little more than the strengthening of some neural connections and the weakening of others, because the overall structure of the brain and its various neural networks were fixed. This idea went hand in hand with the belief that individual differences in abilities were due mainly to genetically determined differences in the brain's wiring and that learning was just a way of fulfilling one's genetic potential. One common metaphor depicted the brain as a computer: learning was like loading some data or installing new software — it allowed you to do some things you couldn't do before, but your ultimate performance would always be limited by such things as the number of bytes in your random-access memory (RAM) and the power of your central processing unit (CPU).

By contrast, the body's adaptability has always been easier to recognize, as we've noted. One of my favorite examples of physical adaptability involves pushups. If you're a relatively fit male in your twenties, you may be able to do 40 or 50; if you can do 100, you can impress your friends and probably win a few bets. So what might you guess is the world record for pushups — 500 or 1,000? In 1980 Minoru Yoshida of Japan did 10,507 pushups nonstop. After that, *Guinness World Records* stopped accepting submissions for the number of pushups done with no rest periods and switched to the most pushups performed in twenty-four hours with resting allowed. In 1993 Charles Servizio of the United States set what remains the world record in that category by doing 46,001 pushups in 21 hours and 21 minutes.

Or consider pull-ups. Even relatively fit guys can generally do only 10 or 15, although if you've really been working out, you may have worked your way up to 40 or 50. In 2014 Jan Kareš of the Czech Republic did 4,654 in twelve hours.

In short, the human body is incredibly adaptable. It is not just the skeletal muscles, but also the heart, the lungs, the circulatory system, the body's energy stores, and more — everything that goes into physical strength and stamina. There may be limits, but there is no indication that we have reached them yet.

From Maguire's work and that of others, we're now learning that the brain has a very similar degree and variety of adaptability.

Some of the earliest observations of this sort of adaptability — or "plasticity," as neuroscientists would say — appeared in studies of how the brains of blind or deaf people "rewire" themselves to find new uses for the parts of the brain that are normally dedicated to processing sights or sounds but that in these people have nothing to do. Most blind people cannot see because of problems with their eyes or optic nerve, but the visual cortex and other parts of the brain are still fully functional; they're just not getting any input from the eyes. If the brain actually were hardwired like a computer, these visual regions would sit forever idle. We now know, however, that the brain reroutes some of its neurons so that these otherwise-unused areas are put to work doing other things, particularly things related to the remaining senses, which blind people must rely on to get information about their surroundings.

To read, for example, the blind run their fingertips over the raised dots that make up the Braille alphabet. When researchers use MRI machines to watch the brains of blind subjects as they read words in Braille, one of the parts of the brain that they see lighting up is the visual cortex. In people with normal sight, the visual cortex would light up in response to input from the eyes, not the fingertips, but in the blind, the visual cortex helps them interpret the fingertip sensations they get from brushing over the groups of raised dots that make up the Braille letters.

Interestingly enough, it is not just otherwise-unused areas of the brain where rewiring occurs. If you practice something enough, your brain will repurpose neurons to help with the task even if they already have another job to do. Perhaps the most compelling evidence of this comes from an experiment done in the late 1990s, when a group of researchers examined the parts of the brain that controlled various fingers on the hands of a group of highly skilled Braille readers.

The subjects were three-fingered Braille readers — that is, they used their index fingers to read the patterns of dots that make up individual letters, their middle fingers to pick out the spaces between the letters, and their ring fingers to keep track of the particular line they were reading. The wiring in the part of the brain that controls the hands is normally set up so that each individual finger has a distinct part of the brain dedicated to it. This is what makes it possible for us to tell, for example, which fingertip is being touched by a pencil tip or a thumbtack without looking at our fingers. The subjects in the study were Braille instructors who used their fingers to read Braille several hours each day. What the researchers discovered was that this steady use of the three fingers had caused the areas of the brain devoted to each of those fingers to grow so much that those areas eventually overlapped. As a result, the subjects were exceptionally sensitive to touch on these fingers — they could detect a much gentler touch than sighted subjects — but they often couldn't tell which of the three fingers had been touched.

These studies of brain plasticity in blind subjects — and similar studies in deaf subjects — tell us that the brain's structure and function are not fixed. They change in response to use. It is possible to shape the brain — your brain, my brain, anybody's brain — in the ways that we desire through conscious, deliberate training.

