Prologue

I envision this book as creating a journey for the reader, not a mere vacation. I want anyone to discover the potential for a transformative journey, the kind that expands a person. I want to guide practical explorations of the workings of learning and memory that enable the reader to find better ways to learn and remember. At the finish, I want your memory and learning to feel as real to you as a paper you write, as real as a sports event in which you compete, or as real as a piece of art you created yourself. At the end, I want you to be able to choose what to learn and how to learn it, to know why you’re making each choice, and above all to learn new things as efficiently and effectively as you can.

The end of your journey into learning may not come for a long time. To progress, you need to learn and practice the learning tools, keeping the tools that work as you experiment, and tossing out the tools that don’t work for you right now. Within months, but not days or probably even weeks, you should be able to tell that your learning is more efficient and more effective. Most simply, you should be able to tell that it is easier to remember and understand what you learn. Learning is not only memorizing and understanding, and by practicing with new methods, you should also find that you can be better at making connections with other things you remember. If you practice with the right methods, you should also find yourself better at solving problems. For my students, and I hope for you, the change shows, over time, as higher grades.

Reading this book gives you a map and some directions. You have to decide to make the journey happen, following the map and the directions. My directions are just the start. No one can write directions that substitute for knowing the land, the roads, the towns, and the cities. In a complex journey, the map and directions show you where to go. The map and directions don’t make you smarter. They do not make you know the city or the country. However, the map can help you know the landscape much faster than trying to understand your voyage without a map. When you do not understand learning, you are like a traveler without a map or directions. You might get to a goal, but you’re likely to waste a lot of time getting there. This map helps you get where you’re going more quickly and efficiently. But you have to think and work—you have to do the work to get there. You have to want to learn.

For the chance to gain the most from this journey, I think that you will need to follow my directions with an active mind, even when it gets boring, dull, hard, or painful. Every good journey has dull parts, and this one does, too. When you want astonishing views, sometimes
you have to climb hard trails or stairs – even when it hurts. I’ve tried to give you directions with manageable steps, but hard work is often essential.

There is no magic in this book. If you read and follow the directions with an active mind, you will improve as a learner. Behind this promise is a large amount of well-documented, rigorous science and research. We know that a lot of this stuff works, but we also know that people are different. **Most importantly, unless you try different methods, you cannot discover what will work best for you.** Most of what I suggest will probably work for most people, if they learn it and practice. Some of what I tell you to do comes straight from well-supported research on teaching, learning, and memory. Other parts (chunking methods, minute sketches, folded lists, test analysis) are logical methods that are based on old and new published research, or they are modifications of effective methods – I try to make those clear in the text. If what we think is correct, then what I tell you to do can work well. However, you have to test it – you have to do the experiments on yourself to see what works for you and what doesn’t.

**Will this work for you?**

I cannot tell you that following any of these specific methods or using any specific learning tools will give you better grades and accomplishments or allow you to spend less time but still earn the same grades and results. Some of the learning tools are not tested in the form that I present them (minute sketches and folded lists, for example), but I based them on extensive research by others on similar activities, such as concept mapping, drawing to learn, mind-mapping, limits to working memory, retrieval practice, and many others. I can also tell you that many of my former students believe that some of the learning tools helped them tremendously. As a learner, you should still be skeptical. Such reports might be confirmation bias (the tendency to believe that whatever we are doing is useful) or our human tendency to believe that whatever happened just before an event caused the event. Even though bias is possible, my own experience as well as careful research by others shows me that students who keep trying these methods find ways to improve.

**Using the book as part of a course**

This book is designed to go with a one-credit course on “Memory and Learning” that I teach to incoming college freshmen. I also teach a one-credit course on “How Students Learn” to college seniors and graduate students who plan to be high school science and mathematics teachers. Both courses include information from cognitive psychology, the neuroscience of learning and memory, and the relatively new science of what it means to become an “expert.” In the text, I try to highlight the difference between what we know with some confidence versus what is still theory or speculation. I want my students to be skeptical users of new insights into learning and teaching. Overall, my goal for freshman college students is that they develop an understanding that helps them become more effective learners. My goal for college seniors and graduate students is to help them become more effective teachers.

Students in my two courses include some who major in biology or neuroscience, and they often know something about the biology of learning. Other students are majors in mathematics, geology, chemistry, and physics, usually with little background in biology or psychology. I needed a book for any and all of them; one that I can use with my college freshmen, college seniors, and graduate students. I have been unable to find one. I think that’s a problem for learners. Many people, including me, believe that recent advances in the understanding of memory and learning could improve how students learn and improve teaching.
I think it is possible to present the information concisely and clearly at the introductory level. I also hope that the book might also be useful as an introduction for teachers or professors. I am planning an Instructor's Guide with teaching materials to go along with this textbook. For those who want to read more of the background or find the sources for the book, I am planning an revised version that includes numbered endnotes, each referring to references at the end of the chapter, sometimes with my comments. (Please check back at the book website if you are interested in that updated version of the text.)

The organization of the book: Three sections, thirteen chapters

Each chapter of the book can be used for one lecture/discussion.

**Section 1**, chapters 1-6, is information on learning from the studies in education, psychology, and cognitive neuroscience. Section 1 includes the background, terms, and explanations to understand why the learning methods in section 2 (chapters 7-9) might work.

**Section 2**, chapters 7-9, includes study methods and learning tools for efficient and effective learning. Most of this is based on research about effectiveness of different learning methods. In Section 2, the second half of chapter 5 explains how a student can do experiments on their own learning. To gain from reading this book, I think that these experiments are necessary for nearly all students. Why? In early versions of my courses, this section on experiments was missing, and follow-up with my students showed that most of them did not change how they learned. Only when I added the experiments (and required students to do experiments on their learning) did most students tell me in later semesters that they were still using new methods they found helpful. In addition, students also began telling me that they were still testing new methods.

**Section 3**, chapters 10-13, is a beginner’s guide to the biology and neuroscience of memory and learning. I've written the last section so that it could make sense even to a student who remembers very little biology. The reason for the last section is to help readers understand why the complex process of changing the brain is slow. Learning new ways to learn takes time because complex changes in the brain take time. The last section of the book persuades some students that they really do have to practice, and that the way they practice will matter. An important question is whether students could skip the last section. Maybe. While some students say that Section 3 was the most interesting part of the book, and some say that Section 3 made them understand why they need to practice, others have said it could be skipped. When I ask, at the end of a course, what changes I should make for next year, the biggest debate is usually over chapters 10-13.

Why did I write this book?

While I can coach individual students to start them on the road to expertise in learning, there are always more students than I can help, even in just my own courses. For fifteen years, I have wanted to find a book with this information in a form that enables students to develop the skills on their own. I wanted the book to offer practical advice as well as contain exercises that help students understand their own learning and improve their learning skills. I never found that book, and I finally decided to write it myself. I hope that my attempt helps get useful information out to more students. For any expert who studies and thinks about learning, I would love it if this book either inspires you or infuriates you to write a better one.
I am dismayed that many students never understand how they might become far better learners. My hope is that this book gives enough information, enough confidence to believe in their own potential to learn better, and an understanding of ways to get there. When that happens, people do astonishing things. My experience suggests to me that any beginner—any student, any of you—can learn and apply knowledge far better than you do now. For some, perhaps better than you have ever believed possible.

My qualifications

What qualifies me to write this book? Should you trust what I offer? My experience and qualifications are practical. You should decide if that’s enough. For the past twenty years, I have been working hard to coach students on improving their learning. Even earlier, I was tracking the research literature on methods of learning and their testing on students. From the beginning, I followed up with students to ask what seemed to work and what didn’t. Months and years later, I asked as many as I could if they were different or felt different in their learning and studying. I asked if their course grades had changed. I asked how they were studying, and I paid attention to which methods and learning tools they were still using. I have spent thousands and thousands of hours on this process. That practical experience in coaching students to try new learning methods and tracking them over months and years forms my qualifications for this book. This book is based on my experience applying the ideas and research findings developed by others, but the way I’ve organized and written the book comes from my experience teaching and coaching my students.

On the other hand, I am not a researcher on learning and memory – not a researcher in the neuroscience of learning and memory, cognitive psychology, or the science of education. What I am is a neuroendocrine physiologist, which is a very different field. My scientific publications are in neuroendocrine physiology: the study of how neurons and hormones regulate the body. Therefore, perhaps I have made errors when I interpret or explain other fields. However, I hope that as a non-expert with practical experience, this is a book that is helpful for students, teachers, or other professors who are not experts. Where there might be errors, I hope that they are minor. Some experts in these other fields have read the book, and I have made many changes based on their comments or corrections.

Neuroscientists may feel that my last section is too simple (some do feel that way); so simple that students will not understand the biology correctly. That may be so, but right now I don’t think I can add more details and principles without making the book too long or too complicated. My cognitive psychologist readers have felt that I oversimplify some concepts in their field, but their opinions (so far) suggest that my simplifications won’t be a serious problem in an introduction for beginners. If users of the book, especially those who are experts on these topics, continue to feel that sections are too simple, then I plan to rewrite those sections.

Any errors or oversimplifications in this book are my own. The expert reviewers of the book provided hundreds of excellent suggestions for changes and improvements. I was not able to follow all of their suggestions, but the many – most – suggestions I followed made the result much better than it was.

Evaluating my claims about learning for yourself

Many books and web sites claim to offer ways to learn better, often with wonderful and amazing stories and testimonials about how well they work. Many have poor evidence or none. How can you tell that this book (or any source) might be any better? That’s a tough problem. I
think I am using information and methods with reliable evidence. I think that my modifications are closely related to methods that are well tested and based upon evidence. It isn’t easy for me to show you the ways in which I think the information in this book is reliable. Likewise, it isn’t easy for you to know whether you should trust I’m being as careful as I claim. If you want to dig further, I recommend you take a look at a useful book about how to tell what works from what doesn’t in education and learning: When Can You Trust The Experts, by Daniel Willingham. Daniel Willingham presents methods anyone could use to distinguish reliable stuff from junk.

**Why is this book free?**

I have always wanted this book to be free. If the book turns out to be useful to learners, I want **ANYONE** to be able to get it. If the book is not useful, then I don’t want anyone to have wasted money on it. I am deeply grateful to the Jessie Ball duPont Fund for believing that this book was worth developing and for sharing my goal of it being universally accessible – free. A project like this has costs, and the Jessie Ball duPont Fund paid most of them. The College of William and Mary supported me for the rest. The initial one-credit summer class of teachers whose members told me they wanted me to write this book was supported by a grant from the Howard Hughes Medical Institute to the College of William and Mary. The course underwent further development with support from the National Science Foundation’s Noyce Grant program to develop new teachers in science and mathematics. Many friends, colleagues, and students were interested in contributing time and enthusiastic comments and ideas. I’ve named many, but certainly not all, in the acknowledgments. Thanks to all.
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Chapter One

How Our Mind Sees the World

Two rivers of thought compete in your mind: new information from the world versus past memories you recall. Learning brings in information from the world and triggers memories of what you’ve learned and experienced. Together, the new information and your memories change the way you think and act. This is learning.

We see the world not as it is …

In the book Fish is Fish (Lionni, 1970), a frog comes back from land to visit his or her old friend, Fish. Fish is fascinated when the frog describes a bird, a cow, and people. Fish imagines each, but poor Fish only knows the pond. In Fish’s mind, birds, cows, and people appear not as they actually are, but as fish. Fish cannot imagine correctly what Fish has never seen.

Figure 1.1. When Frog (on the left) describes a bird, Fish imagines a fish with wings.

Figure 1.2. When Frog describes a cow, Fish pictures a fish with horns and udders.
Chapter One: How Our Mind Sees the World

Figure 1.3. When Frog describes a person, Fish can only imagine a fish in clothes.

Fish sees the world not as it is, but only through Fish’s experience. Fish understands something new only by using the images and knowledge that Fish already has.

All of us are like Fish. There is an old saying that "We see the world not as it is, but as we are."* This book is about understanding our own learning. As we learn, we start with Fish-versions of new information. With experience and practice, we see things more as they are; we develop new connections and memories through learning. We begin with no understanding, starting as Fish. Fish cannot picture what Fish does not yet know. Neither can any of us. In Fish is Fish, Fish cannot even understand that there is something missing. Our human mind is more complicated than a storybook fish, but we have similar problems. We all start with a Fish-version of our own learning. Our Fish-understanding of learning can mislead us about how we learn, and so we make mistakes. When we discover our learning as it is, we can learn faster and better.

(* The quotation, "We see the world not as it is, but as we are," has an uncertain origin. It may be a saying from the Talmud. It also has been attributed to the writer Anais Nin, who wrote a passage similar to this. In 1982, Herb Cohen wrote a similar sentence in his book You Can Negotiate Anything, and in 1990, Steven Covey used this sentence in his book, The Seven Habits of Highly Successful People.)

One more thing you should know about Fish-versions. When I say “Fish-version” from now on, I don’t mean something that looks like a fish. Fish-version is my metaphor for a thing we picture that is as close as we can come to a strange new concept. That picture in our head is the best we can do, but it isn’t yet correct, just like Fish’s strange conception of a bird. A Fish-version isn’t completely wrong—a Fish-bird is better than nothing—but has important and maybe even silly errors. A Fish-version is a first impression—not complete, and almost never fully correct.

What is knowledge?
For everything you learn that is truly new, you learn like Fish. As you learn new terms and ideas, you have to learn them based on the knowledge you already have. Your first thoughts about each new piece of knowledge will be like Fish imagining a bird. A bird is not much like a fish with wings. However, a fish with wings is more like a bird than anything Fish knew before. Learning a new concept starts with Fish-understanding. As we think about a fish-bird in more ways, with corrections, gradually our Fish-understanding comes closer and closer to the real thing. Every new thing I try to learn in science starts out incomplete and with errors. As I can only understand the new information based on what I already know, I expect errors from my limited imagination. The more I learn and practice about anything new, the more my understanding encompasses a real bird instead of a Fish-bird.

**Chunks**

The things you know are **chunks**. The shape of the number 2 is a chunk, the shape of the letter A is a chunk, and your image of a flower is a chunk. We can combine two or more chunks we’ve learned into a new chunk. 20 is a chunk made of “2” and “0” that is a new chunk, a symbol for twenty. For you, but not for a beginning reader, “CAT” is a chunk. A new chunk can be made from each new word you see. Every word you know well is a chunk you made as you learned how to read. Learning to read is the process of learning and combining chunks. With growing reading skills, phrases and even some sentences also become single chunks. Short sentences such “Good morning” or “How are you?” are probably a single chunk as you read.

For a beginning reader, every line or curve of a letter is a separate piece of a chunk. The letter A is three separate pieces for a beginner, and you had to learn to combine them as a letter to learn your new chunk for A. If a beginning reader already has a similar chunk – maybe the end of a swing-set – for A, that might make it easier to learn the chunk for A as “similar to the end of a swing-set”.

![Figure 1.4](image-url)

Figure 1.4. Your chunks for the letters A and B were made as combinations of simpler pieces. You combined the three pieces at left—a line leaning right, short line in the middle, and line leaning left—together to make your chunk for the A (in the middle). The letter B was also made from three pieces: a vertical line, an upper curved line on the right, and a lower curved line on the right.
Before you can learn a new chunk, you have to have learned the chunks that are a part of the new chunk. You cannot learn “CAT” as one chunk made of the three chunks C, A, and T until you have learned the letters C, A, and T as individual chunks.

We must base every new thing we learn on things we already know. We need to have learned straight lines, diagonals, and connections in order to learn to recognize the letters A and F. We need to learn each of the letters f l o w e r in order to recognize the word “flower.” We need to have learned something about flowers and gardens in order to know what is meant by the words “flower garden.” If you have never seen or noticed the flower of an orchid (and many people haven’t), then you can have only a Fish-understanding of the word “orchid.” Almost no one reading this chapter would have learned chunks for the phrase “flower of pleurothallis grobyi” (Figure 1.5). Pleurothallis grobyi is the scientific name for a tiny species of orchid. The whole plant can be only one inch (25 mm) in size, and each flower is only ¼ inch (5 mm) long. They are quite different from orchids sold in flower stores. I collected one of these tiny orchid plants on a trip through Mexico. At the time, it had no flowers. Before my orchid flowered, I read a description of the flower as “yellow with red stripes looking like a bird mouth.” From that description, the picture in my head was not much like the real flower. However, it was more like the real flower in Figure 1.5 than what I had pictured before reading the description. This happens to us all the time. I have friends in the Philippine Islands who have never experienced winter. They can have only a Fish understanding for the phrase “a flower garden in winter.”

Figure 1.5. A photograph of a tiny orchid flower, each flower smaller than a pea. If all you know about this flower is “a tiny orchid flower that is yellow, has red stripes, and looks like a bird mouth,” then your picture would be a little like this but very much a Fish version.

What else is a chunk? A chunk is any single thing you can hold in your mind, like a bird, a bus or a fish. I have a task for you now. Close your eyes and think of the word “flower” and your image for a flower. (Were your eyes closed? Did you think “flower?”) What did you see? The shape you saw is your combination of pieces that you combine into your chunk for flower. Perhaps you saw the flower of Pleurothallis grobyi. When I ask this question in a workshop or a class, most people discover that their chunk is a circle with curved petals around it, but for a few the shape is like a tulip. (Is one of these shapes your chunk for flower, or did you see something completely different?) For the rest of this week, please ask yourself every now and then: what are the chunks in your mind right now? Ask your friends or family to close their eyes and think of
a flower, house, fish, or anything else, and have them describe to you what they see. (It helps if their eyes are closed, because closing your eyes gets rid of visual distractions.)

At first, you’ll be like Fish as you think about chunks. Your understanding of chunks is still like a Fish-version of a chunk as you are beginning to chunk the concept of “chunk.” The concept of a chunk is an important part of understanding learning because poor choices in making new chunks is a common error of students. When my students try to combine too many chunks at once or try to combine chunks they haven’t yet made and practiced, they get jumbled up, incorrect, and confusing chunks. They, and you, need to learn what it feels like to make the error of jumbled, too-complex combinations of chunks.

A Fish-version of Knowledge

As a Fish-version, I’ll define your knowledge as the following: (1) the chunks you know, (2) the connections between your chunks, which become new chunks with practice, and (3) the problems you can solve using your chunks. It’s a Fish-version of knowledge, but it's pretty good.

Thinking and working memory

A moment ago I told you to close your eyes and imagine a flower. What happened in your brain is important. As you imagined the flower, you recalled your memory for flower, and by recalling “flower,” your memory entered working memory. Working memory holds what you are thinking about in any given moment. In each moment of your life, working memory includes chunks you recall along with things you are seeing or hearing (or smelling or touching?). The limit to what you can think about at any moment is the amount you can fit into working memory.

Working memory has chunks flitting in and out all the time. Stop for a moment. Close your eyes, and imagine yourself surrounded by yellow flowers under a golden light. Try to hold this image in your mind for just one or two minutes. This matters! (As I write, I’m stopping to do just this.) I want you to discover what happens.

I can guess what happened because I’ve done this exercise with many people, and it just happened to me. At first, success! I was in that golden light, with yellow flowers around me. Then, 15 or 30 seconds later, my mind drifted away. For a little time, I had the flowers, the light and a vision of me all in working memory. Working memory doesn’t last, and so I lost my image. Instead of flowers in golden light, I was thinking about picking up my daughter after school. Failure. Working memory can hold old chunks (memories) or new information from your eyes or ears, but not for long. Working memory can retrieve old knowledge to solve a problem, but holds it only for 30 seconds or so, unless you check again. Working memory is a butterfly. It flits from thought to thought, never staying stuck on the same thing.

As you are reading, using your working memory, your eyes move across words on the page. The words you see bring chunks into your working memory. Working memory holds those chunks for about 30 seconds or a little longer. Try now to hold something in working memory for two minutes. Hold in your mind the sentence, “Working memory holds about 7 chunks for 30 seconds.” Check the time, and then close your eyes and try to hold just that thought in your mind for two minutes, with your eyes closed. Good luck! I just tried it: I lasted only 20 seconds.
You may have better focus than I do, but I'll be impressed if you can hold it for two minutes, which is very difficult to do.

New words and phrases you read steadily replace the old words and phrases. When you look up as a person walks by or you hear a sound, those events enter your working memory. The process of identifying the sound or the person pushes out the words you just read on a page. You go through life constantly losing the contents of your working memory. It holds anything to which you pay attention and then loses it after about 30 to 60 seconds.

How well can you recall (remember) something that was in your working memory 10 minutes ago, an hour ago, or five hours ago? Try the following. Close your eyes and think back over the day so far, and make a list of all the things you did. Can you also give me a moment-to-moment account of what you were thinking? Can you tell me the words in the paragraph a half-page above this one? I already know the answer. You can probably list what you did, but almost nothing about what you were thinking from moment to moment. Working memory doesn’t last. By tomorrow, you will have forgotten most of what you read today. Most of what you read never gets deeper into your head than working memory. In Chapters Twelve and Thirteen we’ll talk about what has to happen to make memories that you can recall.

**Working memory holds about seven chunks**

Working memory can hold around seven things or seven chunks. Trying to hold more than seven chunks is hard, uncomfortable, or even impossible. When we try holding more than seven chunks, we start pushing out one of those prior chunks from our working memory. But holding fewer than about five chunks is usually boring. When I’m bored, it is often true that whatever I’m doing requires too little of my working memory. That seems to be true of most people. On the other hand, if I try something that needs too much of my working memory, I get frustrated. I soon give up, deciding that the problem is too hard. Then, other things creep into my working memory, distracting me. When a math problem or a complicated sentence frustrates you, a common reason is that the problem needs too much working memory. From here on, I’ll write as if you can hold exactly seven things in working memory. That, too, is a Fish-version of what working memory can hold. Most people differ a little, and a few differ a lot. Most of us, however, hold about seven things in working memory.

Each thing in your working memory has to be something that you already know—something you’ve already chunked. In auditory (hearing) and visual (seeing) working memory, the chunk is usually a word or a picture of something you’ve heard or seen before and can recall. In the figure below (Figure 1.6a), I show you a sketch. Look at it briefly (10 or 20 seconds). Then cover the sketch, and try to draw it from memory on paper.
Figure 1.6-a. Most people find this sketch of a house familiar, with chunks they have practiced recalling many times.

My guess is that redrawing the sketch was easy. You probably could draw the sketch or picture it with no errors. If you try, you can probably hold the complete sketch easily in working memory while your eyes are closed. (Try that now, if you haven't already.)

Now try it again with the new sketch in Figure 1.6-b. Hide Figure 1.6-b, and try to draw it from memory.

Figure 1.6-b. A set of lines in an abstract pattern has only few chunks that are familiar (some rectangles and triangles).

Figure 1.6-b was probably impossible for you to redraw from memory or to picture in working memory with your eyes closed. It is for me. That should surprise you, because the house and Figure 1.6-b have exactly the same set of lines and the same black spot. All I did was move around the lines and black spot from the house. Look back and check for yourself. Every line is there, and every line is the same length, size, and angle. The difference is just that
I've connected them in different ways. One is a chunk you know well: a house with a door, window, roof, and walls. The other is something you don’t know and have never learned. The sketch of a house with 15 lines, one black dot, and about 17 connections fits easily into working memory, because you’ve already learned chunks for house, door, window, and roof. The same set of 15 lines, one black dot, and about 17 connections in the sketch in Figure 1.6-b is far beyond the capacity of your working memory. When I’ve tried to sketch 1.6-b from memory, if I start at a lower corner, I can usually get about six or seven lines plus the black spot. (I can do a few more if I remember the two triangles, two squares, and other shapes.) This result makes sense, because working memory holds about seven things.

Why can you easily remember the sketch in Figure 1.6a? Because you had already chunked the very familiar image of a house and so you were easily able to fit it into your working memory. The amount you can hold in your working memory does not depend on your working memory capacity. It depends upon how many chunks you already know, and how complex those chunks are.

**Holding completely new information in working memory**

Your working memory can hold new information in two ways. First, you can hold new information as a combination of chunks that you already know. Look at the images in Figure 1.7a. After looking at 1.7a, close your eyes and put the letter R from the left side in your working memory (in other words, imagine the R). That should be easy. Next, try the rearranged lines from R on the right side. These are exactly the same set of lines, but I have arranged them differently. Now, close your eyes and try to put and hold the image on the right in working memory. (Please close your eyes and try; you only need to do it for a few seconds.)

![Figure 1.7a](image)

Figure 1.7a. Three lines with three connecting points are arranged in two ways, as an R and on the left as a symbol you’ve probably never seen before.

I predict you can do both. In both arrangements, just three lines connect at three points. The R uses only one space in working memory, and the symbol on the right side uses fewer than seven spaces in working memory. It isn’t easy to hold, but it isn’t hard. More importantly, the symbol on the right side is a new image for you—something I hope you have never seen before. Ask yourself this question: do you hold it in working memory as one thing, or do you hold it as several things? In other words, does this new thing require more than one space in working memory? My prediction is that you have to hold this new thing as about three or four things in working memory: (1) a vertical line, (2) a half-oval touching the line about halfway down, (3) a
diagonal line starting at the top left of the half-oval, and (4) the diagonal line extending a short
distance past the lower part of the half-oval. (Here’s another question: does it help if I give the
symbol a name? Let’s call it the letter FFruh. Try now to hold the shape of the letter FFruh in
working memory.)

![Figure 1.7b](image)

Figure 1.7b. Two images sort of look like things that you’ve already chunked. Two people often
see the same image in different ways, so you may not chunk them the same way that I do.
Which letters, numbers, or other images seem most similar to the images above?

The second way to hold a new thing in working memory is to decide that it is actually an
old thing—something you already know as a chunk—but it just looks a little different You can
probably do this with the new images in Figure 1.7b. If you close your eyes and try to picture the
one on the left and then the one on the right, you probably can, but you are likely to need three
or four spaces in working memory. What happens if you decide that both of these are the letter
R? You might find that you can hold these in working memory as “a letter R with messy lines.”
We do something very much like this when we decide a person we know actually is the person
we know but with a really different new hair style, We do the same thing when we wave or say
hello to a person we know (“Hi Seyjun!”) and suddenly realize it isn’t that person (“Sorry, I
thought you were someone else.”). When we look more carefully, we discover that the person
doesn’t actually look much like Seyjun.

You can probably hold the new images in Figure 1.7b more easily in working memory
when you think of them as the letter R. I can, and I am guessing that you can. If I they were part
of the word “run,” I could recognize them:

RUN

But what if one is not an R? What if the image on the left really is a letter R, but the
image on the right is actually the letter A. Try two things. First, can you make yourself see that
difference—an R versus an A? Second, can you close your eyes and hold both figures in
working memory at the same time, the one on the right as an R, and the one on the left as an
A?

Sensing the limits to your working memory space

Next, please place the image from the left side of Figure 1.8 in working memory. After
you hold that image RAN in working memory, try to place the rearranged letter shapes on the
right side of Figure 1.8 in your working memory.
Figure 1.8. A further exploration of working memory space: On the left is the word RAN; on the right are the letters rearranged (including Ffruh). One is easy to hold in working memory, probably as a single chunk. The other reaches or surpasses the limit of my working memory.

The word RAN is easy. The rearranged letters on the right were hard, even though I only moved four lines. On the right, nine lines have six connections. With a little effort, you can probably hold it, but for most of us, it reaches the limit of working memory. Even after you notice patterns in the lines—maybe a mountain with a hat (my rearranged A) and a slanted V with a line through it (my rearranged N)—this takes at least seven spaces in working memory for most people.

You might be thinking that the ability to hold the rearranged lines on the right side of Figure 1.8 in your head would violate the ‘seven things’ rule, but it doesn’t. Two things helped you. First, you began the process of learning the rearranged R from Figure 1.7. In addition, some of the lines were in recognizable patterns (the slanted V, the mountain). Try again with these lines in Figure 1.9, with exactly the same lines, but now with each line set apart.

Figure 1.9. The lines from Figure 1.8 are separated as individual lines and arranged in different order.

The version in Figure 1.9 exceeds working memory capacity for most people. You might be able to hold more, maybe all, if you start chunking the parts. For example, you might
consider this figure as three vertical lines, four slanted lines, one horizontal line, one half-oval, and so on.

So what does this tell you? You can hold and understand a new pattern in working memory if it has no more than seven chunks, each of which you already know. New patterns are possible only if they have no more than about seven things you already recognize. Complex new patterns with more than about seven chunks you already know (as in Figure 1.6-b) are impossible to hold in working memory. We've all had the experience of looking at a diagram in a textbook that is too complex to hold in our working memory (like Figure 1.6-b), even though the teacher seems to think we can. That's because we don't yet know enough of the chunks. For these complex diagrams and figures, you can start learning them by simplifying the initial task. You can cut out some of the chunks, allowing yourself to start with a chunk of no more than seven things, each of which you can hold in working memory. When you have mastered that chunk, you can combine it with others to learn the more complex pattern.

This is an important new conclusion: **when you begin to feel confused as the task exceeds your working memory capacity, you need to start with smaller chunks.** Whatever we do in this book reveals conclusions for learning. In the section you just read, one conclusion is that difficulty holding any new image, sound, or concept in your head means that the task probably exceeds the capacity of your working memory. In order to learn that new thing, you need first to combine smaller parts into something you can remember as a chunk. Then, when you have mastered the smaller chunks and hold them in a memory, you can combine these new chunks to recognize the entire concept and hold it in working memory. Is this always true? I believe it is. As we’ll come back to later, you can check for yourself, and decide if I’m right or wrong.

**Missing chunks**

Overloading working memory is the first of two problems in learning a new chunk. The other problem is that we might be missing a chunk that we must have in order to understand the new chunk. How clearly and accurately we can picture something new depends upon the smaller chunks within it. The HIGH PLAINS OF PATAGONIA is probably something that most of us have not chunked very well, if at all. We have missing chunks, such as where is Patagonia? How does a high plain differ from a plain? How are the high plains of Patagonia different from other high plains, such as the high plains of Mongolia? Like Fish, we might picture the HIGH PLAINS OF PATAGONIA in our working memory as something quite different from what it really is.

Before reading, a pre-reader has to know and recall each letter of the words he or she sees as a chunk. Missing chunks, which happen when a pre-reader decides on the wrong letter, block reading. Comparing any two letters, such as M and E, can use all of working memory for a beginning pre-reader who finds it impossible to recognize entire words, because comparing even simple letters like M and E, requires all of a pre-reader’s working memory. There’s no space left over to decide that M and E together form the word “ME.”

If a new reader mixes up pairs of letters, such as M and N, he or she will struggle to read. Repetitively looking at and trying to read complete words probably won’t help. A new reader needs to get M and N chunked separately and into his or her memory. Later, a new problem appears. You can’t understand sentences with more than seven words until you can combine groups of words into a single chunk. Stop for a moment, and reread the last sentence.
Chapter One: How Our Mind Sees the World

If the sentence was easy to understand, my guess is that you understood that sentence in fewer than seven chunks. For example, perhaps one chunk was “you can’t read sentences,” and another chunk was “with more than seven words.” Another chunk might be “until you can combine,” and then “groups of words,” and finally “into a single chunk.” You probably have a chunked image of “groups of words” as a single chunk, a group of words. You may have a chunked image that fits with “into a single chunk,” such as sticking lumps of mud or clay together. Most readers at the level of this book probably hold that underlined sentence as 4 to 6 chunks in working memory. However, a beginning reader would not understand it and could not understand it while reading. The sentence has too many words (twenty). Even if a beginner has chunked all of the words, a beginning reader cannot hold them all in working memory. A reader has to have chunked the phrases in order to understand the sentence. If a reader has too many missing chunks, comprehension isn’t possible.

When you are lost and confused as you learn, some chunk is probably missing or wrong. Before you can learn the new concept, you must first master the essential chunks to hold the new concept in working memory in seven or fewer chunks. If you don’t notice that you are missing a chunk, you can waste a lot of time on practicing an incomplete chunk that you don’t understand. Teachers or textbooks often cannot see that we do not yet know all of the essential information for a new concept. They often cannot tell that we have forgotten something that we need to know for the new chunks. Probably at all stages of learning, and certainly by college, it helps if you can figure out for yourself what chunk(s) of information you need to learn new concepts.

The new chunks to learn about how our mind sees the world

Here are six new concepts with terms for which I hope you have at least a Fish-understanding:

1. Each thing that we know is a chunk.
2. We learn new chunks as does Fish. Only with correct information and practice do we develop more accurate understanding.
3. More complex chunks are a combination of simpler chunks. We cannot learn a more complex chunk until we master the simpler chunks it involves.
4. At any time, we can hold about seven things in working memory. Each must be a chunk we already know from our memories or from the world around us.
5. If a new chunk needs more space than we have in working memory, we can’t learn it.
6. If an essential chunk is missing, we cannot learn a new chunk that involves the essential chunk.

There is one important conclusion:

You will learn best if you notice when you have overloaded working memory space or you are missing an essential chunk. (Of course, you have to do something to fix the problem when you notice. Otherwise, it’s wasted.)

What comes next?
From this chapter, you should have a Fish-understanding of chunks and working memory, though with misunderstandings and misconceptions. You can’t have a better understanding yet, because I can’t explain it to you all at once, with perfect details and connections. In the same way, Fish can’t gain a good understanding of birds, cows, and people without learning many more chunks (feathers, beaks, hoofs, horns, hands, fingers, shoes) and connecting the new chunks to the new words—bird, cow, and person. Chapter Two will give you new chunks for different strengths of memory and how those strengths relate to knowledge. The next chapter will also connect these new chunks to the concept of working memory and chunks. Chapter Two and later chapters will help you develop more accurate and useful understanding of chunks, memory, and working memory.

NONE of these new chunks will be of any value until you use them. This book is not about the content. You have to test your own learning and discover better ways for YOU to learn, and these chunks are necessary for you to understand what you’re doing. Your first task is to start noticing when you have (1) an overloaded working memory, and (2) might be missing an essential chunk. You’ll need practice at noticing when your memory is overloaded and missing chunks. Here’s a sentence for you for practice:

“In mice without HoxA1, the ear develops abnormally, but adding Retinoic Acid at the normal time of HoxA1 expression results in a near-normal ear, apparently by effects on retinoic-acid-binding proteins that function as transcriptional repressors. What might you predict about the normal function of HoxA1 protein?” (from an exam in my college course, “Integrative Biology of Animals”)

Can you hold the first sentence in your working memory? I’m guessing not, unless you’ve had a lot of biology classes and built the necessary complex chunks in your memory. If you cannot hold it in working memory, please try to remember, for later, this feeling you have when you began to overload your working memory. Finally, can you circle the missing chunks—the things you would need to understand in order to understand the sentence?
Chapter Two: Types of Memory

Chapter Two

Types of Memory

Chapter One gave you a Fish-version of two vital concepts: chunks and working memory. **Chunks** are things you have learned and can recall. **Working memory** holds the 7 chunks in your thoughts at any one time. We have not yet talked about an obvious problem in learning: how chunks move from working memory, which lasts only 30 seconds or so, become new chunks that you remember for longer. With practice recalling the memory, we can remember these chunks for hours, days, weeks, months, or years. This chapter will also present another new chunk: **procedural rules**, which are a sequence of steps to solve a problem.

To improve your learning, it is useful to know good ways to strengthen memories when you want them. We need Fish-versions of chunks for some different kinds of memory and for how memory develops and lasts. Here in Chapter Two, we’re going to focus on one kind of memory that we use all the time in school and in life: **declarative memory**. Declarative memory is the kind of memory we can declare or say. We can explain it to others in words. For example, we have declarative memory for the spelling of words, for what we ate yesterday morning, for directions to a house, and for chemical formulas.

We hold on to some of the events of our lives and some information from school as declarative memories. To develop these memories that last longer than working memory, we need three things: (1) We need focused attention when the new event is in working memory. (2) The event needs to feel important to remember. (3) We have to practice recalling the memory. The less important the memory feels, the more practice we need in order to hold on to it. Each practice recall of the memory makes it stronger.

**Stages of memory**

The first time we experience something truly new to us, we literally don’t see it as one new chunk. We cannot recognize a new chunk as one thing, just as you could not recognize the pattern of my rearranged the lines of a house in Figure 1.6-b. The first time you saw a letter Q, you had no memory for Q. You probably took it into working memory as two chunks: (1) a circle and (2) a small diagonal line crossing on the lower right side. When told that this was the letter Q, if you thought about it and decided it was important, then you began to form a memory that was separate from working memory. The new memory formed, like drawing in mud on a sidewalk, as temporary changes in your brain (more on these neural circuits of memory later). Mud drawings on a sidewalk don’t last long. People walk on them. Rain washes the mud away. If you want to keep your mud drawing fresh, you have to go back and redo it while the lines are still at least faintly there. In the same way, if you wanted to keep your new memory for Q, you had to go back and practice redoing Q while you could.
Chapter Two: Types of Memory

Recognition memory, effortful recall, fluent recall, and automatic recall

Each time you practice a new chunk, the memory lasts a little longer. With each bit of practice, the chunk is easier to recall. When the memory is still bright and fresh, you have fluent recall; it comes easily, without clues. As time passes, without practice, the memory is smudged and worn and harder to see and harder to recall. At this stage, you have effortful recall; you can still recover the memory, but you have to think hard. Often you need clues. For example, you might have made yourself the clue that “Q is sort of like an O.” At the stage of effortful recall, memory is not easy. If even more time passes without practice, then you have only recognition memory. You’ll know it if you see the drawing again, but the drawing is too smudged to see without help. My two years of high school French is in this final category. My French mud was walked over, worn off, and washed away long ago. I have lost even recognition memory for French.

Here’s an example to show you the differences. Seven people are around you. Two of them you don’t know, but your friend Justin just introduced them as Zeba and Maria. The other five you know well, including Justin (fluent or automatic recall). No one told you their names today. If you think about the names of the seven people around you, you are holding those seven names in working memory. In this case, five came from your fluent or automatic recall, and the other two—Zeba and Maria—are new. One might be a name you’ve not heard before—maybe Zeba—and that’s a totally new chunk. You’ll have the most trouble remembering this one, because you need to remember two things: the name and the connection to the person. The other new person may have a name you have heard many times for other people—Maria—but the new chunk is the connection of Maria to this person. Now imagine that you start talking and thinking about something new. There is a good chance that, three minutes from now, you’ll not be able to remember the names of the two new people. Later, when Justin says, “Zeba would know,” you might not remember which one is Zeba. (This happens to me all the time. I think I’m awful at learning names.) If Zeba is the name less familiar to you, then you are more likely to have forgotten Zeba than Maria. In this case, you had both names in working memory for 30 seconds. You had just started developing recognition memory for these two new people, and you do not yet have any form of recall of their names.

Memory can change from recognition to fluent recall and back.

Every new person’s name or new concept you learn has to come to you first through your working memory. If the new information goes right back out in the next 30 seconds, which happens often, nothing has changed in your brain, and you have not learned anything new. However, if you decide to start practicing that memory because it is important to you, then you begin the process of forming first recognition memory, then effortful memory, fluent memory, and finally automatic memory. Two things make you begin to develop recognition and recall: repeated recall and caring about it. The more you recall and review the memory, the faster this happens. The more you care, the fewer repetitions we seem to need. The less you review and care, the faster you lose the memory. You can have fluent memory for something today, but in two weeks only have recognition memory. In two months, you might not even have recognition memory. Declarative memory—all of memories that we can test on quizzes and exams—gets weaker and fades, sometimes completely away, unless it is recalled and practiced often enough. We’ll talk about this much more in later chapters.
Memories last due to practice with interest.

As you begin to learn new chunks, the chunks shift from fluent recall to effortful recall and recognition memory and back. One or two days without practice recalling the memory is often enough to put a new chunk back into recognition memory or lose it completely. If you didn’t develop fluent recall lasting even 10 minutes when you first saw the chunk, then you lose the new memory even faster. This is why it is so easy to forget the things we learn as soon as we stop studying or practicing. The things we care about are easier to remember because we are interested in our practice. I learned very quickly the complicated rules and strategy of the board games Monopoly and Risk and then later, computer games because I recalled them over and over as I played. I thought about the rules even when I wasn’t playing—when I was supposed to be practicing French, for example. I practiced what I found interesting and important. I wanted to win at games, so those felt interesting and important. French rarely felt interesting or important, so I only practiced when I had to, and I never again practiced French after the classes ended.

The more you practice a chunk and the more you care about it, the longer the memory lasts. A Fish-version of this might help: each time you draw in mud on the sidewalk, there is a bit of glue in the mud. Each bit of glue holds a tiny bit of mud. Gradually, over time, the glue builds up, making it easier and easier to hold on to your memory. Practice gradually makes a memory stronger.

How much practice we need

How many times do you have to redraw your memory in mud? How many times do you have to practice a chunk to make it easy to hold in fluent recall for years? I haven’t seen research on this question, so I’m just guessing. I suspect that the answer is at least a thousand times. Think back over your life. How many times have you read the words in this sentence (“How,” “many,” “times,” “have,” “you,” “read,” “the,” “words”)? I would predict that you have recalled nearly all of those printed words while reading at least a thousand times while thinking about them. If you have recalled the meaning of a word three times a day for a year, that’s a thousand times. In fact, many of you have probably read most of the words on this page 10,000 times. When you have practiced a chunk 1000 times, you are beginning to develop automatic recall. You have automatic recall for the chunks that you always remember without any effort and without needing new practice—chunks like the words yes, no, or stop, the names of close relatives, and maybe your phone number.

Long-lasting automatic recall probably takes years with many hundreds or thousands of practice times. There seem to be unusual exceptions in which automatic recall can happen much faster. For example, if you care so much about something that you recall it dozens or even hundreds of times a day, automatic recall can develop quickly. Automatic recall is especially fast if the chunks or events were very good (or very bad or even terrible). These are chunks that we cannot stop thinking about. Perhaps we recall them with interest so much more frequently that we get a large amount of practice recall very quickly.

What counts as practice? Once you have a chunk in fluent recall, you can practice it in a few seconds or less, and that means you can practice hundreds of chunks in an hour. If you cannot stop thinking about something, you might practice a single new chunk more than a hundred times in one hour and many hundreds of times in just a few days. Even so, it seems to take periods of months and years of practice recalling the same memory in order to convert fluent recall to automatic recall that seems permanent.
We each need a different amount of interested practice.

I have not seen enough research results on how much practice recall is needed to make memories last. I don’t think such results matter, because the only important answer for YOU is how many interested practices YOU need in order to develop and keep fluent recall. You might need less than I predict. To find out, I want you to do metacognition experiments on yourself. Some of my students have done this, but I don’t have enough results from them to change my guesses. (I have done this experiment on myself with some specific concepts, including “metacognition,” a word and concept I learned for the first time about a dozen years ago. For me the answer seems to be about 1000 recalls, with interest, over at least eight years. I predict that people are not all the same, though. I know people who seem to be much faster than I am. I don’t know anyone who seems slower.)

Working memory space and the form of your recall

When a chunk is still in fluent recall, you can hold that chunk in a single space in working memory. With effortful recall, you may need two spaces or more in working memory, perhaps because you need to recall a clue as well as the chunk. For example, if the shape of the letter Q is in effortful recall, you might need to remember the clue (“Q is sort of like an O”) and only then recall the shape of a Q. The clue and the chunk fill two spaces in working memory as you recall.

If you understood a concept once, then with recognition memory you would probably understand it again, but only when you are reminded of all of the chunks you need, using more than one space in working memory. Something outside of your own brain must put some of the necessary chunks into your working memory, which needs space. Recognition memory is sometimes the only memory and understanding you need on a multiple-choice exam. Some multiple-choice exams have most of the necessary chunks somewhere in the question or answer choices. With those chunks as reminders, you can answer the questions correctly. If you need to solve problems and to develop more complex chunks without hints, then recognition memory is not enough.

With effortful recall, your memory is slow and awkward. If noises or images distract you, or if you are too tired, you may not be able to recall the memory at all. Often, effortful recall requires much of working memory capacity, leaving nothing left over to solve a problem or make a new connection. That’s why fluent recall is the level we often try to achieve before an exam. With fluent recall, the memory comes quickly as you actively try to remember. If I ask you about Columbus’s voyage, and you quickly think or say, “Columbus sailed with three ships from Spain to islands near Central America in 1492,” that’s fluent recall.

Most of what you learn in classes never becomes automatic memory. However, as a person develops toward being an expert in something, many fundamental concepts and words slowly become automatic memory with repeated practice. If your sport, hobby, or other interest is something you think about, see, and do over and over again, you will eventually develop automatic recall. It is possible to develop automatic recall of chunks that are part of a skill, a sport, a TV show, a computer game, reading, history, or biology.
New chunks to learn about stages of memory

We will use the concepts from the section above over and over again in this book. I hope you will use them every day in your learning. Here are the new chunks:

1. **Recognition memory**: You cannot recall the chunk without hints, but you know it when you see it. Example: You recognize the name of someone when you see it written out, but you cannot remember it just by seeing the person or having someone ask, “Who is that?”

2. **Effortful recall**: You can remember it, but it takes work, and just one concept may require all of your working memory to hold the separate chunks. Example: you have to stop and think, who is that person? I know I’ve met her. (You have recognition memory of her face.) Where did I see her before? That’s not helping! When did I see her? Oh yes, that’s Justin’s friend whom I met last week—that’s Zeba.

3. **Fluent recall**: You remember easily, but you have to decide that you want to remember it. “Who is that? Oh yes—Justin.”

4. **Automatic recall**: You remember without trying. As soon as you see her, you find yourself saying, “Hi Zeba!” (If you’re on friendly terms.)

5. **Memories can move between categories**. We lose memories we don’t practice with interest.

6. **You have to find out for yourself how frequently and how many times you need to recall a memory to develop and keep fluent recall.**

With these new categories of memory, I want you to understand how your mind works—how the things you recall move into and out of working memory. That’s the goal of the rest of the chapter.

**How do memories develop from working memory to automatic memory?**

We form memories as connections among brain cells. Over days, weeks, and months of repeated recall of a new chunk, the brain gradually strengthens the connections. (Later, I’ll mention ways the brain can form long-lasting memory with less practice, such as with memory palace techniques. Using those techniques to make faster memories can be useful, but not as much as you might think. You need to spend a lot of time practicing the techniques to use them.) As you make and strengthen new connections in your brain, you develop a new memory for that chunk. You need a first Fish-version of these concepts. Let’s start with how you learned to recognize letters, back when you were a pre-reader.

A pre-reader learning the letter “A,” remember, needs to develop a memory for the letter A with two diagonal lines connected at the top plus one horizontal connecting line in the middle. At first, a pre-reader has no memory for “A.” As a pre-reader practices identifying letters over and over, the pre-reader begins to develop effortful memory for the letter “A.” Effortful memory comes slowly. During development of effortful memory, just remembering “A” may require all of working memory. Why? The pre-reader sees the letter and needs to compare “A” with similar letters. Those comparisons all require space in working memory. Working memory has to hold the two diagonal lines and one horizontal line, and then compare those three chunks with the shapes of similar letters such as “N,” “R,” and “Z.” Each comparison has to happen one at a time, because each comparison takes all of working memory. Finally, the pre-reader has to decide that the shape he or she sees matches their concept for the letter “A.” The process of recalling the memory takes effort and time to think. With practice over days, weeks, and maybe
months, the letter “A” becomes a fluent memory, recalled quickly but perhaps requiring working memory for confirmation. For anyone who can read this text, the letter “A” has developed into an automatic memory.

A beginning reader needs all or nearly all letters in fluent recall in order to solve problems. For reading, the problem is, first, recognizing the word from the sequence of letters. The beginning reader has to be able to hold all the necessary chunks—each letter of the word—in working memory. If the number of chunks does not overload working memory, the reader can solve a problem: identifying the word. That usually requires at least fluent recall of each letter of the word.

Overloading the capacity of working memory

You need to recognize what it feels like to overload your working memory. That is the central goal of our next section, Keep that in mind as you think through the problems I give you and as we spend five pages with text and tables on what’s held in seven spaces in working memory.

When you have too many chunks to hold in working memory, you lose some. I want us to feel how working memory works by stepping through some simple mathematics problems. What matters is that you start to notice what you are holding in working memory and what it feels like when you cannot hold everything. To start, try to work five multiplication problems (a–e below) in your head. I plan for you to fail at some. (If you don’t fail at any, you might not understand my point. In that case, add an impossible problem for yourself.)

The problems (write a few notes on your answer or whether you get stuck on each):

(a) 2 x 2 =
(b) 5 x 8 =
(c) 5 x 16 =
(d) 15 x 17 =
(e) 327 x 4819 =

What you held in working memory for each problem

Let’s analyze what happened, using the concept of seven spaces in your working memory. Most likely, problem (a) 2 x 2 = ___ is in automatic memory for you. You didn’t need to work the problem; you just knew the answer (unless you have not practiced multiplication in a long time). If you saw 2 x 2 and automatically thought 4, then this needed one space in your working memory: 1st Space: 2 x 2 = 4.

Problem (b) 5 x 8 = ___ is almost as automatic if you have drilled (practiced) your one-through-ten multiplication tables. This also probably needed only one space of your working memory: 1st Space: 5 x 8 = 40
Chapter Two: Types of Memory

Even if $5 \times 8 = 40$ was not in automatic recall, this problem probably did not exceed your working memory capacity. Those with less practice might have had to work the problem by addition of 8 five times. If so, you could have chunked it into fewer than seven spaces in working memory. The table shows one way to chunk $5 \times 8 = ?$ into 7 spaces in working memory.

<table>
<thead>
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<tbody>
<tr>
<td>8+8=16</td>
<td>two 8's</td>
<td>16+8=24</td>
<td>three 8's</td>
<td>24+8=32</td>
<td>four 8's</td>
<td>32+8=40, the answer</td>
</tr>
</tbody>
</table>

Most people would not need seven spaces, because we know it can be okay to forget an earlier space. Once you have 24 and three eights in working memory, for example, you don’t have to hold $8 + 8 = 16$ or two eights. That means that you could use the same method to calculate $7 \times 8$ or $9 \times 8$ and not run out of working memory. (Go ahead and try, if you wish: $8 + 8 = 16$, two eights, $+ 8 = 24$, three eights...)

Problem (c) $5 \times 16 = ____$ is usually not in automatic recall. Most people do not look at $5 \times 16 = ___$ and automatically think that $5 \times 16 = 80$. I hope that you feel the difference between $5 \times 8 = ___$ and $5 \times 16 = __$. Because $5 \times 16$ is not in automatic recall, we have to solve it using a procedure. From here on, I will call any procedure to solve a problem a set of procedural rules or procedural rules. Procedural rules can be in declarative memory, but once you have practiced a set of procedural rules enough times, they are probably in a different category of memory—skill memory—for the things that you can do. I have not seen enough research results to know.

Below is one way to solve this problem, using one set of procedural rules. The procedural rules are to (1) separate the two-digit number into a ten’s digit and a one’s digit, (2) multiply each by the one-digit number, and (3) add the two results together. You also need chunks for the concept of 5, 6, 10, 16, a chunk for one’s place, a chunks for ten’s place, a chunk for multiplication, a chunk for $5 \times 10 = 50$, and a chunk for $5 \times 6 = 30$. In working memory, you have:

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</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Times</td>
<td>16</td>
<td>16=10+6</td>
<td>5x10=50</td>
<td>5x6=30</td>
<td>50+30=80, the answer</td>
</tr>
</tbody>
</table>

This is the way I do this problem, but you might do it in a different way. Robin, one of the students who worked with me on this book used a different set of procedural rules. Robin imagined she was writing the problem on a sheet of paper. She wrote the numbers in her mind, solved the equation on her imaginary sheet of paper, and got a correct answer. (Right now, you might want to try the problem using Robin’s method. As you do, see if you can decide what you are holding in the spaces in your working memory.) A friend of Robin’s, Sarah, did the same problem in yet another way, as, $(1^{st}) 16 + 16 = 32$, $(2^{nd}) 32 \times 2 = 64$, $(3^{rd}) 64 + 16 = 80$, $(4^{th}) = five 16$’s. Later, we’ll talk more about different procedural rules that can solve the same problem. Usually, there is more than one way to solve a problem. Some are easier than others, and it matters which way you have practiced.
Chapter Two: Types of Memory

Some people would get stuck on the problem 5 x 16 = ___ because they do not have any of these sets of procedural rules or Robin’s or Sarah’s sets of procedural rules. However, they might still have solved this problem using a third set of procedural rules: adding 16 five times. One important point in your exploration of working memory is that a particular problem can be easy or hard depending ONLY on whether you know at least one effective set of procedural rules for that problem. Some problems that are conceptually the same as others cannot be solved with the space available in working memory. Problem (c), for example, needed all available space in my working memory when I used the method in my table. However for a mathematics teacher, 5 x 16 = 80 is probably in automatic recall as one chunk. She doesn’t actually need to solve the problem. A teacher just recalls it automatically, using a single space in working memory, just as you did for 2 x 2 = 4. For the mathematics teacher:

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<th>7th space</th>
</tr>
</thead>
<tbody>
<tr>
<td>5x16=80, the answer</td>
<td></td>
<td></td>
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<td></td>
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Problem (d) is too big for working memory capacity for most people. It needs more space in working memory than we have. Here’s how it might be done:

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</thead>
<tbody>
<tr>
<td>15</td>
<td>Times</td>
<td>17</td>
<td>17=10+7</td>
<td>15x10=150</td>
<td>15=10+5</td>
<td>10x7=70</td>
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</table>

Now we’re out of space, but we still need:

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<th>10th space</th>
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<tbody>
<tr>
<td>150+70=220</td>
<td>5x7=35</td>
<td>220+35=255</td>
</tr>
</tbody>
</table>

the answer

If that is how we had to solve the problem, then it took too much working memory capacity to solve—ten spaces! Now, however, you know that there can be more than one way for working memory to solve a problem. With that first set of procedural rules, the problem might be impossible. However, if we can try a second set of procedural rules, we might succeed. For those who did solve this problem in their head, they most likely had some additional chunks and different procedural rules. For example, a person who has fluent recall of 7 x 15 = 105, can solve the problem with seven spaces in working memory.

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<tbody>
<tr>
<td>15</td>
<td>Times</td>
<td>17</td>
<td>17=10+7</td>
<td>7x15=105</td>
<td>10x15=150</td>
<td>105+150=255</td>
</tr>
</tbody>
</table>

the answer

You need only one space for the chunks in the 6th and 7th space above and only need to add 150 + 105 = 255. Also, a person who has enough practice can train themselves to drop
some things out of working memory, getting some space back. If you have $17 = 10 + 7$ in automatic recall as a chunk, then you don’t need “17” by itself in working memory.

You can solve this problem in different ways, if someone has more procedural rules for multiplication problems or more chunks in fluent recall. Some people have as a chunk in fluent recall: the square of 15 is 225 or $15 \times 15 = 225$. They can use fewer spaces to solve the problem in this way:

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</thead>
<tbody>
<tr>
<td>$15+2=17$</td>
<td>$15 \times 15 = 225$</td>
<td>$2 \times 15 = 30$</td>
<td>$225+30=255$</td>
<td>the answer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This person can solve the problem and still have three spaces left in working memory. Is this person smarter, or did he just have this one extra chunk, $15 \times 15 = 225$, in automatic memory? I would say both. To me, being ‘smarter’ means being able to solve more problems with more chunks. I am smarter now than I was when I was 10 years old or when I was 21. I am still working on getting smarter. Anyone who can read this book could memorize $15 \times 15 = 225$. You just need to practice recalling $15 \times 15 = 225$ a few times a day over many days. That’s how kids practice their multiplication tables enough to get them into fluent recall. After that much practice, any of you would certainly have the chunk $15 \times 15 = 225$ in fluent recall or automatic recall. In that one small way, you would be “smarter.” (Are you smarter in a useful way? What if you never again need to recall $15 \times 15 = 225$ to solve a problem? In that case, we might decide that someone is smarter but in a way that is useless.)

**Some procedural rules are easy to learn, but slow for complex problems**

Another set of procedural rules for this problem is to go back to our addition rules for multiplication: add 15 to itself 17 times. That’s simple but slow.

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</thead>
<tbody>
<tr>
<td>17</td>
<td>15</td>
<td>$15+15=30$</td>
<td>two 15’s</td>
<td></td>
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(From here on, I keep track of each sum in working memory, along with the number of additions I have done. I allow myself to forget the earlier values.)

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</thead>
<tbody>
<tr>
<td>17</td>
<td>15</td>
<td>$30+15=45$</td>
<td>three 15’s</td>
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<td></td>
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</table>
Chapter Two: Types of Memory

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<tr>
<th>17</th>
<th>15</th>
<th>45+15=60</th>
<th>four 15’s</th>
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</table>

17 + 15 = 32

That was slow, but it only used four spaces in working memory at any one time.

**Planning to select the best procedural rules for a particular problem**

Every student reviewing this chapter has given me a different way to solve the problem $15 \times 17 = \_\_\_$. Only one of them developed a plan before solving the problem. Johnathon reported that he first took the information from the problem into working memory and developed a quick plan for analyzing the problem. Only after choosing a plan did he solve the problem. Johnathon based his analysis on procedural rules and problems he had practiced enough to have in fluent recall with understanding. His solution:

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</thead>
<tbody>
<tr>
<td>15</td>
<td>Times</td>
<td>17</td>
<td>15=10+5</td>
<td>10x17=170</td>
<td>5x17 must equal $\frac{1}{2}$ of 170</td>
<td>170/2=85</td>
</tr>
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</table>

Johnathon told me, “Once I have performed this operation, all I need to remember is to add 170 to 85.” He emptied working memory except for those two numbers and added them together.