Researchers are just beginning to explore the various ways that this plasticity can be put to work. One of the most striking results to date could have implications for anyone who suffers from age-related far-sightedness — which is just about everyone over the age of fifty. The study, which was carried out by American and Israeli neuroscientists and vision researchers, was reported in 2012. Those scientists assembled a group of middle-aged volunteers, all of whom had difficulty focusing on nearby objects. The official name of the condition is presbyopia, and it results from a problem with the eye itself, which loses elasticity in its lens, making it more difficult to focus well enough to make out small details. There is also an associated difficulty in detecting contrasts between light and dark areas, which exacerbates the difficulty in focusing. The consequences are a boon for optometrists and opticians and a bother for the over-fifty crowd, nearly all of whom need glasses to read or perform close-up work.

The researchers had their subjects come into the lab three or so times a week for three months and spend thirty minutes each visit training their vision. The subjects were asked to spot a small image against a background that was very similar in shade to the spot; that is, there was very little contrast between the image and the background. Spotting these images required intense concentration and effort. Over time the subjects learned to more quickly and accurately determine the presence of these images. At the end of three months the subjects were tested to see what size type they could read. On average they were able to read letters that were 60 percent smaller than they could at the beginning of the training, and every single subject had improved. Furthermore, after the training every subject was able to read a newspaper without glasses, something a majority of them couldn't do beforehand. They also were able to read faster than before.

Surprisingly, none of this improvement was caused by changes in the eyes, which had the same stiffness and difficulty focusing as before. Instead, the improvement was due to changes in the part of the brain that interprets visual signals from the eye. Although the researchers couldn't pinpoint exactly what those changes were, they believe that the brain learned to "de-blur" images. Blurry images result from a combination of two different weaknesses in vision — an inability to see small details and difficulties in detecting differences in contrast — and both of these issues can be helped by the image processing carried out in the brain, in much the same way that image-processing software in a computer or a camera can sharpen an image by such techniques as manipulating the contrast. The researchers who carried out the study believe that their training exercises taught the subjects' brains to do a better job of processing, which in turn allowed the subjects to discern smaller details without any improvement in the signal from the eyes.

CHALLENGING HOMEOSTASIS

Why should the human body and brain be so adaptable in the first place? It all stems, ironically enough, from the fact that the individual cells and tissues try to keep everything the same as much as possible.

The human body has a preference for stability. It maintains a steady internal temperature. It keeps a stable blood pressure and heart rate. It keeps the blood glucose levels and pH balance (acidity/alkalinity level) steady. It maintains a reasonably constant weight from day to day. None of these things are completely static, of course — pulse rate increases with exercise, for instance, and body weight goes up or down with overeating or dieting — but these changes are usually temporary, and the body eventually gets back to where it was. The technical term for this is "homeostasis," which simply refers to the tendency of a system — any sort of system, but most often a living creature or some part of a living creature — to act in a way that maintains its own stability.

Individual cells like stability as well. They maintain a certain level of water and also regulate the balance of positive and negative ions, particularly sodium and potassium ions, and various small molecules by controlling which ions and molecules stay and which exit through the cell membrane. More important to us is the fact that cells require a stable environment if they are to function effectively. If the surrounding tissues get too hot or too cold, if their fluid level moves too far outside of the preferred range, if the oxygen level drops too far, or if the energy supplies get too low, it damages the functioning of the cells. If the changes are too big for too long, the cells start to die.

Thus, the body is equipped with various feedback mechanisms that act to maintain the status quo. Consider what happens when you engage in some sort of vigorous physical activity. The contraction of muscle fibers causes the individual muscle cells to expend their supplies of energy and oxygen, which are replenished from nearby blood vessels. But now the level of oxygen and energy supplies in the bloodstream drops, which leads the body to take various measures in response. The breathing rate goes up to increase oxygen levels in the blood and to clear out more carbon dioxide. Various energy stores are converted into the sort of energy supply that the muscles can use and feed into the bloodstream. Meanwhile, blood circulation increases in order to better distribute the oxygen and energy supplies to those parts of the body that need them.

As long as the physical exercise is not so strenuous that it strains the body's homeostatic mechanisms, the exercise will do very little to prompt physical changes in the body. From the body's perspective, there is no reason to change; everything is working as it should.

It's a different matter when you engage in a sustained, vigorous physical activity that pushes the body beyond the point where the homeostatic mechanisms can compensate. Your body's systems and cells find themselves in abnormal states, with abnormally low levels of oxygen and various energy-related compounds, such as glucose, adenosine diphosphate (ADP), and adenosine triphosphate (ATP). The metabolism of the various cells can no longer proceed as usual, so there are different sets of biochemical reactions going on in the cells, producing an entirely different suite of biochemical products than the cell usually produces. The cells are not happy with this altered state of affairs, and they respond by calling up some different genes from the cells' DNA. (Most of the genes in the DNA of a cell are inactive at any given time, and the cell will "switch on" and "switch off" various genes, depending on what it needs at the time.) These newly activated genes will switch on or ramp up various biochemical systems within the cell, which will change its behavior in ways that are intended to respond to the fact that the cells and surrounding systems have been pushed out of their comfort zone.

The exact details of what goes on inside a cell in response to such stresses are extremely complicated, and researchers are only just now beginning to unravel them. For example, in one study on rats the scientists conducting the study counted 112 different genes that were turned on when the workload on a particular muscle in the rear legs of the rats was sharply increased. Judging by the particular genes that were switched on, the response included such things as a change in the metabolism of the muscle cells, changes in their structure, and a change in the rate at which new muscle cells were formed. The eventual result of all of these changes was a strengthening of the rats' muscles so that they could handle the increased workload. They had been pushed out of their comfort zone, and the muscles responded by getting strong enough to establish a new comfort zone. Homeostasis had been reestablished.

This is the general pattern for how physical activity creates changes in the body: when a body system — certain muscles, the cardiovascular system, or something else — is stressed to the point that homeostasis can no longer be maintained, the body responds with changes that are intended to reestablish homeostasis. Suppose, for example, that you begin a program of aerobic exercise — say, jogging three times a week for half an hour each time, keeping your heart rate at the recommended level of 70 percent of your maximum heart rate (which works out to something over 140 beats per minute for younger adults). The sustained activity will, among other things, lead to low levels of oxygen in the capillaries that supply your leg muscles. Your body will respond by growing new capillaries in order to provide more oxygen to the muscle cells in your legs and return them to their comfort zone.

This is how the body's desire for homeostasis can be harnessed to drive changes: push it hard enough and for long enough, and it will respond by changing in ways that make that push easier to do. You will have gotten a little stronger, built a little more endurance, developed a little more coordination. But there is a catch: once the compensatory changes have occurred — new muscle fibers have grown and become more efficient, new capillaries have grown, and so on — the body can handle the physical activity that had previously stressed it. It is comfortable again. The changes stop. So to keep the changes happening, you have to keep upping the ante: run farther, run faster, run uphill. If you don't keep pushing and pushing and pushing some more, the body will settle into homeostasis, albeit at a different level than before, and you will stop improving.

This explains the importance of staying just outside your comfort zone: you need to continually push to keep the body's compensatory changes coming, but if you push too far outside your comfort zone, you risk injuring yourself and actually setting yourself back.

This, at least, is the way the body responds to physical activity. Scientists know much less about how the brain changes in response to mental challenges. One major difference between the body and the brain is that the cells in the adult brain do not generally divide and form new brain cells. There are a few exceptions, such as in the hippocampus, where new neurons can grow, but in most parts of the brain the changes that occur in response to a mental challenge — such as the contrast training used to improve people's vision — won't include the development of new neurons. Instead, the brain rewires those networks in various ways — by strengthening or weakening the various

connections between neurons and also by adding new connections or getting rid of old ones. There can also be an increase in the amount of myelin, the insulating sheath that forms around nerve cells and allows nerve signals to travel more quickly; myelination can increase the speed of nerve impulses by as much as ten times. Because these networks of neurons are responsible for thought, memories, controlling movement, interpreting sensory signals, and all the other functions of the brain, rewiring and speeding up these networks can make it possible to do various things — reading a newspaper without glasses, say, or quickly determining the best route from point A to point B — that one couldn't do before.