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<th>6th space</th>
<th>7th space</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td>+ 85</td>
<td>= 255</td>
<td>the answer</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Johnathon’s method uses something that experts often do. First he put the problem in working memory, and next he picked one of many possible procedural rules to solve the problem. Experts often have many ways to solve the same problem, and they select the best way for that particular problem. Non-experts are less likely to have more than one set of procedural rules for the problem, and if they have more than one method, they are less likely to pick the best before they solve. Johnathon was in the process of becoming an expert in teaching mathematics at the time he worked with me. He was graduating from college with a major in mathematics and planning to get a master’s degree as a mathematics teacher. It’s not surprising that he automatically applies a procedural rule to pick the best way to solve a mathematics problem.
Johnathon’s procedural rules are typical for experts. Here is what he told me:

1. I hold the problem in my working memory and compare it to other problems that I remember solving in the past.
2. Then I review potential ways to solve the problem. I noticed that 15 breaks apart more nicely into 10 + 5 than does 10 + 7 because half of 10 is 5. Thus, I chose a plan: multiply 10 by 17 and then add one-half of the product.
3. As I was going through my steps to solve the problem, I knew that could drop some of the chunks from working memory. For example, once I had 170 I didn’t need to remember 10 x 17 anymore. I held 170 in one space in working memory and solved for 170/2. When I had that answer, 85, that was all I needed to add to 170 for the answer to the problem. When I was in the last stage of solving the problem, I think was really only using 2 spaces: 170 + 85.

With years and years of solving many different kinds of mathematics problems in different ways, Johnathon has practiced many ways to solve math problems. This was a simple problem, but I know from working with Johnathon that he does the same thing with any problem he has in mathematics. As we learn and practice in any subject, those of us who choose to gain expertise in the subject learn this skill of picking the most effective ways to solve a problem.

Memorizing the answers in advance is the fastest way to solve any problem

I suspect that you are getting tired of these little boxes, but please don’t give up on the chapter yet. The next sections are important.

There is yet another way to solve problem d above: memorize the answer in advance. That’s the way you solved 2 + 2 = 4, using one space in working memory. Any problem needs only one space in working memory if a person has memorized the answer. If you practiced teens multiplication tables and have 15 x 17 = 255 in fluent recall, then:

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<th>6th space</th>
<th>7th space</th>
</tr>
</thead>
<tbody>
<tr>
<td>170+85=255</td>
<td>3rd space</td>
<td>4th space</td>
<td>5th space</td>
<td>6th space</td>
<td>7th space</td>
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</tr>
</tbody>
</table>

A memorized answer is always the fastest way to answer any question. This is why we prefer to memorize instead of learning and practicing procedural rules for problem solving. But memorizing only works perfectly as long as we only get problems we have seen before and for which we have memorized the answers. Unfortunately, many problems are not predictable. Often, there are so many possible problems that it would take too long to memorize all of the solutions. (I’ll give you an example in a later chapter.)

Of course, you know this! Very few of you have bothered to develop fluent recall for teens multiplication tables (quick: what’s 13 x 14?). I can guess that none of you have memorized three-digit x three-digit multiplication tables. We know that we will have teens multiplication problems infrequently, and it would take a long time to memorize the teens multiplication tables. You’ve decided that the procedural rules for multiplication are better than memorizing teens multiplication tables. (When you’re allowed a calculator, the procedural rules for using calculators are even easier.)
Neither memorizing the answers nor applying procedural rules that we have memorized and practiced is preferable for solving problems. **We need both strategies: procedural rules and memorization.** Memorizing answers in advance takes much more preparation time but gives fast results. Procedural rules are often more complicated to learn and apply, and using them makes us slower to answer a problem, but they allow us to answer problems that are unpredictable. Procedural rules give us ways to solve complex problems without overloading working memory. The solution is to memorize the chunks that we can predict we will need over and over again, and to practice procedural rules that enable us to solve more complex problems.

**Overloading working memory in problem (e)**

Problem (e) 327 x 4819 exceeds working memory space for almost everyone. When I try, I can get only part way through it in my head. I end up with a confused mess that quickly drops a chunk that I need, such as:

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<th>7th space</th>
</tr>
</thead>
<tbody>
<tr>
<td>327=300+27</td>
<td>300</td>
<td>4819=4000+819</td>
<td>4000</td>
<td>300x 400 =120,000 (or is it 1,200,000?)</td>
<td>27x 4000 =94,000? (or is it 112,000?)</td>
<td>27x19=?</td>
</tr>
</tbody>
</table>

I get lost, confused, and give up. The chunks I recall and the procedural rules I know are not enough to solve this problem in my head.

Problem (e) becomes easy if we have two things. We have to (1) know procedural rules for multiplication problems where both numbers have more than one digit, and (2) **be allowed to write on paper.** Paper is a tool that extends working memory capacity. Later, I'll talk more about writing or sketching on paper or a board as a way to assist working memory and improve problem solving.

**Homework on working memory**

Over the next few days, please think about your working memory capacity whenever you do any kind of mathematics problem or read sentences (or do anything else in your life). Discover how you are chunking information. Give yourself problems that might overload your working memory capacity, and practice learning how it feels to overload working memory. For example, right now you could practice solving 27 x 39 = ____ in your head, which overloads working memory for most people, and remember how it feels.

**The chunks we know limit our working memory capacity.**

Learning how you use working memory and recognizing the feeling of overloading working memory capacity is an important part of understanding your own learning. It is important to do this for yourself. Why? Because working memory does not necessarily have exactly seven spaces. When researchers test working memory capacity for different kinds of
Chapter Two: Types of Memory

chunks (names, words, numbers, procedural rules), the results differ. And individuals have differences as well. In addition, working memory is a complicated part of your brain, and my rule of seven spaces is just an approximation. I have given you a Fish-version of the concept of working memory. Keep in mind that we don’t actually care about your exact working memory capacity. Being able to hold more in your working memory is about learning more complicated chunks, after all. I had the same working memory capacity when I was a pre-reader as I do now (though I’ve had a few hard blows to the head that may have damaged it). However, I can hold far more words and phrases in my working memory now than I could as a pre-reader. Back then, it was the chunks I knew that limited me, not my working memory capacity.

How much we hold in working memory

We’re always limited to the seven spaces in working memory, but we can hold far more than 7 digits. I can show you this by having us do a simple working memory task: remembering a number. For the list of numbers below, look at one number at a time, try to fix it in your mind, and then close your eyes and try to repeat the number aloud or in your mind.

(a) 2
(b) 29
(c) 38172
(d) 719584263
(e) Try the number in (d) again, but notice that the year ‘1958’ is after the 7. Try remembering 7-1958-42-63. Another possibility: some of you might have remembered (e) as 719-584-263. I can hold (e) in working memory as ”719-584-263,” but not as “7-1-9-5-8-4-2-6-3.”
(f) 117634947329475
(g) 1111111111 (Does it help if I tell you the number has exactly ten ones?)

Below are three more numbers to look at for a short while, and then look away and try to recopy from memory. You should be able to predict that it will be impossible to hold each digit in working memory. However, each one is easy once you know how to hold them in seven spaces in working memory. It might take you a while to discover the patterns, especially for (j).

(h) 1112223334444555666777888999
(i) 123456789101112131415161718192021222324252627282930
(j) 32933033133233333433536337338339340341342343344345

Let’s analyze what probably happened in your working memory while trying problems (a) to (j). Keep in mind that our goal is to give you a better understanding of working memory and chunks. As you do these exercises and analyses, you are moving from Fish-versions of the concept of ‘working memory’ toward a more precise version.

Numbers with seven or fewer digits (a, b, and c) are easiest to hold in working memory. Usually, a string of 9 or more digits with no pattern (d) is hard, unless you remember it as groups of longer numbers. For example, if you have chunked some parts of the string of digits before, such as the year 1958 in (d), or if you have a combination lock that is 4-26-3, then you might recall that nine digit number using seven or fewer chunks. The sequence in (f) is probably impossible for you (it is for me). The number in (g) might be hard, unless you use a trick. Hold in working memory the digit 1, repeated ten times. The sequence in (h) is far too large to hold in
working memory as a set of unconnected numbers, but easy if you remember the pattern (1st) 1-9 in order, and (2nd) each digit three times in a row. The 51 digits in (i) can be just as easy, if you know the entire pattern: (1st) starting with 1, (2nd) each number in order, (3rd) up to 30. What about (j)? I drove my student assistant Robin crazy, for a little while, because I won’t tell you (or her) what the pattern is. Example (j) has a slightly more complex pattern, but if you notice the pattern, you can hold the full sequence in working memory using about seven spaces, and you could say all of those digits aloud from working memory. However, (j) takes most people a while to notice the pattern, unless they have practiced finding patterns in numbers.

My point from this section is very important. Anyone can hold very long and complicated things in memory if they can hold the pieces as seven or fewer chunks. Later, we’ll talk more about procedural rules that allow us, with practice, to hold more and more in working memory, never needing more than seven chunks and seven spaces in our working memory. They aren’t tricks. They just take procedural rules and practice.

We hold long, complex things in our mind by chunking them as seven or fewer things.

If you chunk it correctly, you can easily hold in working memory the series of letters, “mist on the ocean on a frosty morning,” even though this sequence has 30 letters. You could recall this sequence of letters as “mist on the ocean on a frosty morning.” How do you know that you are holding this series of letters as a set of less than seven chunks? First I can predict that while you can hold the phrase “mist on the ocean on a frosty morning” in working memory, you cannot recall this string of letters if you think of them as a set of separate letters.

Try now. Close your eyes, and think “mist on the ocean on a frosty morning.” THEN try to list the letters, in order. You probably cannot list the letters unless you use procedural rules: think of each word, one at a time, spell out the letters in that word, and then go on to the next word. That might work for you.

It is also important that the words in the phrase make sense as an image in your mind: mist on the ocean on a frosty morning. Most of us cannot recall these easily as eight individual words. You can test yourself. Try it this way: “ocean a morning the on mist frosty on.” Look at those eight words a few times, and then look away and try to write them down in order. My guess is that some of us can do it, but it takes much more work than the original phrase. I just tried. I was not able to remember them in this new sequence. After writing the sentences above, I tried to write out the words in the rearranged sequence, but I got the order wrong (two errors). However, I could remember the new sequence easily after I created a couple of phrases: “ocean a morning” “the on-mist frosty” and “on.” Many methods can help you hold longer sequences in working memory. They all require that you learn and practice procedural rules for connecting sequences in working memory. Memory palace methods are one of these. (Like other procedural rules, they are only worth learning if they will be useful to you. I promise: more on this topic of maximizing what you can hold in working memory will come later, in Chapter Nine.)

Understanding your working memory capacity and knowing when you have overloaded working memory are useful skills. Why does it help to know when you are overloading working memory? (Remember that it is possible to become "smarter" in ways that don’t do you any good!) It is useful to know when you are overloading your working memory because that tells you that you cannot solve a problem with the chunks you have right now. Most of the time,
successful problem solving has nothing to do with your potential to become smarter (or to stay dumb for that task). Until you learn the chunks, it just is not possible! You need to learn the necessary procedural rules and concepts. Only then does it become possible to solve a problem. Only then do you become smarter, and (unfortunately) only in that one specific way. You need to start with a Fish-version of the concepts of working memory, working memory spaces, and procedural rules. You need to practice recalling these concepts and applying procedural rules to use the concepts.

The difference between empty memorization and fluent recall with understanding

As I write, I am looking up at a sign above my desk that says, "No empty memorizing." What is "empty memorizing," and what does it mean to “learn” something? The empty memorizing sign is there because it is easy for us to memorize things that have no meaning. Many of my college students have a different concept of learning than I have. Their concept includes empty memorizing which causes problems.

If we have memorized something, such as the symbol Ŷ, does that mean we have learned it? I would say that memorizing the symbol Ŷ means we have effortful recall, fluent recall, or automatic recall of Ŷ. However, unless we also have chunked what the symbol stands for, we have no understanding. This would be empty memorizing: recall without understanding. As it turns out, I have no idea what the symbol Ŷ represents. At the moment, I have effortful recall without understanding of Ŷ. This symbol was connected with nothing else in my mind (which is why I picked it).

Let’s apply this question to "learning" other things. Can a child memorize the symbols 1 + 3 = 4? Sure. With practice this could use less than seven spaces in working memory. However, if the child does not realize that 1 is a symbol that represents one object or one thing, and that 3 is a symbol that represents three objects or things, and that 4 is a symbol that represents four objects or things, then does the child understand addition? I hope that you immediately say, “No!” What is the difference between simple memorization that results in fluent recall, and fluent recall with understanding? If a person can simply reproduce something, like a copy machine prints out a copy, that is not understanding. A copier or a printer does not understand what it is printing. If your learning is close to simple recopying, just like a copy machine, then you are doing empty memorizing. In contrast, what if a child fluently recalls what all of the symbols represent. What if the child knows that the symbols 1, 3, + and = mean: take the one thing, combine it with the three things, and count the new number, and the new number, indicated by the symbol 4, should be on the right side of the =, because = means a sort of balance on each side. If so, I hope you would agree that our child has fluent recall with understanding.

A common problem for learners is that they do not yet see the difference between empty memorizing and fluent recall with understanding. Let’s say you memorize the rules of genetics, algebra, or chemical equations. However, let’s also imagine that you don’t understand what they mean. Now answer this question: have you learned genetics, algebra, or chemical equations? Many beginning learners would say yes. A teacher would say either no, or perhaps, “This is just the very beginning of learning.” If you memorize a definition but do not understand what the words mean, then you have fluent recall without understanding. If you can recall and sketch out a drawing but do not know what the symbols represent, then you have fluent recall without understanding. It’s a start.
Chapter Two: Types of Memory

Developing fluent recall with understanding happens slowly, with practice and with checking understanding. You can check your understanding with the help of another person, in which case we call the process “teaching.” You can also check your understanding on your own, in which case we call the process “metacognition.” For example, imagine that you memorize the definition for a term that includes the word “nitrogenous base.” If I ask you, "What is a nitrogenous base?" then I am acting as a teacher who is checking your understanding. If you ask yourself, as you learn the definition, "Do I know what a nitrogenous base is? Do I need to know more about this term in order to understand the concept?" then the process is metacognition.

Many high school and college students would state that they have learned a new concept if they have memorized a definition or a sketch of that concept. They probably know perfectly well that memorization is not the same thing as understanding. However, they might view empty memorization as learning, while I do not. Therefore, sometimes they think that they have finished learning a concept because they have fluent recall of a definition or explanation, when I think that they have barely begun.

The new chunks to learn about types of memory

Here are 12 new concepts with terms that are new chunks from Chapter 2:

1. Procedural rules are sequences of steps to solve a problem.
2. Declarative memory is our memory for things that we can declare, or explain in words. (Directions to someone’s house or a definition of a term are declarative memories. How to ride a bicycle or play a sport are not – they are other forms of memories.)
3. We can think of memories as being in recognition memory, effortful recall, fluent recall (easy to recall), or automatic recall (we don’t even have to try to remember these).
4. As we practice, memories become fluent or even automatic.
5. Whatever memories we don’t practice recalling become less fluent, and then effortful, and eventually we may not even recognize an old memory.
6. I’m guessing, but I think it takes many, many practice recalls for a memory to become automatic and stay automatic. (For me, memories that I practice recalling hundreds or maybe a thousand times over a period of a few years seem to become automatic. I have not seen any research on this question, though.)
7. Working memory is overloaded when we try to hold too many chunks at one time. It is useful to know how you feel when you have overload working memory.
8. When working memory is overloaded, you can write down some of what you want to remember and use to solve a problem.
9. We can hold more in working memory by learning new chunks that are combinations of two or more old chunks. Each new chunk needs only one space in working memory.
10. Memorizing answers in advance is the easiest way to solve problems, but often there are too many answers to memorize.
11. When there are too many answers to memorize, it is faster to learn procedural rules to solve problems.
12. Empty memorizing is memorizing without understanding. Empty memorizing is nearly useless.
Knowledge and Learning

Knowledge is what you know. Learning is how you acquire more knowledge. Knowledge is chunks and connections between chunks. These are Fish-definitions. In this chapter, we'll try to add more and better chunks.

Growing up and learning

Sheep, cows, and dogs are born and grow to full size in just a year. Adult humans are about the same weight as sheep and large dogs, but we humans take 15-20 years to grow to full size. Why? Is our diet poor, or is it just impossible for humans to grow that quickly? Neither is the reason. In fact mutations exist that cause humans to grow nearly as fast as a sheep or big dog. However, the mutations cannot speed up the experiences we need to learn. Humans are capable of growing to adult size with a full-size brain in just a few years, but we cannot learn fast enough to function like a full-sized adult when we are three years old. From the moment we are born, our brains are learning. It takes 20 years to learn to be an adult.

Our brains are not born with all the right connections already made. We are not born smart. Instead, we are born learning. Even before you were born, your brain was changing the connections between brain cells. That's what learning is—making new connections, and keeping the ones that are useful. Brains are growing and testing new connections all the time, especially as we are growing up. Our brains keep only the connections that do something useful. When a baby seems to be waving its legs or arms for no reason, it is learning. The baby's brain is growing the connections from brain cell to brain cell that it needs to learn in order to grab or roll over. A small child learning to walk is clumsy, not because its muscles are weak, but because its brain hasn't learned all the correct muscle cells to turn on or off. With every staggering step and fall, the brain is growing connections to move the body how we want it to move. The brain gets rid of connections that do the wrong things and make the body fall down. For every movement, skill, or new fact we learned, we had to grow or strengthen new connections between brain cells. The size of our brain is not what is important. What matters are the connections we've grown. Some adult humans have small brains and some have large brains, but the size of our brains doesn't seem to affect how smart we are. What matters is what we have learned. What we have learned comes from useful connections, made slowly and steadily over time. We can speed up the rate of head growth, but we still have to learn all the connections.

Gradually from childhood to adulthood we learn language, rules, concepts, limits, abilities, people, and skills. At two years old, we have just begun to learn the immense number of things we will need to function as adults. Imagine a two-year-old the size of an adult having a wild, screaming, clawing temper tantrum. Even at normal size, an angry two-year-old is hard to manage. Imagine a two-year-old mind in the body of a full-sized adult, screaming and hitting in a temper tantrum. Now you begin to understand why our body growth is slow. As long as we stay small, adults can teach us correctly and safely. Our body grows at a rate that keeps pace, more
or less, with our ability to control our muscles and our ability to understand what is around us. By the time we reach adult size—about age twenty—a typical human has learned enough to begin to function like an adult.

Learning and teaching is at the center of what makes humans unique. Humans learn and learn and learn. We teach and teach and teach. No other animal has the deep hunger to learn and teach that humans do, or the satisfaction we get from learning to read, the rules and movements of basketball, or anything else we enjoy. Before we go on to talk more about learning, we need a good understanding of what we mean by knowledge. After we discuss what knowledge is, we'll talk about learning.

**Everything you learn must build on what you already know**

Whenever you learn something new, you are building it out of the chunks you already know. You must make each new chunk from a combination of old chunks. Until you understood and remembered the digits 0-9, you could not understand what is meant by the number 19. Until you learned numbers 1, 2, 3, 4, 5, you could not learn addition: $3 + 2 = 5$. You must build everything you learn with understanding on things you already understand and remember—the background chunks.

Background chunks affect the way we learn. For example, children believe that down is always the same direction for everyone. If that was true then the Earth must be flat. That's the chunk I drew in the left side of Figure 3.1. When told that the Earth is round, children first imagine the Earth as a flat pancake or tortilla, like in the middle of Figure 3.1. Children may think we all live on a flat circle inside the ball or that people should fall off the sides of the ball.

![Figure 3.1](image1)

Figure 3.1. Children's understanding changes: The Earth is flat (left side). The Earth is round (middle). The Earth is round like a ball (right side). Children may think we all live on a flat circle inside the ball or that people should fall off the sides of the ball.

Children know they don't fall off of the Earth, so they continue to imagine a flat Earth, but make it round at the edges, like the middle of Figure 3.1. On their own, children do not imagine the Earth as a ball or a sphere. As they believe that down must always be the same direction, if told that the Earth is round like a ball, they try to picture a pancake on top of or inside of a sphere, like the chunk I sketched on the right side of Figure 3.1. They imagine people walking on top of the ball or on top of the pancake, as if only one direction can be up. Anywhere else, people should fall off.
Children know that people can stand on top of a huge ball, but people cannot walk on the sides or bottom. People would have to hold onto ropes or they would fall off. Because of that chunk of background knowledge, children cannot understand how a person could walk on the sides or the “bottom” of a spherical Earth. A child could memorize that the Earth is a sphere and that people stand upright on all parts of it, but not understand why. A child can understand why only when she learns the background concept of gravity. The force of gravity from any object attracts other objects toward its center. It is also important that gravity is only detectable if at least one of the objects is very large, like the Earth. Even a mountain doesn’t have enough gravity to be noticed. Within the concept of gravity, “down” is not always the same direction. Instead, down is always the direction toward the center of an object—toward the center of the mass of the Earth, for us humans.

The misconception that down is always one direction makes it impossible to understand the concept of a spherical Earth with people standing all over the surface. The same kind of problem happens to all of us all the time when we learn. If we are missing an important fact or concept necessary to understand a new chunk, then we cannot develop understanding of the new chunk. If something is missing, we can only memorize. We cannot understand.

Knowledge is connected.

As we develop fluent recall for chunks of information, we begin to strengthen connections in our brains. In order to be useful, we must connect the chunks we know to other chunks. The more connections our new chunk has to other important chunks, the more useful the new chunk will be. In contrast, any chunk with no connections to anything else is empty memorizing. Read the two words in Figure 3.2 below and, if you feel like it, memorize them.

<table>
<thead>
<tr>
<th>Tubig</th>
<th>Subig</th>
</tr>
</thead>
</table>

Figure 3.2. Two different words are different chunks. Neither word has connections.

I hope you just read them and moved on. You could memorize both words, but it would be completely empty knowledge, unless you know more. Once you know that tubig means water, then you have a connection that adds meaning. This is still pretty useless, though, unless you know when and where the word might be useful. If I tell you that I learned the word tubig when I was doing research in the Philippine Islands, then you have a new connection. If you know that tubig is a word for water in Cebuano and Tagalog, two languages from the Central and Northern Philippines—then this new knowledge might become useful. It was for me; I was often thirsty. The knowledge is even more useful with more connections, such as the words to make a simple sentence to ask for water. Tubig, palihog. means “Water, please” in Cebuano (but not in Tagalog). If you want to be given any water, you also need the pronunciation: “too-big pall-ee-hoag” (Figure 3.3).
The second word I suggested for you to memorize is subig (Figures 3.2 and 3.3). Subig is a word that I say means rocketship. I made subig up as I was writing. This is new information for you, that subig = rocketship. It could become a new chunk, but it is completely useless. Why? Because this chunk, subig = rocketship, cannot be connected to anything else you know. There is no language in which you can use the word subig for rocketship. The word subig can only be used if you talk to me and if I still remember. The word subig has no useful connections. Without connections, the chunk for subig is useless. Chunks are useful only when connected.

Chunks with more connections are more useful. For you, even tubig and its connections are probably not useful, just like subig. For me in the Philippines, tubig was one of the most important chunks I knew. The more useful connections a chunk has for you, the more important it is to develop fluent recall.

**Useful knowledge is organized.**

The last time I was in Costa Rica, I tried to speak Spanish with a taxi driver. The poor person was hopelessly confused. About four out of every five words I was speaking were Spanish but about one out of every five words I used was actually Cebuano, a Philippine language. It was as if I was talking to you and saying, “May I please have some tubig?” The taxi driver had no hope of understanding my scrambled up sentences. My knowledge was disorganized and useless.

When I give exams, my students sometimes answer questions with descriptions that have 80% of the right things, but 20% incorrect things. Four out of five scientific terms, facts, or principles in an answer are correct. The others are wrong or used incorrectly. The result is often an answer that makes no sense, like my conversation with the taxi driver. An answer like this often is not 80% correct, but disorganized so badly that it is 100% wrong. These students may have fluent recall, but their knowledge is so poorly organized that it is useless. That occurs at test-time, when they have just completed their best preparation! So I know that the organization of their chunks will quickly get even worse. When this happens to my students, I have to explain to them that useful knowledge is organized before they are able to understand why I will not give them 80% credit.

**Organized** chunks are not exactly the same as **connected** chunks. It is possible for your chunks to have many connections but poor organization. It is also possible for your chunks to be
very well organized but have very few connections. *Tubig* has more connections in Figure 3.4 below (eight connections) than *tubig* in Figure 3.3 (only four connections). If you compare the figures, you should notice that the four connections in Figure 3.3 have more organization than do the eight connections in Figure 3.4. A person with the knowledge and eight connections in Figure 3.4 can recognize that *tubig* is the same word as water in eight other languages, but does not know which language is which. Are two of the words for water in Chinese and Hindi, or might they be in Japanese and Arabic? The person with the knowledge of *tubig* in Figure 3.4 does not know where or how to say and use any of these words. None of the words are connected to the organized knowledge on the right side of Figure 3.4.

![Figure 3.4](image.png)

Figure 3.4 Words can have many connections but be poorly organized. On the left is *tubig* connected to words for water in eight other languages, but no connections indicate what those languages are or where they are used. On the right (in gray) are connections that are organized in a way that would make the word *tubig* more useful.

Imagine that you are in the Central Philippines, and you want water. With the poor organization on the left side of Figure 3.4, you will waste time, and the person you’re asking may never figure out what you really want. The useful organization on the right side will connect that fact that you are in the Central Philippines with the language of Cebuano and the words for water and please, along with their pronunciation. Useful organization solves problems. The useless organization on the left side has more connections, but poor organization. You’ll probably stay thirsty. Knowledge that we remember automatically, connect properly, and organize well to many other concepts makes it easy to transfer our understanding to new situations. Getting smarter depends partly on organizing knowledge as we learn.

**Useful organization is like a map.**

Look again at Figures 3.3 and 3.4. You should be able to see that the patterns of organization are like a map. The connections between chunks are the ways you get from one chunk to another on the map. The organization of your chunks is the pattern of connections you use to move from one chunk to another on the map in the correct ways to think correctly or solve a problem correctly. For that reason, one of the best ways I know to develop organization of new chunks uses drawings like the mind maps in Figures 3.3 and 3.4. We call them mind maps because they show connections in our minds between chunks, how we get from one concept to another.

Mind maps can help you see and practice how to move from one idea to another—from chunk to chunk to chunk. When I am learning new chunks, mind maps help me to organize
them efficiently. I still use such maps when I’m learning and practicing new chunks in my research on the brain, hormones, and fertility (neuroendocrine reproductive physiology). Did you notice that I just did something to organize new chunks for you, connecting the phrase brain, hormones, and fertility with neuroendocrine reproductive physiology? Finally, mind maps can also help us discover weaknesses in our organization, including missing chunks. We’ll talk more about uses for mind maps in other sections, but for now, hold on to the concept that chunks are connected and organized like places on a map—a Fish-version, but a pretty good one.

How do we organize knowledge in useful ways as we learn? Humans don’t start out with mapping. Much of the time, we organize knowledge by where we need it, when we need it, and with whom we need it. Learning basketball is organized pretty well in this way (though if we want to become expert players, we need much more complex organization). For much of what we learn in school, however, even this basic where, who, and when information fails. It turns out that the best procedural rules I know for organizing knowledge uses mind maps that you make for yourselves. Mind maps let us see our organization, practice it, and develop fluent recall. Just as it takes repeated practice recall to develop fluent recall of chunks, it takes repeated practice to develop fluent recall of useful organization.

A definition for learning

I keep talking about learning, but I haven’t yet told you what I mean by learning. A definition for learning used by biologists is a change in behavior due to experience. For us humans, that’s not a very useful chunk. Learning would include almost anything you do that creates some form of memory. The definition is correct, but is too vague. We need a better Fish-version of the concept of learning as part of education. I think of as learning as two things:

1. New or more fluent memory with understanding of chunks or sets of procedural rules (procedural rules are the steps used to do something such as riding a bicycle, open a sugar jar, or solve a long division problem in math).
2. New or more fluent connections between chunks or procedural rules. Some of the new connections are more fluent application of chunks and procedural rules to solve problems.

Learning is more chunks and more connections. This is a simple chunk, but it is a useful one to have in your head. It doesn’t cover all kinds of learning, but it covers a lot. Later, we’ll add other connections and chunks to the concept of learning.

What to learn?

Is all knowledge equal, and is all learning equally good? No. Most of what you could learn is a waste of time. Memorizing a telephone book. Learning the rulers of every country in the world in the year 1899. Many words are important, but many uncommon words are not. If you are reading this book, then most of the 10,000 most common printed words in English are useful and important. If you had to choose the most important of these 10,000 words to know for this book, the words and phrases teach, memory, learning, connections, organization, and fluent recall would surely be near the top of your list.
Because we can only build new chunks out of old chunks, the most important things to learn and practice are the necessary chunks we will need in order to build new knowledge (build new chunks). If we are missing those necessary chunks, we cannot learn anything new with understanding.

Finding and learning a missing chunk

Look again at Figure 3.3, and think about what happens if we are missing a chunk or a connection between two chunks. If we are missing a chunk that is necessary for a new concept, we cannot learn the new chunk correctly. That happens all the time, to all of us. What causes missing chunks? It might be that in the past we mastered that chunk with fluent recall or recognition memory, but we no longer recall or recognize it. It might be that we never learned it. It might even be that we have it in fluent recall, but without understanding.

I can give you an example. After I had completed graduate school for my Ph.D. degree on the tropical ecology of bats, I wanted to change what I studied. I wanted to learn neuroscience—how the brain and nerves work. Learning completely new subjects is hard to do alone. Having a teacher explain things to me in a logical order is much easier than learning by myself. I signed up for a class on neuroscience. In the first week, I understood almost nothing. I was lost, confused and failing. We had hardly even started! My decision to study neuroscience felt like a bad mistake. Fortunately, there were no quizzes or exams yet, and no one else noticed my confusion. By then in my life, I knew what to do, because I had a lot of practice with being lost, confused, and failing.

Good learning always includes many, many chances to be lost, confused, and failing. Those are not pleasant feelings, but they are normal. In high school and often in much of college, classes and books are designed to help fix that. Students in graduate school and often in college don’t receive much help. If you feel lost and confused, but you don’t do anything about it, then you flunk out and you go on to do something else that you like better (we hope). Some high school students, more college students, and nearly all Ph.D. students learn how to learn when they are completely lost. They discover how to stop being lost, confused, and failing. A key is to discover missing chunks.

In my neuroscience class, I started looking for missing chunks. While I had no clue how to understand my neuroscience class, I knew exactly how to discover and learn missing chunks. My procedural rules to discover and learn missing chunks were simple. I started by making a list of terms that the professors used often but did not explain. Then I worked on learning those terms, going for fluent recall with understanding. There were about ten terms that professors used all the time, over and over in each lecture, and another ten or twenty that they used often. The first set of ten included “sodium,” “Na,” “potassium,” “K,” “sodium current,” “voltage gated channel,” and “action potential.” I had recognition memory for all of these words on my first list, and I could have defined any of them. What I didn’t have was fluent recall with connections. My second list of words had completely new chunks. There were phrases like “voltage clamp” that I had never seen before. Guessing wasn’t helpful. I had fluent recall with understanding for both “voltage” and “clamp.” My Fish-version of a voltage clamp was a huge pair of pliers with a car battery attached. It was completely wrong, with the wrong connections.

Why did I make my lists? Terms used over and over without any explanation are usually the background chunks are necessary for understanding new chunks. Teachers or authors expect that you already know them. If you can’t picture the concept for that term, and if your
recall doesn’t come quickly—fluent or automatic recall with understanding—you get lost and confused. In my neuroscience class, the instructors talked often about the elements sodium and potassium. They also used letters for these elements: Na for sodium and K for potassium. However, I couldn’t remember quickly which was which (“Is sodium Na or is sodium K??!!”).

Over a weekend, I made little sketches and practiced and drilled myself on my list of terms, several times each day. I looked at each word (or read it aloud) and practiced being able to picture in my head a simple image of what the word actually was. Sometimes I redrew the sketch, especially if I couldn’t picture it easily. I practiced looking at the simple sketches and trying to fluently think of all the connected terms used in a description the sketch. I drew a map on paper with all the terms and practiced recalling the connections between them. Once I had my list of terms and images, all of this took less than an hour a day. It worked. By Monday, I had fluent recall with understanding of all of those chunks.

As it turned out, that short list was all I needed to begin understanding most of the lectures. With a few more weeks of drilling those and some additional chunks, I developed fluent recall with understanding and connections organized well of the most important background information. I kept up by practicing the essential chunks and developing fluent recall with understanding, connections, and organization of the most common new terms.

### Box 3.1

**A Term for “Fluent recall with understanding, connections, and organization”**

I want a word for this chunk, “fluent recall with understanding, connections, and organization.” It helps to have a word for new chunks, especially since I am going to be writing it over and over again. I’m going to use *fruco*, from the first letter of the five key words of the phrase: fluent, recall, understanding, connections, organization, or F-R-U-C-O. Practice a few times: close your eyes, and ask yourself, “what does *fruco* mean”?

I’m also having you think about an important part of your learning: that sometimes invented terms for chunks are very useful. Experts in anything invent new words and phrases all the time. Laser, radar, and scuba were all invented in the same way we just invented fruco, as the first letters in a phrase of five words. People use the words if they save time or help us remember a new concept, even the word may not be useful with anyone else. My students sometimes invent acronyms in the same way to help remember something, or as a shorthand when they write notes in class. Earlier, I invented the word *subig*, which is useless. It might be that *fruco* for fluent recall with understanding, connections, and organization is also useless. I think that *fruco* will save us time, because it will make my sentences easier to read. It is only going to be really useful, though, if it helps you remember the concept. For the rest of this chapter, I’ll use *FRUCO* most of the time, but occasionally use the whole phrase. You can decide what works for you.

Failing to have *FRUCO* for essential chunks is a serious problem. My college students often won’t believe that their problem in learning might actually be this simple. Even just one missing chunk or connection can prevent learning. I find it incredibly frustrating when a student tells me, “I already know that” about something essential, when, really, they only have recognition memory or effortful recall plus understanding. That’s not enough for an essential
chunk. Every year, I see college students wasting time memorizing new chunks they cannot understand. They’ll spend hours and days on new chunks, but not look for and practice FRUCO for their essential chunks. They drop points and grades. In my neuroscience class, finding and practicing necessary chunks allowed me to learn and understand neuroscience. It allowed me to change failure into success. Developing FRUCO takes time and practice, but it always works.

Discovering essential, missing chunks

You want to become good at discovering essential chunks, especially if they are completely missing. They might be missing because the teacher or book did not notice that they did not provide the missing chunk. Or, perhaps they provided the chunk, but you forgot it. Usually, my students who are not getting good grades stop studying a chunk once they understand it and have good recognition memory recall. The reason a chunk is missing or is not in FRUCO doesn’t really matter. What matters is that you notice and that you discover and practice the chunk.

A lot of research shows us that the more a person knows, the faster he or she learns new chunks and connections. Some new chunks and connections are impossible for you (or me) to chunk and understand right now. Those can become very easy later. Easy learning happens with FRUCO of the essential background chunks. People who have learned to discover and correct their own misconceptions, to replace incorrect chunks, and to improve Fish-understandings, can learn much faster than those who have not.

It is your teacher’s job to present all of the information needed for a new concept in a class. However, we teachers cannot control what you learn and then forget. We cannot control the connections you never make or don’t practice! It is your job to discover what might be missing, and then FRUCO it. (I am taking such license with creating words that I am now turning FRUCO into a verb.)

Thinking about your missing chunks: the chunk for metacognition

Thinking about your missing chunks and whether you have FRUCO are parts of metacognition. Metacognition is thinking about your own thinking and learning. Figure 3.5 shows me thinking about how well I am learning in a lecture: asking myself why I don’t have fluent recall with understanding, connections, and organization for the commutative principle.
Figure 3.5. A person (me) thinking about whether I understand why division is non-commutative with *FRUCO*. I am doing metacognition—thinking about my thinking.

Learning how to use metacognition is an important part of making learning better, faster, and easier. I could have wasted a huge amount of time in my entire neuroscience class if I had not thought about what I was missing, discovered those missing chunks, and drilled and practiced until I had *FRUCO*. It wasn’t enough just to drill the missing chunks. I also had to use metacognition in order to know when I had fluent recall of each chunk with connections and organization and to know when I understood the chunk well enough for the class. I also had to use metacognition to decide which chunks were essential and which were unimportant for *FRUCO*. There were hundreds or thousands of chunks to choose from, but few were truly important.

We’ll develop a better concept of metacognition later, but you need the chunk in Figure 3.5 first, along with the following two questions to ask yourself over and over:

1. What chunks am I missing that are essential? (often, this becomes the question: *What words does the professor and/or textbook often use that I do not understand, picture, and recall fluently?*)
2. How do I know that I understand this chunk deeply enough? (*Or is my Fish-version good enough for now?*)

Figure 3.6 gives you a Fish-example of the process. I am imagining something that might not make sense to me as a learner. I am thinking, *I’ve been told the Earth is a sphere. People don’t fall off the sides and the bottom. WHY NOT?! I’m lost and confused. What am I missing?* Everything I know tells me that a person should fall off of the sides and bottom of the Earth, as in the left side of Figure 3.6. *I’m missing some necessary chunk.* My professor and the textbooks keep using the word “gravity.” They obviously think gravity is important. Gravity, I think, means down, though the text uses other words, like “center of mass.”

Figure 3.6 Why don’t people fall off of the Earth? A child can be told and can memorize the fact that people do not fall off, but until they understand the concept of gravity, they will not understand the memorized answer. Without the concept of gravity, they can have fluent recall, but not understanding. The lack of understanding makes it hard to gain correct connections and organization.
I memorized the definition, but I cannot remember it easily (no fluent recall), and I cannot picture what it means. So, I'll work on fluent recall with understanding of gravity, mass, attraction, proportional to mass. I develop an image in my head and a simple sketch, showing masses of molecules being attracted to each other and moving toward each other. I make the attraction “proportional to their mass.” I have a sketch showing molecules in a large mass, such as the Earth, that pull strongly on a nearby small mass of molecules, such as a human. Therefore, the large mass will pull the human towards it. Specifically, a large mass of molecules will pull a group of molecules toward its center. That makes sense. With this new chunk in fluent recall with understanding, I always know right away why the Earth is a sphere, and why even when I break off some dirt and throw it in the air, it falls back to the Earth, and why when I jump, I always fall toward the center of the Earth.

Now I know that I know why people don’t fall off the bottom of the Earth. My new image is the one on the right of Figure 3.6. There is no bottom of the Earth (or sides), because everyone is pulled toward the center of a large mass. On Earth, down is always toward the center of the Earth. People cannot fall off. I don’t have to memorize that people don’t fall off of the Earth. I just need fluent recall with understanding that gravity is masses of molecules attracting each other, and therefore gravity is always pulling anything toward a center of mass. Now I can predict which way anything will fall.

That process of asking questions about how you are learning or what is keeping you from learning is metacognition: thinking about your own thinking. Any questions about your own learning are metacognition. You are applying metacognition when you ask yourself why you understand gravity but not electricity or airplane flight. You are applying metacognition when you ask yourself what is in your working memory when you solve $11 \times 11 = ___$ or whether you have fluent recall with understanding, connections, and organization of the different parts of an animal cell. Learning to apply metacognition with questions like these will help you identify missing chunks and correct errors in chunks. Metacognition saves you time by helping you to learn better.

**Rearranging old knowledge to fit new chunks**

We begin learning new chunks early. Most children are curious and ask questions all the time, which is how they discover and correct their misconceptions. For example, children learn that the Earth is spinning: rotating—and rotating fast—at 1000 miles/hr on the surface (at least on the equator; on the North or South Pole, it’s just a 24 hour turn in place, and at my desk in Virginia, I’m moving at 800 miles/hr). Children expect, very reasonably, that we should feel a wind of 800 or 1000 miles per hour outdoors as we rotate on the surface. They might expect, very reasonably, to find that the Earth spins away beneath them (even just a little) if they jump up in the air. They might decide, again very reasonably, that the Earth’s rotation is why the clouds move. As they begin to learn facts that conflict with these misconceptions, they question their understanding.

The early expectations are chunks that are wrong, and we have to unlearn them so we can learn the right chunks. We have to adjust (or even forget) any misleading chunk before learning the new concept. In my example in Figure 3.3, a child has to adjust (or forget) their chunk that down is always the same direction before it is possible to learn with understanding that people cannot fall off of the Earth. Because it takes time to develop fluent recall, and because it takes many hundreds or thousands of practices to develop automatic recall that lasts
years or decades, we can adjust the wrong chunks and misconceptions. That is important for
learning. Don’t ever wish for an instant memory, unless you want to struggle forever with all the
wrong things you cannot forget.

Often our Fish-versions of earlier concepts get in the way of new chunks. For example,
there is a common problem in learning fractions and negative numbers. The problem happens
because students have a misleading Fish-version for the concept of larger versus smaller
numbers. The Fish-version is a rule about deciding whether one number is larger than another.
Here’s the rule: a number with 8 in the highest place (one’s place, ten’s place, and so on) will be
greater than a number with 4 in that same place. In other words, 8 is greater than 4, 84 is
greater than 48, and 822 is greater than 499. Problems arise when we extend this Fish-version
to negative numbers. Negative 80 is less than negative 40. The rule we used for positive
numbers is wrong for negative ones. There’s a related problem for fractions, because \( \frac{1}{8} \) is
less than \( \frac{1}{4} \). In this case, it isn’t that the old knowledge is wrong, because 8 is larger than 4,
and 822 is larger than 499. The problem is that the Fish-version of the concept gets in the way
as we learn fractions and negative numbers.

To understand the concept of greater and lesser in these contexts, a child has to learn
two new concepts: the concept of negative and the concept of fractions. Instead of focusing only
on the value of the digits (eight versus four), they have to think about something completely
new. For negative numbers, they have to develop recall with understanding of the new concept
that a minus sign in front of a number means less than zero. The value of the number tells us
how much less than zero.

For fractions, they have to learn to think of a fraction as a single object (or number) and
to separate it into a number of pieces of equal size, and then counting how many pieces of the
object we have. Figure 3.7 shows some ways a child might chunk these concepts correctly. To
determine which of two numbers is larger, a child might develop fluent recall with understanding
of sequences from lesser to greater that include negative numbers, zero, and positive numbers.
A child’s mental image might be like the top of Figure 3.7. Fluent recall of this chunk would tell a
child that negative numbers are less than zero, that negative numbers are always less than
positive numbers, and that negative 8 is less than negative 4. For fractions, a child might
develop fluent recall with understanding using the pie diagrams teachers sometimes use to
teach fractions. I’ve included a pie diagram for fractions in Figure 3.7.

![Figure 3.7](image)

Figure 3.7 A sequence of numbers goes from negative, through zero, to positive. The sequence
helps a child understand that a negative 8 is less than negative seven. Pie diagrams help some
children understand fractions (although they didn't for me).

For some learners, a slightly different mental image of negative numbers might be
better. For example, if we have a mental image in our head with a list of negative to positive
numbers from bottom to top instead of left to right, then negative numbers would correctly be lower than positive numbers. I’ve shown that on the left side of Figure 3.8.

Often, an individual student understands a particular set of chunks with fluent recall more easily. For me, this was true for understanding the concept of fractions. I remember being puzzled by the pie diagram concept of a fraction. Finally, a teacher told me to draw a big numeral 1 and cut it up with scissors. She showed me that when I cut a number 1 in pieces, a $\frac{1}{8}$th piece is smaller than a $\frac{1}{4}$th piece, which is smaller than a $\frac{1}{2}$ piece, as I have sketched on the left in Figure 3.8. I had difficulty holding pie diagrams of fractions in my head as a useful chunk. With much less practice I could easily cut up the number 1 in my imagination. I replaced a chunk for the concept of fractions that didn’t work for me—pie diagrams—with a chunk that did work for me—cutting up the number 1. (I still don’t like pie diagrams, unless I’m slicing pies.)

![Figure 3.8](image)

Figure 3.8. On the left, there is a simpler sequence of numbers from negative, through zero, to positive. A number that is on top of another number is also bigger than the other number. Seeing a sequence in this different way might help some students develop useful chunks. On the right is the method a teacher gave me to chunk the concept of $\frac{1}{2}$, $\frac{1}{4}$, and $\frac{1}{8}$ in order to understand fractions. This chunk worked for me, though I’m not sure it would work for others.

Children learn to modify their Fish-versions. In my example, children eventually modify their understanding of greater and lesser numbers by understanding with fluent recall three different contexts: positive numbers ($8$ is always greater than $4$), negative numbers ($-8$ is always less than $-4$), and fractions ($\frac{1}{8}$ is always less than $\frac{1}{4}$). Later, as they develop even more connections, including the connection between fractions and decimals, they come to realize that all three of these chunks are really part of the same concept—the value of numbers, fractions in decimal form, and negative numbers, all in relation to zero.

The sooner you, as a learner, recognize any incorrect chunks and inadequate Fish-versions of concepts, the faster you can learn more effective new chunks and start forgetting the old chunks. It is not possible for humans to learn everything correctly and completely all at once. You can only build your understanding of new concepts from the chunks that you already have in your mind. We always start with Fish-versions. Even our new, complex chunks are usually Fish-versions for an even more complex chunk.
What you do not remember, you cannot use.

Why do we need fluent recall and FRUCO when so much is available instantly on computers or smartphones? Why isn’t it enough to have information in a book, a computer, or a smartphone? The problem is that what you do not remember, you cannot use as a single chunk in working memory.

The activity of searching for the information takes space in working memory. Once you find what you need, you can hold it in working memory, but you’ve lost other things that were in working memory while you were looking. If you don’t have fluent recall, you cannot hold it as well, and it takes more space in working memory. We all wish that understanding and recognition memory (or effortful recall) of some new chunk will be enough. Unfortunately, that is only true if you never need to use that new chunk in a problem that uses most of your working memory.

I require that my college students remember (fluent recall with understanding) many facts or concepts that I believe are essential. I sometimes hear them say, “But I understand it perfectly. Any part I forget I could look up in a book or on the web.” I admit that I said the same thing to my college teachers. The statement is true, but so what? If you cannot remember something, you cannot use it to solve a complex problem or understand something more complex. If you are on the wrong path without a map and being followed by a tiger, it helps not at all to know that you could look up the direction to safety. If you don’t have information in memory, you’re tiger food.

You need fluent recall of many facts, principles, or procedural rules so you can build more complex concepts out of the chunks you have. If you cannot recall a necessary chunk, you cannot build a new chunk out of it. You cannot build new chunks out of things you have to look up. When I was confused because I could not remember whether sodium was element Na or element K, it did not help to know that I could look it up in an instant on the web or in a book. To use these concepts, I had to drill “Sodium = Na” until it was automatic. I needed fluent recall of those chunks in order to develop the new chunks for how nerves work.

In the real world we often need to apply information without any chance to look it up. Imagine you are bleeding to death at the scene of an accident. It would be easy to stop the bleeding, if the person nearby knew what to do. Would it help to know that the person could look up all the steps to save you on your phone in a few minutes, spend 5 more minutes reading them, and then try to hold the steps in working memory as they try to save you? (Oops—they got those two in the wrong order!)? No. Of course, you won’t need to remember essential chunks fluently if in your career you will always have the time to look anything up, no matter how complicated it is. I can’t think of a job where that is true.

Learning is easiest with interested, focused practice.

In order to develop FRUCO, you need to think repeatedly about something, and you need to pay focused attention. You do this naturally when you are interested. Events or facts that are really important to us we think about over and over—sports, fashion, games, songs, history, science. In turn, the repeated thinking strengthens memories. Interested, focused practice makes it easier to recall and make new connections to other things. This is a reason why it is much easier to learn things that you care about. That doesn’t make it impossible to
develop FRUCO for things you hate to think about. It just means that it's going to take much, much more work and time. If you can find ways to become interested, learning is easier.

Most of us can make effective choices of what to practice and how often to practice. We can use metacognition to improve the ways we practice. With practice, most students improve their focus. Students can search for ways to be interested, and students can learn ways to avoid distractions. When I watch my daughter studying with the television on, I know that she is learning more poorly because the studying is not interesting enough to her. The television is helping to keep her interested enough to study, but every moment that she pays attention to the television is a moment that she is not strengthening memory pathways with new knowledge. (She claims that if she turned off the TV, the studying would be too boring to continue, and that she’ll turn off the TV for the hard or interesting stuff.) I know, and she knows, that she would learn better if she was interested and focused as she studied, with no distractions.

This applies to reading, writing, science, history, mathematics, basketball, football, dance, art, and anything else. If you want to get better and smarter, you need frequent interested, focused practice.

Learning requires increasingly hard challenges.

In order to learn, you need to do more than just practice what you already know. We all need increasingly hard challenges. Why? Imagine that, as you are learning to read, I have you practice the alphabet over and over, an hour each school day for 12 years. I give you new books every week, but only books with no words longer than five letters. Let’s imagine that for several hours each day for ten years you have practiced the alphabet and read your new books each day, but only with words of up to five letters. Would you have become an expert reader? No.

While it is true that chunks you do not practice will gradually fade away and be lost, extra practice you don’t need won’t make you smarter. I could spend hours a day practicing an old chunk, such as \(2 + 2 = 4\), but it won’t make me any smarter! If I want to get smarter, I need to practice my important old chunks and procedural rules only enough to keep fluent recall. If I can tell that I still have FRUCO for a chunk, I don’t need more practice. Instead, to become smarter, I need new challenges—new chunks, connections, and organization. I need new, harder problems to solve using procedural rules and my existing chunks. I need to continue developing fluent recall with understanding of more complex chunks, more connections between chunks, and more procedural rules.

Learning is much faster with good coaching.

Coaches watch what we do, and good coaches can tell when to give us new challenges and when to drill the fundamentals. We need good coaching because it is easy to waste time learning unimportant things, making useless connections, or developing fluent recall for wrong information. Good athletes find and use coaches, but they also learn to coach themselves. They try to notice when they need to drill and when they need to learn and practice something new.
Chapter Three: Knowledge and Learning

My students often work very hard to develop fluent recall of figures and facts that they do not understand. It is common for them to try to memorize information that they copied with mistakes. They may have been coached to check their work and understanding, but they don’t do enough of it. That’s a terrible mistake, and a waste of time, even though it feels to them like learning. A good coach—a teacher, a tutor, or a more advanced student—can help you learn the most important things first, correctly, and in the proper order for good organization. A coach stands apart, watches what you are doing, and suggests small steps to improve. A good coach gives you increasingly difficult challenges. To get better, an athlete accepts the challenges, tries to do them on their own, and remembers and applies the lessons from their coach. To get smarter, we all need to accept increasingly hard challenges, do as much as we can on our own, and remember and apply the lessons from our coach.

Good coaching can come from many places, including teachers, parents, or friends. Sometimes you can even coach yourself, using books or the web. (I hope that this book turns out to give you useful ways to coach yourself.) Unfortunately, bad coaching can also come from teachers, parents, friends, books, or the web. Good coaching is not easy; like anything else, good coaching takes practice. It has taken me many years to become a good coach for anything, and I’m only an expert coach in biology and (I hope) in ways to learn. I would be a poor coach for basketball and a terrible coach in Russian.

In my learning, I have had good coaching more often than bad coaching, but some was bad. In my high school sport, tennis, my coach had never played tennis or paid any attention to tennis before he started coaching our team. After four years of practicing hard at tennis, I was no better than when I started. My tennis coach was a bad coach for tennis, but he was a good coach when I was in his history class. I had terrible coaching in a college computer science class. That professor was fired at the end of the year. Friends who over the years have tried to help me learn something often just made it more confusing, but a few really did coach me well. People without good coaches usually develop slowly their learning and expertise. However, a lot depends on you. If you can apply metacognition and try to learn, you can learn well even without good coaching.

It is possible to receive good coaching and then turn the good into bad coaching. If a coach shows you good methods, but you practice your same old bad methods to dribble a ball, shoot at a goal, or study biology, then you’ve turned good coaching into bad coaching. If you fail to practice a necessary chunk to keep FRUCO, and a teacher thinks that you have it, then you will turn the good coaching they offer to build more complex chunks into bad coaching. My failure to improve at tennis might have been my own fault.

Part of your task as a student is to learn how to make your coaches be as good as they can be for you. You can develop metacognition skills to know when you need to practice your old chunks (the important ones) and old procedural rules (also the important ones) and when you are ready for and need new challenges. You can try to understand which of your coaches are good coaches (and for what things). You can try to find extra coaching from people, web sites, or books when you need it.

Checking and correcting your understanding

Your understanding will often be wrong or only partly correct, like a Fish-understanding. It is important to check your understanding. Some things you learn will be wrong for two reasons. First, you may have understood it incorrectly. Second, the book and teacher (and
maybe even everyone else in the room) may believe something that is not correct. The second is less common, but it happens.

As you learn, it is important to check facts, concepts, and procedural rules against what you already know. If I told you in class, “Today I want you to memorize that the sky is really green, even though it might look blue,” you should check to make sure this is sensible to learn. In your learning, you should be asking, “Well, yes, this is what I think I should learn, but what is the evidence that I am learning correctly?”

When I work with my college students, I frequently check their study materials and discover that some are wrong. They might be learning about DNA (genetic material), but trying to memorize facts that are only true for proteins or are just plain wrong. These students are not just studying a Fish-version for a concept (that would be okay, if they are just starting out). They have misinterpreted or wrongly described something, and they have not checked their work. The undesirable result is that they work very hard to develop fluent recall with wrong understanding of that concept. This leaves them worse off. They wasted time to learn something false, and they then need to remove those memories in order to progress further. Working hard without metacognition has made them less smart!

Studying incorrect things or useless things often feels to my students like useful learning, but it is not. In fact, sometimes they want me to give them credit towards a grade because they tried hard. I am often sympathetic. I’m glad they worked hard. However, I don’t give credit for wasted time learning wrong things that made them dumber instead of smarter. I know exactly how they feel, because something similar often happens to me. As a neuroendocrine scientist, I collect experimental data or read about other people’s experiments. I try to learn the conclusions as fluent recall with understanding with connections and organization. I often study and practice to make these into fluent new chunks. However, sometimes an experiment has a mistake, or sometimes it was misinterpreted. Often, what I think and learn first turns out to be wrong. That doesn’t make me smarter, and that doesn’t deserve any credit. It is my fault if I don’t check often, and it is my fault if I waste my time.

We cannot avoid this problem. Even my very best students, as well as my most brilliant fellow-scientists, learn some things that are wrong. They actually work hard to learn these wrong things. The important point is this: a good scientist and a good learner constantly check their facts. “Well yes, this is what I think now, but what is the evidence that it is correct?” “Does it fit with everything else I think I know?” An example from the gravity example would be a child wondering about a helium balloon floating up. Gravity should attract any two objects, so balloons shouldn’t float up. Does that mean that down isn’t always the same direction? Metacognition would direct the child to discover the new chunks. You should check what you are learning to make sure it is accurate enough. As beginners, we always learn like Fish, but we can check with a teacher or a book (or with Frog) to make sure that our concepts are as close to reality as possible.

You cannot escape learning some things that turn out to be wrong. You can check what you learn to make it as accurate as possible.

The new chunks of knowledge and learning

The new chunks you need to develop as FRUCO are:
Chapter Three: Knowledge and Learning

1. You can only make new chunks from old chunks for which you already have fluent recall with understanding. What you do not recall cannot become part of a new chunk.
2. Chunks that are missing or not in FRUCO will prevent learning. Find and learn them.
3. Tubig versus subig. Useful knowledge has useful connections.
4. Useful knowledge is organized. Unorganized knowledge doesn’t make you smarter.
5. Learning is having more chunks in FRUCO.
6. FRUCO: Fluent Recall with Understanding, Connections, and Organization
7. Metacognition is thinking about your own thinking and learning. Metacognition can help you learn faster and better.
8. What you do not remember isn’t part of your knowledge. If you have to look up a chunk, you can use it only slowly with effort and wasted space in working memory. If you have to look it up, it cannot become part of a new chunk, and you aren’t smarter.
9. FRUCO takes interested, focused practice.
10. Learning requires increasingly hard challenges.
11. Learning is much faster with good coaching.
12. Use metacognition to check what you think you know and what you need to know.
Chapter Four: Experts, Expertise, and Learning

Chapter Four

Experts, Expertise, and Learning

Have you ever been told that you can do anything you want to do? It’s not true. Wanting is not enough. I wanted to be a scientist, but that only got me to the starting point. To become a scientist, I had to become an expert. Becoming an expert is a long hard task. It requires (1) deep interest, (2) focused study and practice, (3) good coaching, (4) steadily increasing challenges, (5) for ten years, (6) spending an average of four hours each day. With those six ingredients, anyone can become an expert in anything: science, law, writing, medicine, business, or art. If you don’t become an expert, then you are missing one or more of the six ingredients.

What is an expert?

A Fish-definition of an expert is someone who has put in at least ten years, averaging four hours a day of focused, interested study and practice, with good coaching and increasing challenges, on a specific subject or skill. We’ll analyze this Fish-definition in detail, for a very practical reason. In this chapter, I expect to convince you that you already are an expert in at least one thing. If I am correct, then your expertise means you know a way to become an expert in anything else that interests you enough.