In the brain, the greater the challenge, the greater the changes — up to a point. Recent studies have shown that learning a new skill is much more effective at triggering structural changes in the brain than simply continuing to practice a skill that one has already learned. On the other hand, pushing too hard for too long can lead to burnout and ineffective learning. The brain, like the body, changes most quickly in that sweet spot where it is pushed outside — but not too far outside — its comfort zone.

SHAPING THE BRAIN

The fact that the human brain and body respond to challenges by developing new abilities underlies the effectiveness of purposeful and deliberate practice. The training of a London taxi driver or an Olympic gymnast or a violinist at a music academy is, in essence, a method of harnessing the adaptability of the brain and body to develop abilities that would otherwise be out of reach.

The best place to see this in action is in the development of musical ability. Over the past two decades brain researchers have studied in great detail how musical training affects the brain and how those effects in turn make possible extraordinary musical performance. The best known study was published in 1995 in the journal *Science.* Working with four German scientists, the psychologist Edward Taub at the University of Alabama at Birmingham recruited six violinists, two cellists, and a guitarist, all of whom were right-handed, to have their brains scanned. They also recruited six nonmusicians to serve as controls against whom the musicians would be compared. Taub wanted to see if there was any difference between the two groups in the areas of their brains that were devoted to controlling their fingers.

Taub was most interested in the fingers on the musicians' left hands. Playing the violin, cello, or guitar requires exceptional control of those fingers. The fingers move up and down the neck of the instrument and from string to string, sometimes at incredible speeds, and they must be placed with extreme accuracy. Furthermore, many of the sounds coaxed from the instruments, such as vibrato, involve some sliding or vibrating motion of a finger in place, which generally requires extensive practice to master. The left thumb has fewer responsibilities, mainly just providing pressure on the back of the neck, and the right hand generally has much less to do than the left — mostly just holding the bow for violinists and cellists and strumming or picking for guitarists. In short, most of a string player's training is aimed at improving control of the fingers on the left hand. The question Taub asked was, What effect will this have on the brain?

Taub's team used a magnetoencephalograph — a machine that maps out brain activity by detecting tiny magnetic fields in the brain — to determine which parts of the subjects' brains controlled which fingers. In particular, the experimenters would touch a subject's individual fingers and observe which parts of the brain responded to each touch. They found that the region of the brain controlling the left hand was significantly larger in the musicians than in the nonmusicians — and, in particular, that the brain regions controlling the fingers had taken over a section of the brain region that was normally devoted to the palm. Furthermore, the earlier a musician had started to play his or her instrument, the greater the expansion was. By contrast, the researchers

found no difference between the musicians and nonmusicians in the size of the region controlling the fingers of the right hand.

The implication was clear: Years of practice on a stringed instrument had caused the area of the brain that controls the fingers of the left hand to gradually expand, resulting in a greater ability to control those fingers.

In the twenty years since that study, other researchers have expanded on the results and described a variety of ways that musical training affects brain structure and function. For example, the cerebellum — a part of the brain that plays an important role in controlling movements — is larger in musicians than in nonmusicians, and the more hours of training a musician has put in, the larger the cerebellum is. Musicians have more gray matter — the brain tissue that contains neurons — than nonmusicians do in various parts of the cortex, including the somatosensory region (touch and other senses), the superior parietal region (sensory input from the hands), and the premotor cortex (planning movements and guiding movements in space).

The details of exactly what happens to which region of the brain can be daunting to anyone who is not trained in neuroscience, but the big picture is clear: musical training modifies the structure and function of the brain in various ways that result in an increased capacity for playing music. In other words, the most effective forms of practice are doing more than helping you learn to play a musical instrument; they are actually increasing your *ability* to play. With such practice you are modifying the parts of the brain you use when playing music and, in a sense, increasing your own musical "talent."

Although less of this sort of research has been done in areas other than music, in every area that scientists have studied, the findings are the same: long-term training results in changes in those parts of the brain that are relevant to the particular skill being developed.