Does a person have to be unusually smart or brilliant to become an expert? No. Ten years of interested, focused study and practice for hours a day with good coaching and increasing challenges seems to make an expert out of anyone. It is worth repeating all the pieces you need: (1) being interested, (2) focused study and practice, (3) good coaching, (4) steadily increasing challenges, (5) for ten years, (6) building over time to several hours per day.

If you can read and understand this book, you can become an expert in science or medicine and many other things. Hard work alone is necessary, but not enough. It has to be the right kind of hard work. Interest is necessary, but not nearly enough. Good coaching is necessary, but not sufficient. Studying the wrong things, in bad ways, and without focus prevents expertise. It requires hard work for a long time and time away from things that may be easier and more fun. You might choose not to develop expertise.

Why, then, am I so sure that you can become an expert in something important to you? Because you probably already are an expert in something that is very difficult. (Might you give examples? Video games, Magic, playing an instrument?) Most people started spending just 20 or 30 minutes a day on difficult study and practice. By the end of ten years, though, they are often doing six or more hours of practice a day. Nearly all humans who do the interested, focused time become this kind of expert. My example, which I present below, is arguably as hard as becoming an expert scientist, medical doctor, teacher, or businessperson. However, so many people are interested in and focused on a subject, work hard, and get good coaching and steadily increasing their challenges, that nearly all become experts in that subject.

Before I get to that example, I need to provide more chunks. Expertise (being an
expert) in a subject means FRUCO\(^1\) for a lot of chunks (10,000 – 50,000) plus being able to solve many different kinds of problems fast in that subject. Being smart means being able to answer many different questions and solve many different problems in the area of expertise. Brilliance means being able to come up with ideas and concepts and to solve problems that almost no one else would be able to do, even experts in the same field. In their field, experts are always smart, though only a few are brilliant. I’m not brilliant, but that’s okay; I’m thrilled just to be an expert.

**How much does an expert know?**

Experts on anything seem to have developed fluent recall with understanding, connections, and organization of 10,000-50,000 chunks in their area of expertise. Many thousands are "complex" chunks built from combinations of simpler chunks. A heart specialist’s (cardiologist’s) 3D image of a heart is built from layers of simpler shapes and concepts. A cardiologist does not just memorize each chunk but connects it with many other chunks in logical, correct ways. The cardiologist then organizes chunks and connections so that the connections adjust automatically to circumstances. The organization of connections for a young patient differs from that for an old patient, differs from that for a pregnant patient or an obese one. Finally, experts connect their chunks to many hundreds or thousands of procedural rules for problem solving. A heart specialist has many procedural rules for ordering medical tests, fixing a damaged blood vessel, or repairing a scarred heart valve.

Experts practice using their connections, organization, and procedural rules hundreds or thousands of times in many different conditions. They practice these problem so many times that their procedural rules for problem solving become FRUCO. An expert solves ordinary problems quickly, because he has practiced them so often. An expert reasons easily through complex problems because he has practiced so often. When an expert gets a completely new problem in a form that he has never seen before, an expert has a good chance of solving it if a solution is possible.

**How long does it take to know 10,000 chunks plus many sets of procedural rules?**

Research on experts suggests that they have had 20,000 - 50,000 hours of study and practice by the time they become an expert. However, they have not spent ALL of that time improving their expertise. For example, as I was becoming an expert scientist, I spent many hundreds of hours counting things—seeds, chromosomes, cells in the brain, grains of pollen, bone fragments, behaviors, sounds from recordings, and many other things. I spent hundreds of hours making chemical solutions. Some of it was work for pay that was not developing my expertise. Counting seeds in my 1000\(^{th}\) tray, the 1000\(^{th}\) bone fragment from wildcat feces, and neurons in my 1000\(^{th}\) brain slice was not developing my expertise. (I can clear my end of a restaurant just by describing how I’ve counted 10,000 sperm.)

How long did it take me to become an expert? It took me about 10 years, working an average of 6-12 hours on a typical day, including many weekend days, to become an expert in my first area of science—tropical ecology. That was probably around 30,000 hours in total. As a reasonable guess, I spent only about 10,000 of my hours in interested, focused study and practice with good coaching and increasing challenges. It’s hard to believe I wrote “only” in front

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* fluent recall with understanding, connections, and organization

† I made up the term “procedural rules” because I wanted a phrase that explains itself.
of the 10,000 hours. It was a huge amount of time and work, and it is the hardest thing I have ever done. It was hard because every day involved concepts and procedures that were hard, confusing, and challenging. I made mistakes every day, and I had to find the reasons and then relearn and practice. Often I didn’t believe I could do it. I needed a lot of FRUCO.

The Fish-estimate on expertise was true for me—about 10,000 hours. Imagine that you are like me, and let’s do some calculations. You start lightly in your 1st year, because most people do. In the 1st year, you manage 1 hour/day x 300 days = 300 hours of interested, focused study and practice. (You think, at this rate, I’ll never get there!) In your 2nd year, you do 2 hours/day x 300 days = 600 hours (hardly better!). By your 3rd year, you are doing 4 hours/day x 300 days = 1200 hours (this would be typical of a serious 3rd-year college student doing study and practice in their major). As you continue seven more years with 4 hours/day, you add another 8400 hours (7 years x 1200 hours/year = 8400 hours). Added up: 300 + 600 + 1200 + 8400 = 10,500 hours. Is that enough hours for expertise? The Fish-answer is yes.

Ordinary or genius, it still takes about 10 years of interested, focused study and practice.

Even a genius takes about ten years to develop expertise. Even the best can’t do it much faster. Two of the best, Amadeus Mozart (genius in composing music) and Bobby Fisher (a world champion in chess) were experts in their mid-teens. They started daily hours of interested, intensely focused study and practice with good coaching and increasing challenges when very young, but they still needed at least eight years from when they started until they were truly experts. They both did focused study and practice for many more hours per day, and they managed to accumulate their expertise in eight years instead of ten. However, when you read about how they mastered their subjects, it seems they probably spent much more than 10,000 hours. Everyone has to do the work.

Does a “good” memory help a person become an expert faster?

I used to think that a good memory—a memory that learns and remembers very quickly—would help expertise develop faster. However, I cannot tell you for certain that it does. Research on experts suggests they perform about the same on tests of memory as non-experts. My working memory and other kinds of memory are very ordinary in memory tests. (I have a great memory for many areas of biology, but I have an ordinary memory for politics, and I can only remember four birthdays [one is mine]. I once forgot my older sister’s name [please don’t remind her].) So how do experts remember so much? Experts are interested enough to practice important chunks and procedural rules many, many times in many different contexts. My guess is that experts think about (practice) a thousand times for every important chunk. That’s a guess, because I cannot find research that suggests a number. I have tried to estimate the number of times I’ve thought about the automatic chunks in my own area of expertise, and it does come out to around a thousand. Things that I’ve recalled only a few hundred times I still forget, if I don’t review (practice) the memory for a few months. What is true for me may not be true for others. I’m sure people have differences, but I suspect I’m not that different from most people.

What about a bad memory? Does a bad memory make it impossible to become an expert? If a bad memory means a person has trouble remembering things, then a bad memory might just be lack of interest and practice. I have friends and family who seem to have bad memories because they cannot remember basic things in science, history, art, or literature.
However, they can be incredibly good at remembering fashion, sports, information about their hobby, or movies. Does that mean they have bad memories? Perhaps the good side of their memory reveals what they find interesting enough to practice. Some of them want to remember science, history, art or literature, often for grades. Sadly, wanting is not enough. You have to care, and you cannot fool yourself. You may want to be a doctor, an officer, a lawyer, a politician, or a mathematician, but you won’t remember enough to become an expert unless you care enough for interested, focused study and practice on many days spread over many years.

It is not enough to just care about a class for another reason. You may want and need a good grade in order to become a doctor, but that won’t make you care about the subject. I have students who are wonderful human beings but do not care, in their heart, about biology or chemistry. They struggle in those courses. To learn well, you have to be genuinely interested and fascinated. Interest and excitement are known to help make memory traces stronger. However, it might be that interest and excitement makes you review and practice the memory, over and over again, just because it’s so interesting to you. If you like thinking about something, you'll recall it more often and enjoy it each time. If you’re so interested in fashion that you think about it all the time, you’ll develop FRUCO for fashion. If you’re obsessed with sports, it’ll be sports. Whatever it is that you think about all the time, perhaps games, music, government, or medicine, that’s what will be easiest to learn. High interest produces your best memory.

Is it possible to develop high interest, even in a subject that wasn’t originally interesting to you? Sometimes. Many of my students who originally dislike a subject become more interested as they put time and practice into learning with FRUCO. For example, a former student of mine who originally hated statistics became fascinated as she began learning more about it. She's now a statistician. There's no guarantee that familiarity breeds interest, though. Sometimes, the more you know, the more you hate it.

**TEN YEARS!!!! No way!**

You may be saying (or thinking), *ten years is too long!* I’ll never want to practice anything that often and for that long. If you think that, you’re wrong. Truly. I know, because you have already developed expertise. If you can read and understand this book, you are already an expert or are approaching expert status. You have put in about ten years of interested, focused study and practice, with good coaching and increasing challenges. It was often hard for you. Even though it has been very hard mental work, you probably enjoyed a lot of it. So what is this area in which you are an expert or approaching expertise? You are an expert or near-expert in reading. Reading.

**Expertise in reading**

I may need to convince you, first, that skilled reading is expertise, and second that expertise in reading is expertise just as skill in medicine, science, teaching, law, or business is expertise. I hope that I can convince you completely. Why? Because if you remember and understand the things you have done to become an expert reader (or a near-expert reader), that can help you become an expert in other things.

First, we need a Fish-version definition of what I mean by expert reading. As a Fish-version, an expert reader is a person who can read this textbook easily and quickly, interpreting automatically or fluently almost all of the words and phrases I use. This level of skill as a reader
probably requires ten years of interested, focused study and practice with good coaching and increasing challenges. If this book is hard work for you, and if you find it exhausting and slow to read, then you’re probably a near expert rather than an expert. Below, we’ll go through evidence that you have (or are approaching) expert status in reading.

You have more than 10,000 chunks for written words.

Children can begin as novice readers as early as age four. However, learning to read may start at any time from before first grade into adulthood. When any reader begins, even as a child, he or she already knows how to speak and understand many words and sentences. No matter how much English he or she can speak, however, a genuine pre-reader does not yet recognize the letters of the English alphabet. If someone already recognizes the letters of the alphabet, then she has already begun learning to read. As a pre-reader, you began by developing 26 chunks, one for each printed capital letter of the English alphabet. Actually, each of those 26 chunks began as combinations of simpler chunks. For each letter, you needed one chunk for each line, curve, and connection of the lines in that letter. For a pre-reader, even a single letter takes effort to hold in working memory.

After two or three years of study and practice, you had fluent or automatic recall for many simple printed words. You had learned the ways in which to combine short words into printed sentences. You had learned to tell when written sentences were in a form that was logical or not. By three years of practice, you had automatic recognition and understanding of which of these is wrong:

(a) Jack went up the hill.
(b) The hill went up Jack.
(c) Went hill the up Jack.

One of these is correct. Another is grammatically correct, but you automatically know it is nonsense. The third one is grammatically incorrect and nonsense.

At first, you sometimes had to test sentences for meaning by reading aloud. That’s because at early stages you could understand sentences you heard much more easily than sentences you read silently. By the time you could read and understand simple sentences without speaking aloud, you already knew at least 500 chunks for printed words, including individual syllables, words, and short phrases. Each of these syllables and words was a combination of simpler chunks—individual printed vowels and consonants. You began to develop fluent or automatic recall with understanding for many short phrases. Those were phrases you could read as single chunks, such as green leaf, yellow banana, or blue sky. These phrases had become chunks that are combinations of two or more words. Each word, in turn, was a chunk you made from a combination of letters. Each letter was a chunk that you had learned years before from combinations of straight lines or curves.

You practiced on harder and harder text. In each year, you developed FRUCO for an average of about 1000 new word families. A word family is a group of closely related words, such as “read,” “reader,” “reading,” and “unread.” Another is “cook,” “cooked,” “cooking,” “cooker,” and “uncooked.” Most likely you were gaining around 80 new word families each month, or 20 each week. You were practicing your old word families often each week, and you
were also making new connections with word families. You were organizing your chunks, which is how you know automatically that *Jack went up the hill* is correct and sensible, while *Went hill the up Jack* is both incorrect and nonsensical. If this book feels easy to read, then you’ve probably practiced reading with regular new challenges for about ten years of your life.

Actually, you learned none of these words in just a day or week or even month of studying. Rather, you practiced with each until they were in fluent or automatic recall. You repeated your practice by reading most words many, many times in hundreds of different sentences. Hmm—is that true? Maybe I’m wrong about this. You can check: tell me (or yourself) how many times you have read each of the following words [0, 10, 100, 1000, 10,000 times]: (A) red = ________, (B) hot = ________, (C) basketball = ________, (D) extraneous = ________, (E) gibbous = ________, and (F) metacognition = ________.

You have read the word *red* ten thousand or more times. At the other extreme, you may never have seen the word “gibbous,” which is the shape of the moon when it is more than a half moon but not a full moon. Now go back and mark the words for which you have (a) recognition memory, and then (b) effortful recall, (c) fluent recall, and (d) automatic recall. (It would be automatic recall if you feel that even if you didn’t see the word for 20 years, you would still know it.) The strength of memory you have is probably related closely to how often you have seen the words—how many times you practiced (thought about) that memory in different sentences. For the printed words *red* and *hot*, you have automatic recall. For “basketball,” it is most likely fluent and maybe automatic. For “extraneous,” you may have anything from recognition memory to automatic recall, and the answer is related to how many times you’ve practiced reading the word with interest and focus. With each new printed word you practice, you become slightly more expert. For each word you stop practicing, you gradually forget, and you lose a little expertise.

How about *metacognition*? I first read the word *metacognition* eleven years ago. I read *metacognition* about 20 times on that first day, but I probably thought about what the word meant only a few times. Though I thought the word was useful and wanted to remember it, by the next day, I had forgotten it. A couple of days later, when I read *metacognition* again, I had recognition memory of the word, but only an effortful Fish-version of the meaning. As I write this chapter, I have read the word *metacognition* over 1000 times, and written *metacognition* at least 200 times. At the moment, I have fluent recall but not automatic recall of *metacognition*. If I haven’t read it for a while, I still have to stop and think about the meaning of *metacognition*. When I want to learn new terms and retain them, I need to think about them while reading them many times.

Your chunks include many levels.

I talked before about *levels* of chunks. You had mastered at least five levels of chunks by the time you were reading short sentences (Figure 4.1). The simplest is level 1 in Figure 4.1, the individual lines and connections that together form letters. Level 2 is the alphabet, each letter of which was a combination of specific chunks (lines and connections between lines). Level 3 is short words and syllables, such as cab, car, and red. Level 4 is short phrases. Your 5th and most complex level at that time was short sentences that included at least a subject and verb.
Chapter Four: Experts, Expertise, and Learning

Figure 4.1. Multiple levels of chunks are required for reading. At level 1, you recognize short straight and curved lines that you can combine as parts of shapes. At level 2, you have combined those lines into specific shapes that you recognize as letters or symbols. In level 3, you have learned to combine letters in order into chunks that you recognize as words. In level 4, you have learned to combine words into things that you recognize as a single concept, such as “red car.” At level 5, you recognize groups of words as single concepts or chunks, such as your mother in a red car that she owns.

At the time you were reading short sentences, you were also connecting and organizing your chunks. Some word combinations in some orders formed words, and others did not. You connected and organized some words as subjects, and others as verbs. You connected and organized some as singular, and others as plurals. In each level of Figure 4.1, I have shown one or two examples of the way in which we combine chunks from a lower level to form a chunk at a higher level. You probably easily hold in working memory the printed words Mother has a red car as one or two chunks. (You might want to close your eyes and check. Do you have a single image in your mind for this sentence, or maybe two? I have two, I think, but I need only a single chunk for She has a red car.)

In order to understand how you might develop new areas of expertise, you need to understand the concept of levels of chunks in expert knowledge. A person MUST have FRUCO of every chunk at a lower level in order to build any chunk at a higher level correctly. For example, if you do not have recall for one particular letter, such as the strange new letter I invented for Figure 4.2, you cannot develop fluent recall with understanding for any printed word that has that letter.

Figure 4.2. Imagine that the strange symbol in this figure is a letter that someone never learned. If so, then that symbol is a missing chunk. Without the chunk for the letter, this person could not recognize or understand chunks at any higher level that have the chunk the person never learned. In the example above, three words could not be understood, combinations of two words could not be understood, and the sentence could not be understood.

You might notice that my strange letter in Figure 4.2 uses only three curved lines. All three are curved lines that you already recognize, because they are all in level 1 in Figure 4.1 as
parts of other letters. However, the curved lines are combined in a new way that matches no letter you know at level 2. If my invented letter were a real letter, you would need FRUCO of that letter (is it a vowel? a consonant?) in order to develop fluent recall with understanding of any printed word that contains the letter. If you have FRUCO for lower level chunks today, but do not recall them tomorrow, then you also lose the higher level chunks. It isn't enough just to recognize and understand—you need to recall.

Expert readers have chunked the alphabet as well as approximately 10,000 written word families. They have most of these 10,000 word families as fluent or automatic recall. Some are in effortful recall and a few just in recognition memory. They have fluent recall of many short phrases that combine two or more words. This is true for most high school seniors and beginning college students: they have learned about 10,000 written word families. Some graduating high school seniors are not yet expert readers. Quite a few—maybe a fifth by some estimates—do not even come close to having expertise in reading. If a person is not an expert reader by this stage, and if they do not have a reading disability, it is because he or she has not spent as much time as most students in interested, focused study and practice of reading, with good coaching and steadily increasing challenges in reading. They could certainly catch up, but they need the interested, focused study and practice time with increasing challenges. Once they do catch up, you wouldn’t be able to tell the difference.

Beginning readers have chunked very few words with more than four letters. In contrast, as an expert reader, you know many complex words of 7 to 14 or more letters, such as illumination, information, emotional, and illustration. Expert readers have many, many single chunks for entire phrases, each word of which they have in turn chunked from multiple syllables and letters. An expert reader has a single chunk for common phrases such as glass of water, text messaging, peanut butter, and clothing store. As an expert reader, you have fluent or automatic recall of even more complex printed chunks than two-word and three-word phrases. You probably treat many word sequences as a single chunk. Examples include sayings such as don’t count your chickens before they hatch (meaning that our expectations often do not come true, a concept which usually has nothing to do with chickens), a house divided against itself cannot stand (which has nothing to do with houses), and putting the cart before the horse (which is never is used to describe a real cart and real horse). Your recognition of these written phrases as a single chunk is at level 6 on my Figure 4.1. These represent complicated abstract concepts that expert readers have built out of simpler chunks from all five lower levels.

**Expert readers have good coaching.**

Many people cannot read English expertly even when they have spent enough hours of study and practice to become experts. It’s not because they are too dumb to be expert readers. With time, interest, and good coaching on steadily harder text, almost every single person will become an expert reader. We are all able. However, a student who receives poor coaching or who reads only simple, easy text is unlikely to become an expert reader. Coaching can come from teachers, from books about reading, or from web sites on the development of reading skills. New challenges are a necessary part of developing expertise.

Coaching matters because it provides increasing challenges along with useful concepts or procedural rules. It provides those challenges at the right times and in the right ways. Our coaches motivate us to improve. They give us more difficult problems to solve that they know are JUST within our current ability, but only if we struggle hard. Coaches provide new procedural rules when we need them. For example, expert readers must learn procedural rules
to find meanings for words they do not yet know. Think about the word *infomedigram* in Figure 4.3—a word that I made up a moment ago.

Figure 4.3. Expert readers have procedural rules to predict the meaning of an unfamiliar word.

**Infomedigram** *(Info-medi-gram? In-fom-edi-gram? In-fome-dig-ram?)*

*(Alizia discovered that she had heart damage when she received an infomedigram)*

Figure 4.3

How does an expert reader begin to understand this new word, *infomedigram*? We use procedural rules to find meaning from word segments plus clues from our connections and organization—‘context’ clues. In *infomedigram*, we most likely have chunks for all three word segments *info-*, *medi-*, and –*gram*, including FRUCO for words like information, medicine, and telegram. Other procedural rules allow us to use previous connections and organization in sentences that use a word. The sentence “Alizia discovered that she had heart damage when she received an infomedigram” allows us to use these procedural rules. An expert reader could predict that an *infomedigram* is a message with information on a medical problem. Without coaching, early readers are slower to learn the procedural rules to identify unknown words.

**Expert readers have put in the interested, focused time.**

By the end of high school, most students are at least approaching expertise in reading, but students differ a lot in their expertise. The differences are mostly in the total amount of interested, focused time in study and reading text that is increasingly challenging. The differences can have big effects on students, especially if students think that they cannot change.

Quite a few students tell me “I am just a slow reader,” as if this is a permanent condition. Nearly anyone can get much faster, but only if they push themselves by practice and increasingly challenging reading. A student who believes that “I am just a slow reader” may avoid hard reading and not try to read faster because they believe that practice will not help. If they are wrong (and most of them are), their unwillingness to challenge themselves and to practice only delays their acquiring expertise even longer. It is as if a basketball player tells their coach, “I’m just bad at shooting baskets, so there’s no reason for me to practice shooting.” Any coach would state the obvious, “You need to practice shots more!”

We all start out as slow readers, especially for the most difficult text. While some people can’t become faster for good reasons, I would bet that their slowness results from lack of interested, focused study and practice on increasingly hard text. In high school, I remember disliking reading 19th century British literature. By age 30, I began to love it (some of it), and I began to read it very quickly. When I was 30, reading any neuroscience was hard for me; now I actually enjoy it. My wife finds nineteenth century British literature hard, but she is fascinated with technical articles on fish jaws that I don’t enjoy. My younger daughter reads quickly through rap song lyrics that take me a long time to decipher. We become fast readers in what we practice reading fast.

To improve their learning, students who are not expert readers can practice more, with good coaching. The coaching matters because often improvements will not happen just by
doing more of the same thing. If your problem is that you do not have fluent recall with understanding important words, then just reading more pages won’t help. You need to practice vocabulary in the right ways to develop fluent recall with understanding important words. If your problem is that you do not have automatic application of procedural rules to find logical meanings for unfamiliar words, then more reading won’t help. You need to learn and practice procedural rules for logical meanings of new words. If your problem is that you are slow, then you need to spend practice time pushing yourself to read fast (faster than you find comfortable) with comprehension. More reading at the same old speed won’t make you faster. In contrast, even a little practice trying to read faster might help.

I can predict some things about you as a reader. If you have been ahead of your grade-level (or age-level) for reading as you learned, then you practiced reading for more hours per day or enjoyed reading more than other students. If you have been behind, I would bet that you were practicing less or were less interested in reading than others your age. If you stopped improving, then you were not trying new challenges, such as new words, complex phrases, and faster reading with good understanding. Of course, some things slow down the development of expertise in reading. Problems with vision, dyslexia, and other specific problems with recognizing words or phrases slow down improvements in reading. Whatever it is, understanding the problem and doing the right kinds of practice can bring improvement. If you quit trying to read (or tried to get out of reading) or if you only read easy books below your level that are not challenging, then you stopped gaining expertise.

There don’t seem to be any short cuts. If you do the interested, focused work, with good coaching and increasing challenges, then you become an expert. If you don’t, then you won’t become an expert. It doesn’t take an unusually smart person to become an expert, but it does take hard work. It happens mostly when people enjoy their hard work.

Your 10,000+ chunks have many thousands of connections.

Learning more chunks is not enough for expertise. You also need connections among the chunks. By the time you could read short sentences, you had also developed hundreds of correct connections between pairs of printed words (I went, they went, went up, went back, or went around, but not went number, went written, or went rain). You had also developed dozens of sets of procedural rules for reading and understanding what you read. You could, for example, interpret sentences that end with a question mark or exclamation mark? You know automatically that the question mark in the previous sentence is wrong, and the explanation point is not needed here!

Correct connections among chunks are an important part of expertise. A person could have automatic recall with understanding for 10,000 chunks in the field of genetics, but still not be an expert in genetics. 10,000 memorized genetics terms, experiments, and facts do not make an expert geneticist, though they might make a good encyclopedia. Genetics requires recall with understanding of concepts such as DNA, genes, proteins, and phenotype, as well as all of the thousands of correct connections among those concepts in genetics and procedural rules to solve problems and answer questions in genetics. We have to learn and test the correct connections, because so many possible connections are incorrect. For example genes are made of DNA and genes code for proteins. However, proteins are NOT made of DNA, and proteins do NOT code for genes. You could have all of the correct definitions, but be missing connections or have incorrect connections.
An expert reader has many thousands of connections among chunks. As you read, you automatically connect the printed word *hot* to *water, tea, weather, stove, roast, heater, fever, pepper, spicy, chili, fire, smoke, incinerator, coal, steam, nuclear, appearance, behavior, trouble,* and many other words. A novice reader would have fewer connections between *hot* and these other words. An expert reader has no trouble understanding all of the contexts and connections of *hot* in the following sentence: “I feel hot from our argument, which is even worse because of the hot tea you poured in my lap, hot peppers you slipped into my cake, and hot diamond you gave me.” Sometimes, correct and logical sentences need more information. An expert reader knows automatically that he or she needs more information to understand “I am in hot water.” The sentence is grammatically correct and logical, but I might be in warm water in a bathtub, I might be in trouble, or I might be in a pool of radioactive wastewater.

Some words, such as *snake* and *serpent,* have the same definition but different connotations. For example, *snake* is a neutral way to refer to snakes, while *serpent* carries connotations of evil or danger. *Boat and ship* share dictionary definitions, but *ship* has the connotation of large size, while *boat* applies to a vessel of any size. In turn, *vessel* has dictionary definitions that match *boat, cup, jar* and *vein.* An expert reader is skilled at understanding these connotations for closely related words in specific contexts—connections with organization.

You might argue with me that understanding the printed sentences above and the connections among words is not about reading, but about understanding spoken language. It is true that the spoken English language (or sign language) is a skill related to reading, but expert spoken English is not the same as expertise in reading. They don’t have to go together. A child beginning to read typically already knows at least several thousand word-groups and can speak and understand many sentences. However, that pre-reader cannot read even simple short words. An adult may know over 10,000 spoken word groups in English, but be unable to read even simple words.

**Your chunks are organized in useful, sensible ways.**

Imagine that you memorize the appearance of 100 buildings in 100 cities, a total of 10,000 buildings. For each, you can picture the building in your mind, and you know what type of building it is. However, you have not learned the names of the cities, the names of the streets, or the street numbers. This would be the same as learning 10,000 chunks (such as word families) with many connections (numbers of windows, doors, colors, decorations, trees, bushes, and flowers), but no useful organization. Organization is critical to allow you to use your 10,000 chunks to solve problems or do something.

Experts have organized their chunks into sensible and useful groupings, often in many ways. Above, I connected *hot* to *water, tea, weather, stove, roast, heater, fever, pepper, spicy, chili, fire, smoke, incinerator, coal, steam, nuclear, appearance, behavior, and trouble.* That’s one way to organize these words. Any expert reader has many other ways to organize the same words. The words *coal, steam,* and *nuclear* can be organized as ways to produce electricity, and the words *pepper, spicy,* and *chili* as tastes. The same words can be grouped in even more ways, such as *coal* with *fire* and *smoke* (the process of burning), or *pepper, chili,* and *tea* (all parts of plants). Experts can move automatically along these different groupings of words and choose the correct organization and connections for the context. An expert medical doctor, for example, will automatically and instantly organize their thinking by the patient’s age if the patient has a cut toe that won’t heal. On a 75-year-old man, failure to heal might be related to poor
blood circulation, which can be caused by poor removal of sugar from the blood, which can be
caused by the medical condition diabetes. However, if the patient is a 5-year-old with exactly the
same problem, the physician’s organized knowledge might connect to a particular type of
infection, how the child was injured, and recent infections of other children or adults in the
neighborhood.

You have many procedural rules understanding what you read.

An expert has fluent or automatic application of many procedural rules to solve problems
in reading. For example, if I use a word that an expert reader has never seen before, the expert
will automatically apply problem-solving rules to figure it out. When reading “The thirsty little girl
was given a glass of tubig,” an expert reader will try different procedural rules to discover the
meaning of the word tubig and the sentence. The expert will try content and context rules: tubig
seems to be something to drink (thirsty and glass of). An expert will check whether this matches
any word families they already know (tu-big? tuba? tube?). An expert who knows French,
Spanish, Latin roots, or Greek roots might automatically apply procedures to check for these
origins. In this case, the word tubig is from a Philippine language. Tubig belongs to no common
word family in English, and the search in other languages for common roots languages would
fail. However, a non-Filipino expert reader would conclude correctly that tubig was some kind of
water-based liquid, maybe flavored, and probably not alcoholic or poisonous. If she saw the
word again, she would have a Fish-understanding of the word tubig. If she saw the word in a
specific new sentence, “Calpito went to the faucet for a glass of tubig,” she would improve her
Fish-version understanding. Tubig seems likely to be a word for water. It is.

Expertise is not guaranteed just because you put in the time.

It takes focused practice to become an expert. It is possible to study and practice in
ways that either do not help or that actually make you worse. In fact, it can be EASY to practice
in such ways. If you memorize without understanding, without connections and without
organization, you are not getting smarter. If you practice new chunks ONLY for an exam, but
never go back to review fundamentals that you are steadily forgetting, then you will not progress
toward expertise. You might feel like you are making progress, but you aren’t getting smarter.

Part of your task, if you want to become the smartest you can be, is to put yourself into
situations in which you study and practice in the right ways as well as the right amount of time.

Expertise develops only in what you learn and practice.

In most cases, expertise in one subject does not transfer well to any other subject. I think
I can convince you that this true. You are an expert reader in English but most likely not in
French, Chinese, Russian, Hindi, and Cebuano. An expert geologist is most likely to be a
terrible flute player. Even for skills that seem very closely related, expertise may transfer poorly.
For example, expert reading does not give expertise in writing. My expertise in writing research
papers in neuroendocrine physiology does not give me expertise in writing short stories (not
even close. I’ve tried). It has helped me some as I’ve been writing this book, but much less than
you might think.

Why doesn’t expertise transfer? It seems like reading and writing should be similar, for
example. In college, I was convinced that expertise in reading ought to result in expertise in writing, but it doesn’t. I was already an expert reader in high school, because reading was how I escaped from the stresses of my teenage life. Becoming an expert writer took me 15 more years, starting from high school. In some of those years, I hardly improved. Often I avoided writing, because it was hard and I could tell I was bad at it. I even avoided my coaches. In graduate school I start practicing nearly every day and for hours each day, but only because I had to do it. After 12 years of practice, including high school, college, and my first four years of graduate school, I was able to write a short (one page), simple published research paper completely on my own. It took another three years of practice with good coaching before I wrote my first published, complex scientific paper on my own. If you’ve been writing daily in a journal or in other ways since you were a child, while constantly struggling to get better, you may be well on the way to being an expert writer. If you are like me at age 18, you may be only at the very beginning of developing expertise at writing.

**Expertise in one area can help develop expertise in another area.**

Sometimes there is at least a little transfer from one area of expertise to another. If the chunks, connections, and procedural rules that you learn for one area of expertise relate to those that you need for another area of expertise, then you can develop expertise in the new area in less than ten years. If I already understand complex chunks and concepts when I read them in English, then I can learn to read them a little faster in Russian. That may be because I do not need to learn all of the connections for the chunks over again. Instead, I can just develop my memory for the printed Russian word, along with practice to make connections to the chunks I already know. That saves time, because I am using organization and connections I already have. Of course, I still need to learn the chunks in Russian and connect them to what they mean and to other chunks in Russian.

My own experience suggests that being an expert in one area sometimes speeds up expertise in another. Before I began intense study in neuroscience, I was an expert in a different subject in biology—tropical ecology. I had spent about ten years of interested, focused study and practice to become an expert tropical ecologist. It took me only six more years of interested, focused study and practice for at least four hours per day to become an expert neuroscientist. I had become an expert in my specific subject area inside of neuroscience, the neuroendocrine physiology of reproduction. I needed fewer than ten years because some of my earlier expertise in science transferred to neuroscience. For example, neuroscience uses the same general rules as tropical ecology for experimental design and mathematical analysis of results. However, I still had to learn and practice many, many new chunks and procedural rules for my new subject.

There are no true shortcuts. An expert reader in English would make stupid mistakes when translating Russian. Experts who stray outside their area of expertise can get into deep trouble. Even though I teach premedical students in an area of biology that is closely related to medicine, I would make terrible mistakes if I tried to practice medicine. It doesn’t matter how brilliant an expert might be. Outside of his or her area of expertise, an expert doesn’t know enough to avoid mistakes.

**Is it equally challenging to become an expert every area?**

The challenges differ. Expert readers, piano players, and scientists, for example have obvious differences. The skills are not exactly the same, and the way each of us learns and
practice is at least a little different. Some kinds of expertise feel easier to people than other kinds of expertise, even if what we learn is actually just as hard. In fact, even though expert reading is very hard, many people continue improving in reading until they become an expert. More people are expert readers than experts in any other thing I know about. Why? I have guesses.

First, as we become expert readers, we read stories. Humans love stories, which can make it enjoyable to practice hard in reading. We may keep going through difficult stories or books because we want so badly to know how the story ends. This might be the most important reason so many of us become expert readers: We stay interested and focused as we practice and study.

Second, it is easy to get good coaching. Many, many experts, web sites, and books can help you understand words, phrases and sentences. You know many expert readers. How many expert piano players, chemists, or chess players do you know? You would have much more trouble finding good coaching in violin or neuroscience than in reading.

Third, it is easy to notice our improvements in reading. It feels satisfying when we read something harder that we enjoy. We can see our progress from easy books to hard books. Seeing steady improvement makes us more willing to work hard.

Fourth, it is easy to find increasingly hard challenges as we develop our expertise. Books are labeled for age, grade, or reading level. Even without those labels, a friend may tell us about a book he or she liked, and often that book is at the right level as a new challenge for us. Often, we want to read fast to get to the conclusion while still understanding, which makes us try to read faster. That makes us practice fast reading, which is an important part of expert reading.

Fifth, we automatically study and practice the lower-level chunks we don’t know while reading. When we are reading an interesting story, we are willing to struggle to learn a word or phrase we don’t have in fluent recall, such as wingardium leviosa or penseive. In a chemistry class, it isn’t nearly as much fun to work on concepts such as enthalpy or oxidation-reduction reaction.

Sixth, even after ten years of study and practice reading, anyone can find many more books or articles online that are fun and interesting, and many of these are hard new challenges. Reading is an inevitable part of our daily lives, which pushes us as readers to keep practicing and improving.

I think that expert reading requires just as much knowledge, with as many connections and as complex organization as expertise in many other subjects. In reading, though, far more people have all of the necessary ingredients available for success. For most other areas of expertise, the ingredients are not so easy to pull together. The result is that many of us become expert readers, often early in our life. Far fewer of us become experts in other things.

Expertise can be in skills or subjects that are useful or not.

It is possible to be an expert in anything that is complicated and challenging to learn. People can be experts in painting, playing the guitar, quilting, playing chess, soccer,
neurosurgery, or maritime law. People can be experts in subjects they learn in school, and also in topics such as analyzing sports, collecting, or computer games. Whatever it is, a true expert will know many thousands of chunks in a certain area. An expert will be able to answer questions, do performances, and solve hard problems in their field.

Expertise can be part of a career. For example, some people who develop expertise in fashion or sports history use that expertise in a good career (maybe a great career), but others might have the expertise but never use it in a paying job. Expertise may instead be in some subject that has no particular use to us, other than being fun. Some people are experts (or near-experts) on the language *Klingon*, for example. These experts might read *Klingon*, understand spoken *Klingon*, and speak *Klingon*. How useful is that? A language expert invented *Klingon* for imaginary aliens (*Klingons*) in the *Star Trek* movies. It is not especially practical to learn this made-up non-human language of *Klingon* that does not help you communicate with any other human. However, for the right person, it might be fun. The thought of being an expert in *Klingon* is fun for me, but I’m not willing to put in the hard work. I have found working toward expertise in the Central Philippines language of *Cebuano* much more useful than *Klingon*. For you as well, gaining usable expertise is probably a better use of your time than learning *Klingon*.

**Do experts ever stop making mistakes?**

Even experts make mistakes, but most experts make few mistakes in their field. In general, I can think of two major reasons for mistakes in answers or solutions. One reason is that a person is missing necessary chunks or procedural rules. If a person does not know a necessary chunk or connection for a problem or has the wrong procedural rules or has not practiced enough, then mistakes are likely. Experts with enough practice make few of these mistakes. A second reason for mistakes is exhaustion or carelessness. A person can make mistakes even with all the information and practice to do something correctly. If we are too tired or too careless to use the information or to follow the correct procedural rules, then we often make mistakes. An expert can do something wrong even when he or she knows better. However, as long as an expert is focused, alert, and attentive, he or she can escape mistakes of exhaustion or carelessness.

Of course, if there is not enough information to work with, then an expert might do the wrong thing, but it isn’t really a mistake. In that case, it’s just an educated guess with too few facts to work with.

**Experts can stop developing or continue improving for life**

Expertise develops steadily and very slowly as a person continues adding up hours, day after day, of interested, focused practice and study with good coaching and increasing challenges. However, a person may stop. After they graduate, my research students are often good enough in physiology to find a good job long before they become an expert in something related to physiology. When people feel satisfied, they tend to stop their interested, focused study and practice with increasing challenges. If they only practice the same old things, they get no further, and they never become an expert. That’s fine, unless they need or want to be an expert.

There is no single moment at which you become an expert. It happens gradually. With about ten years of interested, focused study and practice, averaging four hours per day, with
good coaching and increasing challenges, a person is likely to be an expert. Of course, no expert needs to stop there. Some experts may just stay at the same level of expertise, while others develop even more expertise, becoming smarter and smarter, by continuing study and practice with good coaching and increasing challenges.

Are experts smarter than other people?

The answer is yes. The answer is also no. Before I explain how I think both answers are true, we need a reminder of what an expert is. An expert can answer questions, solve problems, and/or perform in their field of expertise much faster and better than other people.

Let’s imagine two identical twins. They have exactly the same genes, which is what makes them identical when they are first born. Of course, the things around us in our environment interact with our genes to change all of us. Where we live, what we do, and the accidents and events that happen to us all affect our body and brain.

Let’s take one of our identical twins (Twin 1), and begin training him (or her) in basketball. (We’ve given him back his leg.) Twin 1 is interested in basketball and has a good coach. He spends four hours a day studying and practicing basketball with strength training, good coaching, and steadily better teammates and steadily better teams to play. At the end of ten years, Twin 1 will be very good, even if he is of average height. He may not be able to outplay a taller person who has spent just as much interested, focused time with good coaching and challenges, but he is probably better at basketball than 99% of guys his size. Twin 1 is an expert basketball player.

At the same time, we have had Twin 2 begin training in football, four hours a day in study and practice with strength training, with good coaching and steadily better team-mates and opposing teams to play. At the end of the same ten years, Twin 2 is an expert football player.

Now, if you ask me, “Which of these two is smarter?” I would have to ask you, “Smarter at what?” It might make sense to ask which of these two is smarter at sports. They’re both experts in a sport. If being smart means being able to answer questions quickly and correctly, solve problems quickly and correctly, and perform in their area of expertise, then they are both smart. However, they are smart in very different ways, each in their own sport. Twin 1 is smarter at basketball. He can answer questions about the rules, strategy, movement, and ways to play basketball quickly and correctly. He can solve basketball problems quickly. For example, he can solve problems about what to do in the last 10 seconds of any game, organized according to the score, the style of the other team, the foul standings, and the offensive and defensive skills of each player on each team. He can play at an expert level in the last 10 seconds of a basketball game. However, that’s not football. Twin 1 has to be considered dumb at football. Twin 1 has never studied football. He doesn’t know the rules, nor can he play. Twin 1 is smart at basketball and dumb at football, while Twin 2 is the opposite, smart at football and dumb at basketball.

Now let’s take Twin 2, and instead of football, have him spend the ten years learning to play chess. Twin 2 is interested in chess and has a good coach. He spends four hours a day studying and practicing chess, with good coaching, and steadily better opponents to play. At the end of ten years, Twin 2 will be very good, even if he has an average memory. Twin 2 may or may not be able to outplay another person who has spent the same 10 years of interested, focused time with good coaching and challenges, but he is probably better at chess than 99% of
people with an equivalent memory. Twin 2 is an expert chess player.

Now, I ask you, which twin is smarter? I’m guessing (hoping) that you would say, “Smarter at what?” We would all agree that Twin 1 is smarter at basketball and dumber at chess, and Twin 2 is smarter at chess and dumber at basketball. However, if we test them on history, we couldn’t predict which was smarter. Expertise doesn’t transfer to other fields.

**We asked the wrong question.**

Back to the question: do you have to be “smart” in order to be an expert basketball player, football player, chess player, or expert biological scientist? This question has it backwards! People become smarter by becoming experts. How much smarter depends upon how interested they are, how focused they are, how well they learn how to learn their subject (good coaching!), and whether their challenges increase in the right ways and at the right times because of good coaching. The development of expertise makes us smart. The reverse is not true: being smart, in the sense of a good memory or quick understanding, does not develop expertise. Being smart does not automatically result in becoming an expert. No one becomes an expert at basketball, football, chess, history, or science without enough interest, practice, study, good coaching, and increasing challenges.

Are experts smarter than other people? YES! Experts are much smarter in their field than people who do not have their expertise. In their field, they are in the top 1% smartest of people. And NO! Experts are not smarter than other people. If an expert has to solve a problem outside of his or her area of expertise, none of us can guess whether he or she will be any better—any smarter—than anyone else.

Keep in mind that I am defining “smart” versus “dumb” as the ability to answer questions quickly and accurately, solve challenging problems correctly, and perform well in a particular subject or skill. Defined in that way, an expert is smart but only in their area of expertise. IQ tests are an attempt to measure the potential to learn and solve problems. However, potential by itself is useless! An IQ test would be a terrible way to choose a person to solve hard problems in any specific area of expertise. I would **never** select someone to cure my disease, defend me in a law case, perform a play for me, or compete in a chess game based on an IQ test. I would want to know if they were an expert physician, lawyer, actor, or chess player. The most brilliant person without expertise would be a disaster. An ordinary person with expertise would have what I need. I would go for expertise over IQ every time. In fact, even if I had to choose between any two physicians (or any two lawyers), an IQ test would be the last thing I would use in my choice. I would want to know how long the two had been practicing, their recent records with patients, their accuracy in diagnosis and logic, and their reputation among other experts.

**Brilliance: some experts are smarter than other experts in their field.**

Some experts are smarter than others in their field. Some experts in neuroscience study exactly the same things I do who can think and do rings around me. A few of them are so smart that we call them **brilliant**. They are faster to answer most questions, and they are more likely than I to be able to solve a particular problem correctly, either on paper or in a laboratory experiment. I could give you a whole bunch of names of neuroscientists in my field who are smarter than I am (in neuroscience).
The reasons they are smarter are important. ONE reason is probably genetic. There might be ways in which I am just not as genetically gifted to do neuroscience, though I don’t know of any test to answer that question, nor can I imagine one. The other reasons they are smarter are more important. Many of these smarter neuroscientists have spent much more time than I have in interested, focused study and practice of neuroscience, perhaps with better coaching, and very likely with better new challenges. I spend too much time at other things. I don’t practice enough in the best ways to become better at neuroscience. For example, how my students learn fascinates me, and so I spend hours a day thinking about learning, talking with students or teachers about learning, thinking about ways to teach, coaching students who are trying to learn, trying out new ways to teach, or writing things related to teaching. These particular hours might make me a smarter teacher, if I am studying and practicing in the right ways, but they certainly do not make me a smarter neuroscientist. The hours I spend on other subjects cannot make me a smarter neuroscientist.

In contrast, I have neuroscientist colleagues who are quite obsessed with science. Some are delighted to spend 8, 12, or even 16 hours a day nearly every day of the week for month after month and year after year on study and practice in neuroscience. (I would go crazy—I want to do other things!) By now, at my age (55), those neuroscientists may have spent 50,000 or even 100,000 more hours of focused, useful study and practice of neuroscience than I have. In each year, they may spend thousands more hours than I do in interested, focused study and practice making connections with organization, good coaching, and increasing challenges. We would all be surprised if they were NOT smarter than I am as neuroscientists! If someone with that many more hours of experience in neuroscience is not smarter than I am at neuroscience, I would predict that it was because he or she was less interested, less focused, or had worse coaching than I have had.

I know some experts in neuroscience who are slower than I am to answer most questions or to solve many problems. In some cases, they have put in less time, and in other cases they may spend less time than I do in practicing their old chunks and procedural rules. They are forgetting. Some may spend so much time teaching or doing other things that they do not have enough time to practice new neuroscience. These neuroscientists might be expert teachers of neuroscience, but they may no longer practice enough to be experts at doing neuroscience.

A few neuroscientists I know spend so much time looking at fascinating new information in neuroscience that they do not spend enough time on any one thing to develop fluent or automatic recall of the new chunks and procedural rules. If an expert spends most of their time letting things go into working memory, while never spending the time to develop FRUCO, then they won’t get smarter. In fact, they might even slowly lose some of the knowledge that they have. I call this neuroscience tourism, because this is like being a tourist who visits places for fun, but never stays to learn and work. I understand this problem better than I wish, because I spend much more time than I should on neuroscience tourism.

Here’s what I think: we can all be experts, even if we cannot all be brilliant. We all can be smarter than 99% of other people in something (maybe even 99.99% of other people), as long as we spend the time in interested, focused study and practice with good coaching and increasing challenges. Even though it is hard work, we all can do it, and we all quite likely could enjoy it. Even the most brilliant people do not have the time to become experts in more than a few things. The evidence suggests that even the most ordinary person has the time to become an expert in something. (Some people may not be able to become experts because of serious
brain problems or damage. But if you’re reading this book, you’re not one of those people.)

Other things stop many of us. It seems that many people are unable to find all of the ingredients. It is not easy to get ten years of interested, focused study and practice making connections with organization, good coaching, and increasing challenges. Who is going to pay for it? What if we want to do other things? Many people who have the opportunity don’t take it. Others just do not have the opportunity. Finally many people in the world would be delighted to work that hard but do not have that opportunity. They are too busy just staying alive and paying the bills, doing work for pay that does not make them smarter. They may not be able to find good coaching, or they can’t pay for good coaches and good teachers. I have had students who could become experts, but chose not to (at least not yet), and students who could become experts, but cannot find the money, time, and access to good coaching.

**A Fish-understanding of expertise**

As you begin to understand the process through which you became an expert reader, you have a Fish-version for the concept of developing expertise. It may not be especially accurate yet, but it is a good start. **In fact, experts on expertise hotly argue exactly what it means to be an “expert.”**

Because you are an expert reader, I am confident that you can understand the sentence in bold font above, even though it requires high-level connections and organization. You might also have noticed that the sentence included the word family *hot* in another new context. It is possible that becoming an expert in any topic might be no more complicated than the procedure for becoming an expert reader. As a Fish-understanding of expertise, this is pretty good. If you can understand expertise this well, you have a good sense of how to get there—how to become an expert in something you choose.

**Developing expertise rapidly is the same as learning rapidly**

Why have I spent an entire chapter on expertise in a book on memory and learning? Because when we want to develop expertise, we want fast, efficient, and effective learning. As a student, you should want to be faster, more efficient, and more effective in your learning. I predict that a person who understands expertise and how an expert gets to be an expert (even with a Fish-understanding), is also developing skills that help for fast, efficient, and effective learning.

You might never expect to become an expert in most of the subjects you study. That doesn’t matter. Learning as if you might want to become an expert is a fast, efficient, and effective way to learn. The things I tell you in this book might not be the best way for you, yourself to learn. No one knows that for you. Memory, learning, and expertise are complicated, hard to understand, and hard to study. No one knows enough to state the BEST ways to learn or the single wonderful technique to “unlock the power of the mind” (a phrase I’ve seen in advertisements for “brain boosting”). I would not believe a person who claimed to know the best way (not even if I knew what “unlocking the power of the mind” means). No one can somehow make you be a great learner; that’s something you have to do for yourself.

Neuroscientists, education researchers, and learners all have to interpret incomplete and imperfect information as best as we can. We all have to do our best to understand what helps
us and others learn. For me as a neuroscientist, as a reader in the subject research and learning, and as a teacher, I know that new college students, on their own, mostly learn with methods that are not very efficient for that stage of their life. We all can improve.

What can help? There is evidence that thinking about how to develop their own expertise—metacognition—helps people become experts. There is also evidence that NOT having the elements that go into development of expertise slows down or stops learning. Learning may not be exactly the same thing as developing expertise, but doing things that help a person become an expert should also help a person learn well. Understanding expertise can help you develop metacognition skills. They can help you learn better and faster.

The new chunks to learn about experts, expertise, and learning

Here are the new chunks you need to learn:

1. An expert has about ten years of four hours per day of focused, interested study and practice, with good coaching and increasing challenges, on a specific subject or skill.
2. Experts have many layers of chunks built from simpler chunks.
3. The chunks and procedural rules of experts are connected and organized.
4. A person who can read this book easily is an expert or near expert in reading English.
5. An expert reader of English has about 10,000 chunks for word families in recall with understanding, with many connections, with logical organization, and with hundreds or thousands of procedural rules applied to reading, all developed over about ten or more years.
6. Experts are smart in their area of expertise. In anything else, they are usually no smarter than an average person with the same amount of study and practice.
7. Time and study alone are not enough; it takes focused, interested study and practice, with good coaching, and steadily increasing challenges.
8. Experts have found ways to make their study and practice time interesting, satisfying, and rewarding.
In what you learn, the chunks are pieces of information, and the procedural rules† are what you do with chunks. Let’s say that you have FRUCO for numbers, addition, subtraction, multiplication, and division. Those are your chunks. Chunks without procedural rules are useless. To solve problems, you need procedural rules for what to do with your chunks plus new information. We went through a Fish-definition of procedural rules in Chapter One. In this chapter we’ll make more connections, give you real examples, and better organize your chunk for procedural rules.

What are procedural rules?

While I knew as a student the concept that methods or rules for procedures helped me learn, I had only a Fish-version of understanding for procedural rules. I find that most of my students are the same way. What do I mean by the term procedural rules? The Fish-version is that that procedural rules are a series of steps you do in order when you want to solve a problem of some kind. This term procedural rules is used for many other things, especially in government and law, but in this book, a set of procedural rules is the specific series of steps we follow in order to do something we have learned. We have procedural rules for doing addition, riding a bicycle, or writing a grammatically correct sentence.

I call them procedural rules instead of procedural steps because I want you to think of them as rules. Rules are something you must do, without skipping anything, and without changes. I call them procedural rules instead of problem-solving rules because you don’t use them only to solve problems in class. For example, we have to learn procedural rules to shoot a lay-up in basketball or do the first moves of a dance routine. Sports and dance moves have rules about where to put our feet, how to move a ball and our body, and which steps to take first, second, and third. In games such as tic-tac-toe, checkers, or Tetris procedural rules that we can learn help us win more often. Writing grammatically correct sentences uses procedural rules, and solving mathematics problems uses procedural rules. In life, we use procedural rules all the time. As you think about this chapter, I hope you start noticing more of the times you use procedural rules (such as procedural rules for checking phone messages, driving, and getting dressed). I want you to think about how you learned each set of procedural rules and how often you had to practice in order to get them into FRUCO. (Now is a good time for some recall practice: what does FRUCO stand for, and what does it mean? Are you thinking of the full meaning when you read FRUCO, or is it just an empty word?)

Learning procedural rules in order to solve problems

In learning, we have to apply procedural rules all the time. When you need to connect chunks that you have in fluent recall to a new situation, finding those new connections uses procedural rules. When we don’t know the procedural rules we need for a particular problem, we

† I made up the term “procedural rules” because I wanted a phrase that explains itself.
feel dumb, and we can’t solve the problem. That is more common than you might realize. When you have a problem to solve and you think to yourself, “I have no idea how to do this,” the problem is either that you don’t have fluent recall with understanding of one or more chunks, or that you don’t have fluent recall with understanding of the set of procedural rules you need. An important part of learning is understanding when and how to learn procedural rules. Good teachers and books teach you procedural rules. You also make up procedural rules for yourself.

As you learn more, you replace easier, simpler procedural rules with rules that are faster, if you know the right chunks. The better you understand the process of making and using procedural rules, the better you can be at noticing when your procedural rules work well and knowing when to make or find new ones.

A new Fish-version of procedural rules with examples from mathematics

When you learn to solve basic mathematics problems, you learn procedural rules. You apply those procedural rules when you see equations to solve, such as \( 12 \div 3 = \_\_ \). Below, I have a set of procedural rules for very simple mathematics problems.

1. Find the symbol between the numbers (+, −, ×, ÷).

2. Discover if the symbol is for addition, subtraction, multiplication, or division.
   (a) If the symbol is plus, then take the value of the first number and add it to the value of the second number.
   (b) If the symbol is minus, then remove the value of the second number from the value of the first number.
   (c) If the symbol is x, then add the second number to itself the number of times of the value of first number.
   (d) If the symbol is division, then count the number of times you add the second number to itself until you have the value of the first number.

3. Write the new number in the space after the equals sign.

These procedural rules tell you how to solve the problem, but they are not the answer to the problem. It is important for you to have a very clear chunk for procedural rules versus a very clear chunk for using procedural rules to solve a problem. To use your procedural rules, you need (1) a procedure to choose the correct set of procedural rules, (2) the essential chunks in FRUCO, (3) fluent recall with understanding of the procedural rules. All three are necessary.

The procedural rules I gave above will solve any +, −, ×, ÷ mathematics problem.

(2a) \( 2 + 2 = \_\_ \). I can show the method using dots. Addition with dots needs only a very simple Fish-version of the concept of addition: counting.
Chapter Five: Procedural Rules

(2b) $3 - 1 = \_\_\_$. For a subtraction problem, a simple Fish-version of subtraction as counting is enough. Here, I’ve put an X through the dot I want to remove.

(2c) $3 \times 3 = \_\_\_$. For a multiplication problem you can use counting too.

(2d) $12 \div 3 = \_\_\_$. For this division problem, I keep adding 3 until I have 12 dots.

In other words, for this division problem, after adding $3 + 3$, the total 6 is not yet equal to 12, so I add another 3. Next, $6 + 3 = 9$ is still not equal to 12, so I add another 3, which gives the total 12. Finally, I count the number of times I added 3. I count 4 times that I added 3. The answer to $12 \div 3$ must be 4.

**Usually, two or more different sets of procedural rules can solve any problem.**

Most problems can be solved in more than one way. Often more than one set of procedural rules result in the solution. Look again at the procedural rules I wrote above, and
answer a question. Could a person follow the procedural rules above for multiplication and division and obtain correct answers without understanding the concepts of multiplication or division? I think so, but you might disagree. Take a moment now to go back and decide for yourself.

I think that my procedural rules for multiplication require only fluent recall with understanding of numbers, addition, and equals. My procedural rules have you add the second number to itself over and over, counting each addition of the second number. When the number of additions of the second number equals the value of the first number, you are done. The number you obtain at the end of all of the additions is the answer. In the problem $3 \times 3 = ___$, you add $3 + 3 + 3$ and get 9. That is the correct answer, and it needed only the concept of addition. It is the same for division. My procedural rules have you add the second number—3—to itself until the total is the same as the first number—12, counting each new addition. In the problem $12 \div 3 = ___$, we add $3 + 3 + 3 + 3$ and find that the sum equals 12. Because we had to add 3 to itself 4 times, then the answer is 4. Again, finding the correct answer requires only the concept of addition.

I want you to understand two things from the examples above. First, more than one set of procedural rules might solve a problem. Second, some procedural rules require fluent recall with understanding of fewer chunks. So why don’t we always use the simpler rules? Because simpler procedural rules with fewer chunks are usually very slow for some problems. We can save time and effort when we learn new concepts if we use simpler rules. However, it might take much longer to solve some of the problems. Often, fluent recall with understanding of higher-level concepts allows us to use procedural rules to solve problems much faster.

As a novice, I would love my multiplication procedural rules that use addition! These rules will get correct answers for any multiplication problem in which at least one of the two numbers to be multiplied is an integer. They work for any division problem in which both numbers and the correct answer are integers. I don’t actually need the concept of multiplication or division. I could solve these problems by easy memorizing of these simple procedural rules, and I would obtain correct answers to multiplication and division problems every time. I would not need the tedious bother of developing FRUCO for the annoying new chunks for multiplication and division. Why, then, should I bother learning those more complex chunks and procedural rules? Let’s try my easy, clear rules for multiplication on some real problems.

Do this exercise, using my procedural rules: $50 \times 60 = ___$

Work WITHOUT a calculator, please start now, and time yourself. Remember, you have to add 50 to itself 60 times.