Some of these studies have focused on purely intellectual skills, such as mathematical ability. For example, the inferior parietal lobule has significantly more gray matter in mathematicians than in nonmathematicians. This part of the brain is involved in mathematical calculations and in visualizing objects in space, something that is important in many areas of math. It also happens to be a part of the brain that caught the attention of the neuroscientists who examined Albert Einstein's brain. They found that Einstein's inferior parietal lobule was significantly larger than average and that its shape was particularly unusual, which led them to speculate that his inferior parietal lobule may have played a crucial role in his ability to perform abstract mathematical thinking. Could it be that people like Einstein are simply born with beefier-than-usual inferior parietal lobules and thus have some innate capacity to be good at mathematical thinking? You might think so, but the researchers who carried out the study on the size of that part of the brain in mathematicians and nonmathematicians found that the longer someone had worked as a mathematician, the more gray matter he or she had in the right inferior parietal lobule — which would suggest that the increased size was a product of extended mathematical thinking, not something the person was born with.

A number of studies have examined skills that have both a mental and a physical component, such as playing music. One recent investigation looked at the brains of glider pilots versus nonpilots and found that the brains of the pilots had more gray area in several different regions, including the left ventral premotor cortex, the anterior cingulate cortex, and the supplementary eye field. These regions seem to be involved in such things as learning to control the stick that one uses to fly a glider, comparing the visual signals that one gets when flying with the body-balance signals that indicate the orientation of the glider, and controlling the movements of the eyes.

Even in the case of what we usually think of as purely "physical skills," such as swimming or gymnastics, the brain plays a major role because these activities require careful control of the body's movements, and research has found that practice produces brain changes. For instance, cortical thickness, a way of measuring the amount of gray matter in a brain area, is greater in competitive divers than in nondivers in three specific regions, all of which play a role in visualizing and controlling the movements of the body.

Although the specific details vary from skill to skill, the overall pattern is consistent: Regular training leads to changes in the parts of the brain that are challenged by the training. The brain adapts to these challenges by rewiring itself in ways that increase its ability to carry out the functions required by the challenges. This is the basic message that should be taken away from the research on the effects of training on the brain, but there are a few additional details that are worth noting.

First, the effects of training on the brain can vary with age in several ways. The most important way is that younger brains — those of children and adolescents — are more adaptable than adult brains are, so training can have larger effects in younger people. Because the young brain is developing in various ways, training at early ages can actually shape the course of later development, leading to significant changes. This is "the bent-twig effect." If you push a small twig slightly away from its normal pattern of growth, you can cause a major change in the ultimate location of the branch that grows from that twig; pushing on a branch that is already developed has much less effect.

One example of this effect is that adult pianists generally have more white matter in certain regions of the brain than nonmusicians do, with the difference being totally due to the amount of time spent practicing in childhood. The earlier a child gets started on the piano, the more white matter that pianist will have as an adult. So while you can learn to play the piano as an adult, it will not result in the same amount of extra white matter that would be produced if you learned to play as a child. At present no one knows what the practical implications of this are, but, generally speaking, more white matter leads to nerve signals being transmitted more quickly, so it seems likely that practicing the piano as a child will lead to certain neurological advantages that you just can't match with practice as an adult.

A second detail worth noting is that developing certain parts of the brain through prolonged training can come at a cost: in many cases people who have developed one skill or ability to an extraordinary degree seem to have regressed in another area. Maguire's study of the London taxi drivers provides perhaps the best example. At the end of the four years, when the trainees had either finished the course and become licensed drivers or had stopped trying, she tested her subjects' memory in two ways. One involved knowing the locations of various London landmarks, and at this the subjects who had become licensed drivers did far better than the rest of the subjects. The second was a standard test of spatial memory — remembering a complex figure after a thirty-minute delay — and on this the licensed drivers did much worse than the group who had never been trained to become taxi drivers. By contrast, the trainees who had dropped out scored about the same as the subjects who had never trained. Because all three groups scored equally well on this memory test at the start of the four-year period, the only explanation was that the licensed cabbies, by developing their memories of London streets, had done something to cause a decline in this other sort of memory. Although we don't know for sure what caused that, it seems likely that the intense training caused the trainees' brains to devote an increasingly large segment to this sort of memory, leaving less gray matter to devote to other sorts of memory.

Finally, the cognitive and physical changes caused by training require upkeep. Stop training, and they start to go away. Astronauts who spend months in space without gravity to work against come back to Earth and find it difficult to walk. Athletes who have to stop training because of a broken bone or torn ligament lose much of their strength and endurance in the limbs they cannot exercise. Similar things have been seen with athletes who have volunteered for studies in which they must lie in bed for a month or so. Strength fades. Speed diminishes. Endurance wilts.