You don’t actually have to do the problem, because I did it for you: 3 minutes and 6 seconds. It was tedious. You might be faster than me. Compare how long the problem takes when you use your normal procedural rules for multiplication problems when you don’t have a calculator. (I took nine seconds, once I remembered my procedural rules correctly, but I started wrong). Knowing the concept of multiplication and a better set of procedural rules saved me 2 minutes and 57 seconds. In the past 45 years, I’ve done many, many thousands of multiplication problems. I have saved many, many hours of work by taking the time to learn (1) chunks with connections and good organization for multiplication and (2) a faster set of procedural rules that uses my chunks, connections, and organization. Learning multiplication and better procedural rules has saved me time.
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A second problem: some procedural rules are terribly slow for some problems.

You can use my procedural rules for multiplication problems even when you have never seen the numbers before. I could ask you to solve:

6,295,367,286 x 2,853,779,211 =

Use my procedural rules from above. How long did it take?

I hope you didn’t do the whole thing, because I worked out that it would take me 7985 years. That’s 7985 years to solve one problem. How do I know it would take about that long? I tried doing the first five additions of 2,853,779,211 to itself, and it took me about 20 seconds for each addition. 20 seconds x 6,295,367,286 times works out to about 7985 years. If you’re faster than I am at addition, you might be able to save a few thousand years. You might also notice that you’ll save about 4000 years by reversing the problem, and adding 6,295,367,286 to itself 2,853,779,211 times. Wonderful, but that would add another step to my simple procedural rules.

What about other options? With a different set of procedural rules, I got an answer to this same problem in 13 minutes. I needed (1) the concept of multiplication, (2) fluent recall of my 0-9 multiplication tables, and (3) some slightly more complicated procedural rules. My answer was 17,865,590,278,295,291,346. I don’t know if it is correct. To check for errors (I didn’t), I would need about an hour of work on paper.

Think about what this example tells you. Sometimes, it is worth the time to develop fluent recall with understanding of more chunks so that you can use a better set of procedural rules and solve problems faster. Even if the only multiplication problem you had to solve in your entire life was this one (6,295,367,286 x 2,853,779,211 = ________________), you would save more than a life-time by learning (1) the concept of multiplication, (2) your 0-9 multiplication tables, and (3) procedural rules for multiplying pairs of numbers. There is an important conclusion here about learning. You can be much, much faster and much, much better at problem solving (and other tasks) if (1) you have good procedural rules, and (2) you can learn those procedural rules (fluent recall with understanding, plus the connections and organization to know when to use them). If we have many procedural rules that give us better ways to solve problems but require more chunks and connections and practice to learn, then getting smarter is partly about learning those procedural rules.

Classes and books often give you new chunks and new procedural rules in order to help you become faster and better at solving problems. Often, we work out better procedural rules for something on our own. Acquiring more useful chunks and better procedural rules is a large part of developing expertise. If you want to be smarter, learn more chunks and better procedural rules for the problems you might need to solve.

Smart and dumb depends on the procedural rules you can apply.

When I was 10 years old, I would have believed that someone who took 7985 years to solve a multiplication problem with two integers was pretty dumb. That was my Fish-understanding of smart and dumb. I understand this better now. Being smart or dumb depends upon the problems I have and the chunks and procedural rules I know. If you are reading this
book, then you can solve my multiplication problem without a calculator in an hour or less. I can predict that you do understand multiplication and that you have good procedural rules for multiplication. However, what if you and I had been taught only the concepts of addition and my procedural rules at the beginning of the chapter? How many of us would have thought that there must be a faster way to do this and tried out ideas, ultimately inventing multiplication? Inventing brand new procedural rules that will save time is brilliance.

**Becoming an expert on poor procedural rules**

I could teach you a lot of mathematics using only addition, subtraction, the concept of equals, and sets of procedural rules using those concepts. You could spend a huge amount of time learning mathematics in this way. With 10 years of interested, focused practice and good coaching with increasingly challenging problems, you might become an expert on those rules. Your rules could solve many, many kinds of mathematics problems, as long as you have enough time. Unhappy you. Those are poor procedural rules. You still won’t solve \(6,295,367,286 \times 2,853,779,211 = \text{__________}\) within your lifetime. A 10-year-old with fluent recall with understanding of the concept of multiplication, along with a better set of procedural rules, can solve the same problem by hand easily in less than an hour.

There are **always** slow ways to solve problems, and there are many poor sets of procedural rules. Here’s a **third** way to solve multiplication problems.

(1) Memorize the expanded, full version of the multiplication table below (1 x 1 = 1; 1 x 2 = 2, 1 x 3 = 3, ... 1 x 10,000,000,000 = 10,000,000,000, ... all the way to 9,999,999,999 x 9,999,999,999 = 99,999,999,990,000,000,000,000 and 10,000,000,000 x 10,000,000,000 = 100,000,000,000,000,000,000,000):

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(2) Once you have memorized this table – you’ll need fluent recall – write the memorized answer to any multiplication problem.

Good news! This set of procedural rules does not require that you understand the concept of addition! Once you have fluent recall with this table, these procedural rules would allow you to solve my problem \(6,295,367,286 \times 2,853,779,211 = \text{__________}\) within seconds instead of 7985 years. That’s even faster than my 13 minutes to solve the problem! You could solve any other problem in the table just as fast, in seconds! Wow! Also bad news. You are going to need billions of years to memorize the table. Sorry.

You can waste a lot of time learning poor procedural rules. I am making the point partly to help you understand that there can be many ways to solve the same problems. Some are faster than others. I want you to understand that you use procedural rules for everything you do, every time you solve any problem in your life. Those procedural rules are not just for math,
Chapter Five: Procedural Rules

grammar, and science. Procedural rules might give you the best route to take to get to school, the best way to avoid someone you don’t want to see, or the best way to play a musical instrument or a sport. You combine old and new chunks with new procedural rules when you learn. I hope that this section helps you realize something. The procedural rules you use for learning right now might be very good. They probably are not the best procedural rules to learn fast and well. As you develop FRUCO for useful new chunks, such as the concepts of working memory, working memory capacity, chunking, working memory overload, and procedural rules, and as you test your own methods, you can probably do better. You can learn when it is better to make the effort for faster procedural rules.

The chunks for procedural rules

What are the new chunks you need to learn for procedural rules?

(1) Procedural rules are a series of steps we follow to solve a problem.
(2) Each type of problem requires a different set of procedural rules, such as multiplication, doing a genetics problem, or checking that a sentence is grammatically correct.
(3) Connections and organization of procedural rules tell us which set of procedural rules to use when we have a problem to solve.
(4) We need at least one set of procedural rules for each kind of problem, or else we can’t solve the problem.
(5) You can usually find simpler and more complex procedural rules to solve a specific kind of problem.
(6) Some procedural rules require more concepts, but are much faster.

Metacognition: your personal procedural rules for learning

Do you have chunks and procedural rules that you use for learning? Take a moment to write down your procedural rules, starting with:

(1) Listen to the teacher (or read the book),
(2)
(3)
(4)

(I’m giving you my guesses about you below, so you don’t have to do this exercise, but I wish you would. If you read my thoughts without writing your own rules, you’ll never be sure whether your actual rules are different from my guesses below.)

When you wrote them out, were your rules anything like these:

(1) Listen to my teacher.
(2) Take notes.
(3) Read the book.
(4) Highlight my book and notes.
(5) Memorize everything I can, starting with whatever the teacher tells me to memorize.
(6) Do any problems the teacher gives me.
(7) Reread my notes.
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(8) Reread my book, trying to memorize the highlighted parts.
(9) Repeat until the exam, as often as I can stand it.

If you went on working on this, would you have included these:

(10) I'm never done, because I never have everything memorized.
(11) I feel guilty because I don't study more than I do. (Or, instead maybe: my parents or teachers try to make me feel guilty).
(12) After each exam, I only study the new next things.
(13) I never go back to old concepts unless I know they are going to be on the next test.
(14) Good grades mean that I learned well. Obviously, I'm a success!
(15) Bad grades mean I did not learn well. Obviously, I'm a failure.

These were my procedural rules for learning in middle school. These were my rules for learning through nearly all of high school.

Before reading any further, look at my rules, or yours (if you were energetic enough to write your own instead of using mine) again. Would you add anything, based on how you studied up until now? There’s a good chance your rules are better than mine. With a few changes, my rules above probably match those of most students a lot of the time.

Those rules actually aren't that bad. They usually got me to learn most of what I needed. Books and teachers generally know what they are doing. When I followed those rules, I gradually developed fluent recall with understanding of the important concepts and procedural rules. Unfortunately, those rules almost never gave me enough practice to hold on to my fluent recall, let alone FRUCO I lost fluent recall within a few months, and sometimes weeks. (That’s why the show Are You Smarter than a Fifth Grader? works so well.) Those rules are also not very good for connections and organization. My teachers made me do some connections and organization but not enough to develop good expertise. (In fact, teachers can't tell a student every connection and type of organization to have. That’s because what everyone already has in FRUCO is different, and so the connections to make and organization to develop are different for everyone.) For reading and writing, my teachers told me to memorize and practice new words and use them in complex sentences. That often required only effortful recall with understanding plus some connections. They made me memorize and practice procedural rules for complex mathematics and many other things. My grades usually matched what I learned. I think I learned a lot. In high school, I was satisfied if I got B’s or A’s, and I was unhappy if I got C’s. I could have learned a lot more. Did I learn as much as I could have learned in the same amount of time? I don’t think so.

Relying completely on teachers and books for what you learn has two problems. First, you will waste some time. What they suggest that you do does not always match what you need to do first, especially if you have forgotten essential chunks or procedural rules. Books and teachers have you practice, which is good. On some days you practice more than you need, and on other days less than you need. Second, books and teachers cannot know exactly what you already know. They cannot see why you are confused and stuck. They cannot tell that you are confused or stuck because you do not have FRUCO for some concept you MUST have in order to learn a new chunk, or to use a new set of procedural rules.
What might be better procedural rules for learning?

You might want to write out your own, but you can use mine.

Yours:

1. 
2. 
3. 
...
10.
(20) ?

Here are mine:

1. Listen to the teacher.
2. Take notes.
3. Read the book. Try to visualize (picture in my head) the important things.
4. Identify the most important new chunks. (In other words, identify the necessary new chunks).
5. Carry out information reduction (more on this term later) to simplify each new chunk to essentials. Try to picture it in my mind.
6. Decide if each chunk needs to be in FRUCO or only recognition memory with understanding. Decide if a new chunk is not really needed at all. Decide which chunks you want to remember for years, and which just for the next test.
7. Plan ways to practice for FRUCO, using shorter and shorter review periods over each time you practice.
8. On each day, know when NOT to practice recall on old, essential chunks. STOP practicing when I can
    (a) hold each new chunk in working memory, and
    (b) when I can still recall each new chunk 5 or more minutes after your last review.
9. Test and improve my understanding, connections, and organization by trying to connect old chunks with new chunks and new procedural rules. (More to come on this topic later, when we talk about study methods).
10. Practice essential chunks more often if a key word or a part of the image fails to trigger my fluent recall with understanding for that chunk.
11. Keep old study materials in a form that is easy and fast to review. These materials will be your fastest way to review chunks and procedural rules. Use these months or years after I first learn them. (We'll cover more on this topic later. It can save you huge amounts of time and pain in high school, college and later in life.)
12. Trust that if I learn, practice and follow these rules, I'll progress steadily and faster toward expertise. Understand that the Fish-version of these rules is just the beginning. To use this set of procedural rules, you need to get FRUCO for the essential chunks and the procedural rules of learning.

What is different between my old procedural rules (and maybe your old procedural rules) and my suggestions? The difference is that what the teacher and books tell you is just the start. You still need both the teacher and the book just as much as ever. However, with better procedural rules, you are selecting what to practice and choosing how to practice. You are making the chunks you learn as simple as possible to learn, while still including everything
necessary in each chunk. You are noticing when you are using empty memorization, because empty memorization doesn’t have useful connections and organization. You are practicing faster ways to develop FRUCO. There might be even faster ways that I don’t know—keep thinking and keep looking for even better procedural rules. You are adjusting how you learn to your own pace. You notice when you are stuck because of a missing chunk. Your teachers would have to guess that you have forgotten that necessary chunk, and your books usually cannot tell you. You review when you need to but only when you need to. Better yet, your reviewing is fast and easy, because you have stored all your old chunks and rules in a way that is fast to find and easy to review.

The new chunks about procedural rules

Here are the new chunks you need to learn:

(1) Procedural rules are the steps we use to solve a problem.
(2) For each kind of problem, you can find many ways to solve it. Ways that require fewer chunks are simpler to learn and understand but are slower, especially for more complicated problems. For complicated problems, the easy procedural rules may be so slow that we couldn’t solve the problem in a lifetime. Procedural rules that are fast even for complicated problems require that we master more chunks and practice more steps.
(3) To get smarter, exchange poor procedural rules that may be easy but slow for better procedural rules that are harder but fast.
(4) To learn better, we must test our procedural rules for learning. We find better procedural rules for learning and take the time to learn and apply the better procedures.
Experiments on your own learning: metacognition experiments

The project you do for this section is the most important part of this book. In this section, I will give you tasks that will help you consider how to change your learning—metacognition experiments. Remember that metacognition is thinking about your own thinking and learning. Metacognition experiments are experiments on your own thinking and learning. They can be simple and short. In fact, if they are designed well, many metacognition experiments will be simple (but elegant) and short. Each experiment gives you information about a person you find interesting (I hope): yourself.

In my class associated with this book, my students develop a portfolio of experiments on their own learning. Their portfolio is just the set of tests on their own learning. In these tests, they apply information from this book in order to try to get insights into their own learning. I provide them with examples such as those below. Their first attempts may not be very good, and they may not provide much useful information. That’s okay. Keep in mind that you can’t perform well in any skill—sports, music, or anything else—without painful and clumsy beginnings. That’s what your first attempts will be. With practice, you’ll get better. If you can find good coaching, that might speed your progress and help you avoid pitfalls. On your own, you need to be self-analytical and check yourself for pitfalls.

You’ll need to be on guard. There is a great quote that is useful here: “The first principle is that you must not fool yourself and you are the easiest person to fool.” (Richard Feynman). You have some room for mistakes. Most of us have a lot of poor learning methods when we are in school, and with a little practice most students seem to figure out how to catch them.

My goal with this book is for any reader—you—to improve your learning. My guess‡ is that the best approach is for you to test what works and what doesn’t work for you in learning. How do you do that? By this point in the book, you have information and tools that you can start trying. In this section I’ll give you a method to design and carry out metacognition experiments, and I’ll give you some examples that you can do on yourself. Learning from metacognition experiments happens best if you can get some coaching, and I’ll do the best coaching I can do through the pages of a book. If you are in my class, of course, I’ll coach you in person. If you can, do metacognition experiments with someone else, and discuss your results with someone else. Two or more novices who are working through metacognition experiments can help coach each other. They will make many more Fish-errors of understanding than they would with an experienced coach but probably fewer Fish-errors than they would make on their own.

In science and in normal life, we use experiments to learn. Usually, our experiments have the goal of learning about something that applies to everyone. We want to know, for example, if a drug can cure a disease in the average person. We do an experiment in which we separate out half of a group of sick people who we give the drug. We give the other half of the

‡ I base my guess on my experience with many students, but I haven’t yet tested this with good controls and careful methods. Many well-meaning educators (like me) have fooled themselves and others with sensible-sounding advice. That’s sometimes been true even when, as in this case, there is research that suggests that the kinds of things I suggest you try are effective. The best advice I can give you is to test different methods on yourself as carefully as you can, evaluate them as well as you can, be alert for common biases and errors, keep checking, and stay skeptical. At the very least, you’ll learn some things about learning, and you might find ways to become a much better learner.
group either no treatment or a placebo, which looks and tastes the same as the drug but is often just sugar, which has no effect. If the people who get the drug recover better than control group with the placebo, then the drug may be useful. When we work with a single person, the experiments change. Now our population size for experiments is just one—our patient. We no longer care if the drug helps other people; we only need to know if it helps our one patient. In this case, we test the drug at one dose and look for effects. We may put the patient on the drug in an experimental period and then take them off the drug or put them on another drug and compare results. In other words, for complicated diseases, doctors experiment on just the person who is sick to find out what works.

Why do you need these experiments? In this book, I’m giving you practical information on memory and learning, but there’s one big problem for each individual reader: you. The information has been learned from studying groups of people, not any one person. A serious problem is that you were not part of any of those groups. We want to know what would make your learning better—faster, easier, or longer lasting. If you’re the same as everyone else (you aren’t), then the average results from some other group of people might be OK (it isn’t). Knowing about learning methods that have worked for other people is a good start, but it’s only a start. In order to know if it works for you, you have to test you. As part of what students do in my course (and hopefully part of what you’re going to do), you’ll find out. Whether you are one of my students or not, you can do these kinds of experiments on yourself. Experiments you do on your own learning are metacognition experiments—learning about your own learning.

The reason for doing metacognition experiments

This section of the book is not easy for at least two reasons. First, it takes work. It takes effort to do experiments on anything, including yourself. Second, it can feel troubling. What if you don’t like what you learn? What if the experiments suggest that you are not able to do better? What if the experiments just make you feel helpless or hopeless? Not to worry. The experiments are not like that. They don’t compare you with others! They don’t reveal your IQ, your verbal ability, or your spatial reasoning score. You will learn only about one interesting human: yourself. What you learn will benefit only one person: yourself. You cannot compare the results in any useful way with anyone else’s. The only thing a comparison could tell you is that you are not identical to anyone else, which I’m pretty sure you already know.

What’s in a metacognition experiment?

My students have designed experiments to test sketching, mind maps, and retrieval practice (see Chapter Nine). Sometimes the methods have worked and sometimes not. When they didn’t work, sometimes my students discovered they were not following the directions correctly. They had to understand the directions better, practice, and try again. What else have they done? My students have designed experiments to test their reading speed, number of distractions, and comprehension after reading. They’ve tested, for example, reading and studying with or without music playing or ocean wave sounds. Many found that they could do different readings faster or slower, with better or worse focus and comprehension, depending upon the background sounds. My students have designed experiments to test whether their amount of sleep matters. They’ve tested their ability to solve problems after eight hours of sleep versus six hours of sleep. If the amount of sleep does matter, that would be great to know. My students also designed experiments to test the effects of “power naps,” visualization, snacking
(didn’t help), identifying missing chunks, and many other things. The important point is not which experiments you do but just that you do experiments on your own studying and learning.

What can the experiments tell you? They can tell you whether you are wasting time. The experiments can tell you what you are doing that helps you learn better and what you are doing that really doesn’t help. Most students who start down this pathway of self-testing find their biggest surprise result is that they waste less time. They feel that they learn better, and they waste less time. Is that going to be true for you? I cannot even guess. That’s the point.

Can you skip the experiments?

If your studying and learning are bumping along all right, then you might not want to do the experiments. If you aren’t unhappy with your grades and progress, then you might not to do the experiments. Most students I meet spend the time for the experiments for one of two reasons:

(1) They do experiments if I force them to do it in a course.  
(2) They do experiments if they are desperate about failing.

Thinking back on myself when I was in college, that described me: I usually tried new things (1) if I HAD to, sometimes protesting and kicking all the way, or (2) if I was desperately in fear for my grades. That was pretty much it. Fortunately for me, both happened, especially the desperate fear part. It wasn’t fun, but it did make me test new ways of learning. It made me change. If you are neither desperate nor pressured, then you may be out of luck. I can hope that you are curious and interested to learn about your learning. If so, I’ll ask you to accept my suggestion that you can get better at learning and waste less time by trying metacognition experiments.

What if you don’t? By reading this book but doing nothing else, you won’t get much out of it. You don’t get better or smarter just by the reading. That would be easy and nice but not possible. It doesn’t happen for my students. If you skip the experiments, you are unlikely to change in useful ways. The content of this reading will fade from effortful recall to recognition memory and then to nothing, gone as if it never happened. In a month or two, you’ll fail a pop quiz on this book. On the other hand, if you begin doing experiments and using the ideas, you are likely to change.

Students who did not do experiments often told me that the way they studied did not change. They did not feel that they began to learn any better. One comment was, “I thought the information was interesting, but I didn’t really see how it could apply to my studying, and so I didn’t change anything.” The many comments like these made me decide to start making students do metacognition experiments. Those students have been much more likely to report that they changed. Those who did about ten or more experiments nearly all described specific things that they changed, sometimes soon after doing specific experiments. For example, many students who compared reading while listening to their playlist of favorite songs versus reading with ocean wave sounds discovered that they were more focused, faster, and/or had better understanding with the ocean wave sounds. If they were sleepy when they studied, sometimes music helped them stay awake. Those students began to pay attention to their level of interest in the reading, and they adjusted their selection of music, ocean waves, or silence to match the text that they needed to read. (A few students tested the sound of rain as well as ocean waves, and several reported that rain sounds seemed to make them want to pee.) Students who found
that after 6 hours of sleep it took 50% longer to solve the same problems than it took them after 8 hours of sleep began to make sure they got to bed earlier on the nights before exams.

If you want to get better, you cannot skip the experiments. You will learn enough about your studying from these first experiments to change a few things. (Of course I don't know what, because I cannot guess your results!) Some of those first changes will work, though some might not. Most importantly, you will discover questions about your learning that you never thought you would have. Your questions will, I hope, spark new experiments on your learning. If I am successful, you will never stop testing your own learning. Never. In fact, experiments designed by my students just last semester, as I wrote this book section, gave me ideas to test for my own learning. I changed some things. I never guessed that would happen—that my students who were testing their own learning would teach me new things.

Starting the metacognition experiments

I'm going to have you start with some specific experiments. These will, I hope, give you some interesting results as well as show you how to construct and run a metacognition experiment. As you start, pay attention to how the experiments are worded as well as to your results. Later, I'll have you design experiments of your own, based on your own questions (or some of mine).

Keep in mind that there is nothing magical or especially important about any specific metacognition experiment. Any experiment that gives you useful, practical information is worth doing. The first experiments that I want you to do many of my students found interesting. You have to start somewhere, and this is where some previous students started.

This first experiment will be on your working memory. We'll have you try to decide how many chunks you can hold in working memory at one time. We don't care what your answer is; in this case the important point is that you understand what it feels like to overload your working memory. You can think of your working memory capacity (how many chunks you can hold) as being like the number of eggs or small balls you can hold in your hands. Holding a few things is easy, but trying to hold too many eggs or balls is impossible. You might hold them for a moment, but then they start to slip out and are lost. (It's pretty exciting to try this with eggs!). As I said above, I don't actually care about the answer, because how smart you can become has much less to do with your working memory capacity than with how you use your working memory. My working memory capacity is very ordinary, except when I haven't had enough sleep. If I'm short on sleep, it's terrible, but so is everyone else's.

This experiment will demonstrate the principles of working memory capacity. Try to talk a friend into doing it. In this experiment your friend's hands represent his or her working memory capacity. Eggs represent the chunks they are trying to hold in working memory. Buy some eggs. Next, add eggs to your friend's hands, one at a time, until your friend drops one or more eggs. Your friend's working memory capacity is the number of eggs (chunks) he or she could hold before the first one falls. After you clean up§, repeat this a couple of times to check that you get approximately the same number each time. Once you know this number, you'll know two

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§ It's less messy if you do this with plastic eggs (the kind that can be opened and filled with candy) or with any other rounded objects about the same size. It's more entertaining if you use real raw eggs, but someone else in your house may get upset.
important things: (1) how many eggs your friend can safely carry at one time, and (2) what it feels like when your friend is overloaded and the eggs are starting to slip. Working memory is just like that: you can safely carry only a certain number of chunks in your working memory at one time. It is very helpful to know what it feels like as the chunks are starting to slip out of your memory.

I mentioned above that we don’t really care about the actual number you get for your working memory. Why is that? Because your working memory is only a tiny part of how you learn. Think again about carrying eggs. If you add eggs together in bigger chunks (in egg cartons, bags, or small boxes), you can carry far more eggs at a time. In the same way, you group and connect facts and principles in your head (Figure 4.1). There’s another reason we (and you) don’t care what number we get for your working memory capacity. That number is not exactly the same for different kinds of chunks—not the same for number of digits you can hold in working memory versus number of shapes you can hold in working memory (or faces, colors, and so on). Again, what we really care about is that you know how it feels to start dropping eggs, as the too-many chunks flutter out of your overloaded working memory.

**Metacognition experiment 1: Working memory capacity**

**Purpose:** To test the capacity of my working memory for random numbers

**Methods:**
1. List 20 random one-digit numbers and spend 30 seconds reading over them and attempting to memorize as many as possible.
2. Wait a brief interval of 10 seconds.
3. Attempt to write down as many as I can remember in the correct order.
4. Repeat five times with a new list of numbers each time to eliminate outliers, ensure consistency, and give me plenty of numbers to average together to estimate my working memory.

**How you’ll decide:**
My estimate for my working memory capacity is the average of the scores from the five trials.

**Results and Conclusion:** (An example from one of my students)
After listing the numbers and learning them for 30 seconds, and then waiting 10 seconds before listing them, my scores (or the number of numbers in the list I got correct) were 7, 13, 4, 7, and 6 digits. My best estimate for my working memory capacity for digits is the average of those 5 trials, 7.4. In the outlying trial with 13 correct, I found myself chunking the list into groups with two or three digits, which led to the much higher score in this trial than in the others. If you exclude the trial with 13, my average is 6.

Please do Metacognition Experiment 1 for yourself now. Keep in mind that this is not a competition. Do try to do your best. If you wish to, you can redesign it for yourself for example by doing letters instead of numbers, or by doing a list of words chosen at random.

The next experiment is about whether silence, music or “white noise” (like rain or ocean waves) might be best to help stay focused during studying.
Metacognition experiment 2: Music and reading

**Purpose:** To test the effects of different music and noise on reading and retention.

**Methods:**
1. Use a random number generator to assign a number to each of four different music and noise conditions—no noise, music with words, music without words, white noise like ocean waves—then order the treatments numerically. (My order was music without words, music with words, no music and white noise.)
2. Read 15 page sections of a book assigned for a class using the first noise condition and time how long it takes, including rereading due to lack of focus and having to go back to understand concepts.
3. Repeat for the other noise conditions.
4. In order to have a trial with a different kind of reading, repeat steps 1-3 with novels from my freshman seminar.

**How you’d decide:**
The faster I can read will indicate the type of sound situation that allows me the best retention.

**Results:** (An example from my student)
While reading a book I was assigned for class, *Four Fish*, reading while listening to music with no words took me 24 minutes and 5 seconds, with music with words took 26:40, without music took 23:15, and with white noise (ocean waves) took 23:10.

While reading for the novel from my freshman seminar, reading with music with no words took me 22:00 minutes, with music with words took 22:13, without music took 17:51, and with white noise took 23:57.

**Conclusions:**
When reading something that interests me (my Freshman Seminar reading), I read much faster in general than I do when I am reading something more technical that I am obligated to read (*Four Fish*). When I am reading something technical, I read faster while listening to white noise, blocking out all other distractions. With *Four Fish*, I found myself getting distracted by the music, with or without words, and by the people around me if I was not listening to anything at all. While reading something I found very interesting (the novel), I was able to tune out everything no matter what I was listening to. However, I read much faster when I did not have anything to tune out (no music). The longer time reading the novel with white noise can be partly attributed to the fact that the first part of the novel I was reading was much duller than farther into the book. My conclusions are that when I read something technical, I should listen to white noise and when I read something of interest, I should read in silence.

Please do this experiment as soon as you can with reading material required for a class and then something for fun. You may change parts of the experiment. For example, you might want to try shorter sections (10 page sections?) or longer sections (entire chapters?).

Notice that the student whose results I shared discussed the amount of times she was distracted, but did not actually record each time she found herself distracted. Perhaps she was incorrect in her recall of distraction. Some of my students doing this experiment made a tick-mark each time they discovered that they were distracted. Those students did not have to guess at their level of distraction. Other students also tested comprehension after each reading by
doing end-of-chapter questions for each type of reading and recording the number of correct answers.

The same student who reported being distracted also reported that reading with white noise took longer for the novels but then decided that the difference did not matter. That is dangerous. It is risky to conduct an experiment, but then decide not to trust the results—not to trust your data. If you cannot trust your data, then you cannot reach a conclusion. What should be done is try to obtain better data. In this case, the obvious thing to do is more trials. In fact, the students who changed their use of white noise, music, or silence when they read planned to do more comparisons. They knew that single trials might easily fool them. However, it is easy to time yourself in more trials of assigned readings, and that is an easy way to have more confidence in your conclusions for this experiment.

Metacognition experiment 3: How does amount of sleep affect problem solving?

**Purpose:** To determine how sleep affects the capacity of your working memory and your ability to solve complex problems.