And something similar is true with the brain. When Maguire studied a group of retired London taxi drivers, she found that they had less gray matter in their posterior hippocampi than did active taxi drivers, although they still had more than retired subjects who had never been

taxi drivers. Once these taxi drivers had stopped using their navigational memory every day, the brain changes that had been the result of that work started to disappear.

BUILDING YOUR OWN POTENTIAL

Once we understand the adaptability of the brain and the body in this way, we start to think about human potential in an entirely different light, and it points us to an entirely different approach to learning.

Consider this: Most people live lives that are not particularly physically challenging. They sit at a desk, or if they move around, it's not a lot. They aren't running and jumping, they aren't lifting heavy objects or throwing things long distances, and they aren't performing maneuvers that require tremendous balance and coordination. Thus they settle into a low level of physical capabilities — enough for day-to-day activities and maybe even hiking or biking or playing golf or tennis on the weekends, but far from the level of physical capabilities that a highly trained athlete possesses. These "normal" people cannot run a mile in under five minutes or ten miles in under an hour; they cannot throw a baseball three hundred feet or hit a golf ball three hundred yards; they cannot do triple gainers off the high board or triple axels on ice skates or triple backflips in a gymnastics floor routine. These are the sorts of things that require far more practice than most people are willing to devote, but — and this is important — they are also the sorts of abilities that *can* be developed because the human body is so adaptable and responsive to training. The reason that most people don't possess these extraordinary physical capabilities isn't because they don't have the capacity for them, but rather because they're satisfied to live in the comfortable rut of homeostasis and never do the work that is required to get out of it. They live in the world of "good enough."

The same thing is true for all the mental activities we engage in, from writing a report to driving a car, from teaching a class to running an organization, from selling houses to performing brain surgery. We learn enough to get by in our day-to-day lives, but once we reach that point, we seldom push to go beyond good enough. We do very little that challenges our brains to develop new gray matter or white matter or to rewire entire sections in the way that an aspiring London taxi driver or violin student might. And, for the most part, that's okay. "Good enough" is generally good enough. But it's important to remember that *the option exists.* If you wish to become significantly better at something, you can.

And here is the key difference between the traditional approach to learning and the purposeful-practice or deliberate-practice approaches: The traditional approach is not designed to challenge homeostasis. It assumes, consciously or not, that learning is all about fulfilling your innate potential and that you can develop a particular skill or ability without getting too far out of your comfort zone. In this view, all that you are doing with practice — indeed, all that you can do — is to reach a fixed potential.

With deliberate practice, however, the goal is not just to reach your potential but to build it, to make things possible that were not possible before. This requires challenging homeostasis — getting out of your comfort zone — and forcing your brain or your body to adapt. But once you do this, learning is no longer just a way of fulfilling some genetic destiny; it becomes a way of taking control of your destiny and shaping your potential in ways that you choose.

The obvious next question is, What is the best way to challenge homeostasis and develop that potential? We will spend much of the rest of the book answering that question, but before we do that, we need to address an issue that we have glossed over in this chapter: What exactly are we trying to improve about our brains? It's pretty obvious what leads to improved physical abilities. If you build more and larger muscle fibers, you get stronger. If you improve your muscles' energy reserves, your lung capacity, your heart's pumping capacity, and the capacity of your circulatory system, you build your endurance. But what

changes are you making in your brain as you train to be a musician, a mathematician, a taxi driver, or a surgeon? Surprisingly, there is a common theme to the changes in all of these areas, and understanding that is the key to understanding how people develop extraordinary abilities in any area of human performance with a mental component — which, when you think about it, is just about all of them. We discuss that next.

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Chapter 1: The Power of Purposeful Practice

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handle the increased workload: Again, to be completely accurate, the rats were sacrificed and their muscle tissue analyzed before their muscles could completely adjust to the new workload. This was necessary because once the muscles had adjusted and homeostasis had been regained, the muscle tissue would no longer be expressing all of these 112 genes. But if the rats had been allowed to live long enough, their muscles would have adjusted, and homeostasis would have been regained.

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Chapter 3: Mental Representations

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