**Methods:** (adapted from Dr. Heideman)
1. Create two sets of multiplication problems of similar difficulty with varying numbers. For each set, have a problem with number of digits multiplied as 1x1 digit (such as 3x5), 1x2 digits (such as 7x23), 1x3, 1x4, 2x2, 2x3, and 3x3.
2. Examine each number set to ensure there aren’t any obvious shortcomings that would make the problem easier to solve. (For instance, 12 x 12 = 144 is something I remember, so I would try to avoid picking a number like that).
3. Solve set number one after having six hours of sleep, and set number two after having eight hours of sleep. Solve both sets three hours after waking up.

How I’ll decode:
Things to record are:
1. Which problems you are able to solve correctly from each set?
2. Do you make any mistakes in solving problems (i.e., Do you get an answer that you think is correct but is actually wrong?);
3. Do you get stuck at any point?
4. How long does it take you to solve problems of each size with six and eight hours of sleep?

**Results and Conclusion:**

1x1 digit: Solving 6x7 and 8x4 were both instantaneous and correct on both six and eight hours of sleep. I would assume both of those are in my mind as automatic recall.

1x2 digits: Solving 7x83 took me 9 seconds on six hours and solving 6x34 took me 7 seconds on eight hours, and I got them both correct.

1x3 digits: Solving 9x203 on six hours of sleep took me 10 seconds, and solving 8x957 took me 15 seconds with 8 hours of sleep. However, the number 203 has a zero, so that’s essentially a spot I could skip in solving 9x203. I probably should have changed that beforehand. With more than 1x3 digits, I started noticing differences.
1x4 digits: Solving 9x3842 took me 40 seconds on six hours, and solving 3x2578 took me 17 seconds on eight hours. Although I would concede that the first problem was a bit more difficult, it took me more than twice as much time to solve the problem with less sleep.

2x2 digits: Solving 46x38 took me 37 seconds on six hours of sleep (I used a short cut: 38 is almost 40, so I can do 46x40, or 46x4 and then add a zero. I got 1840, and then I know that 46x2=92, so I can subtract that from 1840 to get 1748.) Solving 92x18 took me 24 seconds on eight hours of sleep. (I used a similar short cut: 18 is almost 20, so I can do 92x20, or 92x2 and then add a zero. I got 1840, and then I know that 92x2=184, and 1840-184 is 1656.) Since I used almost the exact same short cut for both of the problems, my time difference (37 seconds compared to 24 seconds) should still be accurate.

2x3 digits: 31x923, which I broke down to 923x30 + 923, took me 84 seconds to solve. I spent two minutes halfway through solving it, forgot one of my 10s digits in my final answer, and so had to add them again. It was very difficult, and I would say probably maxed out my ability to mentally solve problems with six hours of sleep. Solving 74x312 on eight hours took me 42 seconds (half the time of the other). It might have been a bit easier, but the time difference is still huge, and I only paused once, and I didn’t have to restart the problem.

3x3 digits: I was unable to solve 232x459 in my head with only six hours of sleep. I spent two minutes struggling to connect the numbers and remember the digits in the right order. Even with a strategy (solve 232x460, subtract 232), I was unable to complete the problem. I had a similar strategy for 983x471 (983x470, add 983) I had to eventually give up on that problem, too. However, I did stick with it longer on eight hours of sleep (almost three minutes) before I gave up.

The biggest impact a lack of sleep had on my ability to solve increasingly complex problems was the time. It took me nearly twice as long to solve the problems with six hours of sleep as opposed to eight. There wasn’t a big difference in the level of complexity that I could handle. I would assume that’s because I know my basic times tables, and so I just had to be able to recall the right facts and the numbers in the right order. However, recalling them took longer when I had less sleep. This would be important to know for test taking and even while studying. If I am well rested, recalling facts or compiling an answer during a test would probably take me less time. This would leave me with extra time to review. I can also save time in preparation, because if I am well rested while studying, I won’t struggle as much to recall important details or organize information.

Please do your own version of Metacognition Experiment 3 as soon as is reasonable. Please do not deliberately get less sleep just in order to do the experiment! Wait for a day on which you get the appropriate amount of sleep, and then do that piece of the experiment. If you never get eight hours (ouch), then you might want to compare 5 versus 7 hours of sleep, or 4 versus 6 hours, or perhaps set a day in which you CAN get eight hours of sleep. In contrast, if you always get plenty of sleep, then perhaps there is no reason to do this experiment right now.

This is an experiment that would be more reliable with more trials. Let’s take the example of one of my students. He could have done two or three or four trials with each set of digits on the same day or one trial each on several days with 6 hours of sleep and trials on several other days with 8 hours of sleep. However, he chose not to run more trials. First, he found that on all of the more complex problems, it took him longer to solve the problem and he was more likely to feel confused. There were enough of those results for him to conclude that lack of sleep could slow him down and cause unnecessary confusion. He might also have been
influenced by the results of other students in the class who ran versions of this experiment. He may have decided that others in the class were probably like him. I think that reasoning is a little risky; the results of others may not apply to him (or to you).

An interesting difference between this student’s results and those of others is that other students found that they were more likely to think that they had a correct answer that were in fact wrong while his were correct. That might have been because this student likes math and had practiced a lot, and he was able to do more complex multiplication problems in his head than most others. Unless he does more trials, we cannot know. With so few trials, he (and we) cannot know whether he makes fewer mistakes or just did not happen to make a mistake on these problems.

Metacognition experiments take a little time to understand past the Fish-level, which is why I have you start with experiments designed by my college freshmen students. For more ideas, check the website that goes with this book. With their permission, I'll be posting my student’s experiments and my comments. You don’t really need any of your own experiments, because many of those designed by other students will be good for you to try. That's good, because it is a little harder to design your own experiments or modify the ones my students and I suggest. As you gain experience, however, you'll probably find things you just want to know about yourself.

Box 5.1 Checklist, controls, quantification, and biases for metacognition experiments

As you begin to perform metacognition experiments, they will not be perfect. Some will have bias – especially a tendency to get the results you want or believe. Some will have other kinds of error. This box contains a checklist of things to consider. Some of your conclusions will be incorrect. I’m not too worried about that, because to succeed at this you only have to understand your own learning better than you do now. Students in high school and college usually have many, many misconceptions and incorrect beliefs about their own learning. In my experience, metacognition experiments don’t seem to make my students worse. Instead, people get better at discovering their errors, even if at first they have biases and make incorrect conclusions. Your goal doesn’t have to be perfect understanding of your own learning. You just need to understand your learning better than you do now.

CHECKLIST to include in metacognition experiments:

1. Title, purpose/Introduction, methods, analysis/decision rules, results and discussion
2. Does the purpose/introduction make reference to concepts in the readings?
3. Sufficient information in the methods to understand the experiment?
4. Important variables controlled?
5. Decision rules/analysis clear?
6. Results include quantifiable measures (if possible)?
7. Necessary sketches or other materials attached?
8. Any biases?

Controls, Quantification, and Biases
Chapter Five: Workshop 5.1. Introduction to Metacognition Experiments

1. Controls
   • Often, a control treatment is whatever you normally or typically do
   • Variables to control
     o Environment
     o Time of day
     o Level of exhaustion/sleep
     o Distractibility (e.g., hunger, noise)

2. Quantification for Assessment
   • Time
   • Number of questions correct at the end of the chapter
   • Number of points correct or number of mistakes - drawing, words/terms
   • Number of pauses/hesitations
   • Number of pages read or problems solved
   • Problem solving (example: multiplication without paper or other aids)
   • Subjective information that might supplement quantified measures
     o Rating for comfort and/or understanding
     o Stress level
     o Focus level
     o Interest level
     o Ability to explain

3. Biases – potential problems that could invalidate your conclusion and that are variables to control (see above)
   • Familiarity and comfort level old/new - old is familiar, might be more comfortable
   • Uncontrollable variables - other classes/assignments, life events, amount of sleep if multiple-day trials
   • Content -> difficulty level? not sure what you intend symbol to mean. Content should be more difficult?
   • Non-random assignment of treatments
   • Comparison of mind map to outline (apples to oranges comparisons)
   • Confirmation bias (preconceptions)

To Reduce Bias
   • Quantitative comparisons
   • Controls when possible
   • Multiple trials (runs)
   • Convince a friend (or enemy) to try it
Chapter Six
Transfer

What is transfer?

Transfer occurs when you make a new connection. The new connection is two or several chunks that you already have in memory. In the process you have “transferred” an old chunk (like the number 5) or a set of procedural rules (for multiplication or algebra) to a new and different situation, but you don’t start that way. When you learned numbers and began to learn addition, you first learned rules for adding just one pair of digits. You practiced $1 + 1 = 2$ and $2 + 2 = 4$ over and over until you had them in fluent memory. You started out by memorizing the symbols and the concept. Eventually you mastered the concept of addition, and you developed a deep understanding of the concept of adding a pair of numbers. Knowing that $1 + 1$ makes a total of 2 does not automatically tell your brain that $2 + 2$ will be equal to 4. You had to learn that the concept of addition and the procedural rules of addition could be applied to OTHER numbers. You had to be told that the rules would work for $2 + 2$, and $3 + 3$, and even $4 + 5$. You had to learn to transfer rules to any pair of numbers.

With practice, you learned to transfer the concept of addition of specific numbers to a new connection. After successful transfer, you had a set of procedural rules for transfer to addition problems you have never seen before: Any two numbers can be added to equal a new number—their sum. Even though you have never seen the following problem and these numbers: $398,753,409,379,828,701,984,837 + 113,850,934,840,985,084,858$, you know that the addition rules will apply (Figure 6.1). This is a simple example of novel transfer. You have taken old knowledge (addition rules, the concept of numbers, an understanding of digits and ordering of digits in numbers) and applied your knowledge to a new situation. Your rules are effective and reliable for addition problems. You know immediately that you can solve the problem above and that you cannot solve the problem: $2G72 + 138$.

![Image](image.png)

6.1 You transfer concepts from what you learned to completely new situations and problems.

New transfer is hard. Your brain could connect ANY two facts or concepts or sets of procedural rules. Most of those connections would be nonsense—"Multiply beans times apples." Our brains seem to resist the transfer of concepts, probably because most new connections
would actually make us less smart as in asking ourselves how tall a tree is in grams.

Here's an example of a problem with transfer. Imagine we have a group of children who know how to calculate the area of a rectangle—the length times the width—as well as a square and other geometrical shapes. Now, we give them an envelope and ask them to calculate its area. This actually has been done in a research experiment. Some children would be puzzled (Figure 6.2). No one has taught them how to calculate the area of an envelope. They know that rectangles are lines on a page or sometimes cutout shapes. But no one ever says, “I am going to send a letter in this rectangle.”

This problem requires transfer: the children had to transfer the concept of a rectangle to the concept of an envelope. The children had to decide that an envelope is a kind of rectangle. This is not so simple as it sounds. Some apples and pears, for example, have the same shape. A large orange can be very like a small grapefruit. An orange is even somewhat like a yellow apple. However, no matter how similar they look, apples are not pears, and oranges are not grapefruit. Children know this. They know that similar objects are not necessarily the same. Long before the study, the children had been taught that a rectangle is not necessarily a square, even though they look VERY similar. Apples can look more like pears than envelopes look like rectangles. If you had asked the children, “Does that envelope sort of have the shape of a rectangle if you look at it the right way?” they would have said yes. However, the children might also have pointed out that if you hold it in some ways, an envelope looks like a straight line, and if you hold it in other ways it looks like an irregular polygon. In fact, an envelope only looks exactly like a rectangle when you look at it straight on, with your angle of view precisely perpendicular to the surface of the envelope (Figure 6.3).
Figure 6.3 We can transfer of the mathematical rules for rectangles to use with other objects.

When children in the original study were asked if an envelope is similar to a rectangle, they could solve the problem. The new information was: an envelope can be considered a rectangle. With this new information, the children could carry out transfer successfully: I know the formula for the area of a rectangle, and an envelope can be considered a rectangle, and so I can use the formula for the area of a rectangle to calculate the area of an envelope. I hope you see the point here. It is not as easy as it seems to transfer the formula for area of a rectangle to use with an envelope. In fact, the brain is doing the correct thing to resist transfer. We do not want our brains to suddenly decide that an apple is a pear.

What might happen if the children were asked to calculate the area of a rectangular-shaped tabletop? They might be puzzled again. Think about a tabletop. Have you ever seen one that is EXACTLY a rectangle? Probably not. Tabletops have corners and edges that are at least slightly rounded; if they didn’t, we would get scraped every time we bumped hard against a table edge or a corner. If you showed a student a geometric figure shaped like a real tabletop, the students SHOULD tell you that the formula for area of a rectangle does not apply, because the shape has rounded corners. If the students were asked if the tabletop is sort of like the shape of a rectangle, they would be able to solve the problem. The new information is: tabletops can be close enough to the shape of a rectangle that we can use the formula for area of rectangle to calculate the area. That allows transfer.

At this point, the students might have enough information to develop a procedural rule: When I need the area of some object in the real world, I should check whether it has a shape sort of like a rectangle when looked at in the right way. If it does, then I can use the formula for area of a rectangle to calculate area of the object. This still isn’t easy. Ask yourself if a computer screen or a book seen from the edge is close enough to a rectangle to use the formula. What about a door, or a window, or a computer printer, or the seat of a chair? Look around yourself right now, and decide how many things are close enough to the area of a rectangle that you could use that formula for area? Also, for how many of these objects does your angle of view make them look like they are not a rectangle? It gets difficult. From the proper angle, an unsharpened pencil may look like a rectangle. Should you apply the formula to an unsharpened pencil seen from the side? Maybe, but probably not.
Many students hate word problems in mathematics or physics when they first get them. Word problems are challenging because they ask us to transfer. They force us to make transfer decisions, without telling us if our decisions might be wrong. How can a child predict that a teacher thinks a tabletop is enough like a rectangle to use the formula for a rectangle? How can a child decide that an edge of a building is enough like a straight line to be considered a straight line and the angle of a wall with the ground enough like a right angle, to use rules of geometry or physics? The edges of buildings are clearly not straight lines if they are made of boards, bricks, or blocks or if they have windows, ledges, or decorations. How can a child decide that an imaginary line from the roof to the ground is like a line on a piece of paper, and that the ground itself is like a straight line? The ground is so obviously NOT a straight line! In fact, the only way to make the ground appear to be a straight line would be to stand in a pit with your eyes at exactly ground level, and even then it would appear as a straight line only if someone has carefully flattened out the ground to make it even more flat and smooth than most sidewalks!

As we learn transfer as part of problem-solving skills, we learn many rules like: *A is enough like B that we can use rules about B on A. However, A is not enough like C to use rules about C on A.* You have learned thousands of these rules, for everything from reading and writing grammatically correct sentences to the use of different models of phones or computers. This kind of correct transfer is an extremely important part of our education and our lives.

**Procedural rules for novel transfer**

Often, my students are unable to answer a question even when I know that they have fluent recall with understanding of all of the information they need. When they see a problem that requires transfer, they often think that they just need to study harder to memorize the answer. However, what they really need to learn are procedural rules of novel transfer.

Here is a usable Fish-version of a set of procedural rules for novel transfer:

1. What do I already know that is similar?
2. Are any of the similar things enough alike that I can use the same procedural rules to answer a question or solve a problem?
3. Can I attempt to get an answer with a set of procedural rules I already know?
4. Can I check my answer to test whether it contradicts anything else I know?

As an expert reader, you use these rules all the time. These rules help you understand a sentence with a word you don't know. Remember my sentence from Chapter One, “The thirsty little girl was given a glass of *tubig*?” When you read a sentence with a new word, you (1) check your memory for similar or related words that might fit (*tuba*, *too big*, or from context, *oil, juice, water*, or *gasoline*), (2) decide whether any of those words are alike enough to solve the problem of the meaning of the sentence (*tuba* and *too big* don't make sense; the others could all be in a glass and are something a thirsty person could drink), (3) test any words that might fit, (4) check your best answer to see if it fits. The nearby sentences in a paragraph allow you to check for contradictions. You would make different conclusions for the most likely interpretation depending upon the following sentences. Compare your conclusions if the next sentence was one or the other of the following: “After drinking half of the glass of *tubig*, the little girl was no longer thirsty.” or “After drinking half of the glass of *tubig*, the little girl was severely ill.” As you make your decision, you have carried out novel transfer with your conclusion on the meaning of the sentence.
As an expert reader, you reach conclusions that are either correct or close enough to correct most of the time. If the little girl was no longer thirsty, you might have concluded that tubig was water (correct), juice (incorrect but close enough), or that you weren’t sure whether it was juice, water, or a soft drink (close enough).

Expert readers apply these rules for novel transfer automatically. The rules seem simple (they are) and the rules seem easy (but they are not). You had to learn to apply these rules. You had teachers who taught you how to read, and you practiced reading, especially with challenging texts that often used words that were new to you.

As very young children, we apply transfer rules to almost everything. Children often come to incorrect conclusions. My young nephew recently concluded that the radios of old cars only give old news and old weather reports. He had learned that in an old car, all of the parts were old. He transferred that knowledge to the concept that anything that comes out of an old car will be old, including the news and weather from the radio. My nephew’s transfer rule is true for an old book, an old newspaper, an old magazine, and an old CD. However, when my nephew transferred this principle to the radio of an old car, it turned out to be a transfer error, even though he followed rules of transfer correctly. As we get older, our mistakes of transfer become more costly to us. That can be because we are embarrassed and ridiculed, because inappropriate transfer takes away points on tests, or because the mistakes result in damages or pain. My students are often reluctant to apply the rules for novel transfer. They know that the costs of mistakes can be high. However, that makes it very difficult for them to explore their knowledge and reach new conclusions from old chunks.

Transfer is hard and slow. Memory is easier and quicker. When faced with any problem or question, we first check our memory for a memorized answer. If we have seen the problem or question before and memorized an answer, memory provides the fastest and best solution. If the problem is novel, we check for memorized procedural rules for this kind of problem that might provide an answer. If we have no procedural rules for the problem, we are likely to give up or guess. For example, in my sentence “The thirsty little girl was given a glass of tubig” you can use your procedural rules for novel transfer. However, if I give you the sentence “Moinom lamang akog tubig,” you decide that your procedural rules will not provide an answer. **You will probably give up.** Often, however, we think that we cannot find an answer when in fact we actually know the chunks and procedural rules that we need. Remember the children trying to find the area of an envelope? They could find an answer, but they needed to follow procedural rules for transfer.

You can improve your learning if you (1) understand the procedural rules for novel transfer and (2) learn how to discover and practice specific sets of rules for new situations. I have gone through two examples in which you are already skilled. The first was application of procedural rules to solve novel addition problems. The second was application of procedural rules to discover the most likely meaning of a sentence that includes a word that you do not recognize. Next, I want to take you through an example that I hope you do not know, with a type of problem for which you are most likely not skilled.

**If you are a Cebuano reader, you recognized that the sentence above means “I'll just drink water.”**
Chapter Six: Transfer

An example of complex transfer: the bacterial ruler

An entire large category of scientific questions centers around the sizes of things. In some cases, the sizes of things are very important (will X fit into Y?). In other cases, the sizes of things help us decide whether we have a reasonable answer to a question or problem (“Could these small spots on a microscope slide be a dangerous new virus?”). In biology, it is often important to know the approximate size and the relative sizes of things.

Imagine that I ask you to think about objects in and around a house and to rearrange the objects in order from smallest to largest: house, car, bus, person, truck, horse, banana, statue, dog, tree, warehouse, chair, factory, lamp, and table. You could do this easily, and most people would agree with your list, even though some arrangements are not always going to be true. For example, while most dogs are smaller than most people, some dogs are larger than many people. If I asked you to estimate the height of each object, in either meters or feet, you could do that as well. For any of the thousands of familiar objects you know, you can estimate relative size and height and width. You have procedural rules that compare those objects to other things whose size you know in order to estimate their lengths.

Now imagine that I ask you instead to take another list of real objects and rearrange the objects in order from smallest to largest. All of these items are small: bacterium, molecule of fat, DNA (genetic material), ribosome (a structure that makes proteins), chromosome, water molecule, virus, human intestinal cell, mitochondrion (part of a cell that makes the energy molecule ATP), protein molecule, sugar molecule, fungal spore, insect muscle cell, and pollen. Next, estimate a length for each. Even though this problem follows very similar procedural rules, it is very difficult for college freshmen or sophomores in a biology class; most of them make serious errors. To answer this problem, you need to have (1) fluent recall with understanding of the units of measure for objects in the size range of micrometer, nanometer, and angstrom, (2) the equivalent of a ruler (we call it the ‘bacterial ruler’), and (3) FRUCO of the relative sizes of some common objects the size of molecules, parts of cells, and cells. If you think about it for a moment, you will realize that you have all three of these chunks for the task of estimating sizes of house, car, people, and so on: (1) centimeters or inches, feet or meters, (2) chunks for the lengths of centimeters, inches, feet, or meters, and (3) a sense of comparison of sizes, for example that people are usually about 1 to 2 meters or 3 to 6 ½ feet.

Later in this chapter, I take you through the steps to develop skills at this complex transfer task. These skills are in the required high school science standards in the US. The skills are useful in many areas of science, because size estimation on the micro- and nano-scale is recognized as important for a basic understanding of in science in all countries. You don’t need to do that exercise (though it’s a good one); you do need to understand how this is a challenging transfer problem that requires the same procedural rules, some new chunks, and correct transfer.

Skills in solving one kind of problem often do not transfer to new kinds of problems

How well does a skill with one set of procedural rules transfer to a different but related kind of problem? Not well. Each new skill needs to be learned and practiced. In a paper in 1980, a researcher described his work with a college student who practiced over a year to glance at and remember any new number as a string of many digits. At first, the student could only remember the first 7 digits. After a year of practice, he could memorize around 70 or more. However, the student did not actually remember 70 individual digits. Rather, he remembered...
bigger numbers as groups of digits that he recalled as single chunks. For example, imagine that 1913697826628414579310 happened to be the number 1 followed by his postal code, his grandmother’s postal code, the number 2, and then his home phone number. If so, he only needed five chunks: “1,” postal code, postal code, “2,” and a phone number. Did this skill transfer? Apparently not: when tested with random strings of letters, the student was back to remembering only about the first 7 letters.

You have probably mastered addition, subtraction, multiplication, and division in base 10—the mathematics that we do all the time with the digits 0 through 9. If I asked you to do mathematics in base 7, which includes digits 0-6, and after 6 comes 10-base-7, which is equal to 7-base-10, you would probably find it very difficult. Skills in one topic do not transfer well even to a closely related topic without practice.

**Recognizing when transfer is necessary to solve the problem**

When a teacher or professor gives you a problem they expect you to solve, but you have no idea how to solve it, then you are quite likely to have a transfer problem. It may be that you have forgotten a chunk or procedural rules that you are expected to have in fluent recall, but often the problem is that you need to transfer old chunks to a new situation. You have to make at least one connection that is not yet in fluent recall for you.

My teachers and college professors often gave me problems that I could not solve as they seemed to have no connection to anything I had seen before. After I gave up, the teachers would say, “This is simple! For problem Y, you just had to do this, and then this, and then this. Isn’t that clear?” It was clear, but only after they did the transfer for me. Understanding their explanations was not at all like having found for myself the right connection out of many possible connections.

This is the same problem that all students face with word problems in mathematics and physics (and medicine, business, and law). When you don’t understand, perhaps it is a transfer problem. If you know it is a transfer problem, you can start looking for connections using the procedural rules, the background knowledge, and application of transfer.

Here is an example. Imagine that you are asked, “What number times itself equals 804,609?” Without transfer, the simplest set of procedural rules to solve this problem is start with the number one, and multiply every number by itself until the product is 804,609. You would quickly realize that following these procedural rules will take a long time (1 x 1 = 1, no; 2 x 2 = 4: no; ... 11 x 11 = 121: no; ...21 x 21 = 441: no; ... 117 x 117 = 13,689: no; ... 897 x 897 = 804,609: YES!). If we understand the concept of a square root, we can apply transfer, even if we have never seen this kind of problem before. Transfer could tell us that this number must be the square root of 804,609, even though the term square root does not appear in the problem.

Here is another example. With a piece of string, a typical water glass, and a ruler, calculate pi. If you’ve never had this problem before, give it a try. (Read on without trying if you wish.)

You may recall that pi is equal to the circumference of any circle (the distance around a circle) divided by the diameter of that circle (a line across the middle of the circle). The formula is also easy to look up. However, you need transfer to recognize (1) that the top of a typical water glass is approximately a circle, and (2) that string can be wrapped around the outside of
the glass (the circumference). You probably do not need transfer to know (3) that you can find the length of the string and diameter of the glass using the ruler. The length of the string wrapped around the water glass divided by the width across the top of the class will give you an estimate for pi. Even if you know the formula for pi, it isn’t easy to transfer to the water glass, string, and ruler. (I know this is a challenging transfer problem, at least for me, because I couldn’t solve the problem when I first saw it.) We are like the children struggling with the area of an envelope.

Recognizing when transfer is the solution

Learning requires transfer. Developing skills at transfer is a big part of the goal of an education. However, once we’re adults, it is possible to have a job that involves relatively little transfer. Once you know the necessary facts, concepts, and procedural rules for a job, you may be able to do it without much transfer. Novel transfer may not be important to an adult in a job he or she has had for several years. However, novel transfer is important for the highest success in school, and transfer is important for the development of expertise.

You can develop transfer in two ways. One is to have every new piece of transfer told to you and to memorize it in the right context. The other way to develop transfer is to learn procedural rules for making connections (the study technique of mind maps is one of these procedural rules). Learning procedural rules for transfer is scarier and messier for humans. It is easy to be wrong, just as my nephew was wrong about what comes out of the radios of old cars. There are many ways to make incorrect connections as well as correct connections. My example of the bacterial ruler has this problem. I have been using the bacterial ruler for years, and I still sometimes make mistakes on something new. However, the skill of novel transfer is so valuable that it is often worth making mistakes. In my case, I make an occasional mistake when I use the bacterial ruler, but I would make many more mistakes if I did not use it.

When I hear the phrase think outside the box, I say to myself, “They mean I should transfer.” The phrase think outside the box means making a useful, novel transfer—coming up with ideas by combining old knowledge in new ways.

Requirements for transfer

In order to use transfer, you first need to know enough of the facts and concepts in that subject. The bacterial ruler in Box 6.4 below is impossible to use without facts and concepts. You need the concepts of animal cell, bacterium, virus, protein, DNA, element, molecule, and chemical bond. You need the concepts of units of measurement as well as the concepts of millimeter, micron (micrometer), nanometer, and Angstrom. You need facts, such as the fact that proteins and DNA are parts of viruses, bacteria, and animal cells, and that viruses get into bacteria (or animal cells) and produce more copies of themselves, and that animal viruses are surrounded by cell membrane stolen from the cell in which they were produced.

These concepts and facts have to be in fluent recall with understanding. If you cannot remember what a virus is, or what a virus does, or what is in a virus, you cannot carry out transfer with that part of the bacterial ruler.

For any new transfer (how large is a mitochondrion? a nuclear pore?), you need to have a clear understanding of those concepts and facts. In addition, you probably need to have each
of those additional concepts and facts in fluent recall with understanding. If you cannot remember what a nuclear pore is when I say the words *nuclear pore*, then you cannot carry out any new transfer connected to nuclear pores. Often, I have a student who thinks that they are bad at transfer (especially at word problems) when the actual problem is that they don’t yet have the concepts and facts in fluent recall with understanding. *FRU* is necessary before you can develop *CO*. Only when they have the concepts and facts as *FRU* can I tell whether a student is having trouble with transfer with that subject.

**Incorrect transfer**

An important part of transfer is deciding when a concept does not transfer or when a concept gets in the way of transfer. In order to communicate with other people, it is very important that we do not use transfer in some novel way that destroys meaning. The problem of incorrect transfer is common when we learn a new language. I remember vividly the time I felt embarrassed when talking in Spanish to a student in Mexico, and tried to tell him that I was *embarazado*. He was completely puzzled, because the word does not transfer. In Spanish, *embarazado* means pregnant. Even though they sound similar, the words do not transfer.

During time I spent in the central Philippine Islands, I was learning the language Cebuano (related to Tagalog). Cebuano has mostly words from ancestral pre-Hispanic inhabitants of the Philippines. About 10% of words are derived from Spanish (*lamesa* for table), and a few are from English (*notebook* for notebook). In Cebuano, for historical reasons objects are counted with Cebuano numbers (*osa, duha, …* for one, two, …), but time is told and counted with Spanish numbers (*uno, dos, …* for one, two…). At first, I did not understand this separation. I was in a food market one day, hungry for mango fruit, and I asked for *dos mangos*. The seller looked at me in surprise, and told me that it was not yet two o’clock, and did I want mangos? It was as if I had asked, “May I have two hours of mangos?” The concept of numbers for time did not transfer to the concept of numbers of fruit.

For those of you who are not Cebuano speakers, think about this for a minute. Time is not a thing that you can touch; one hour is not like one mango. However, you can talk about *una hora*, so why can’t you ask for one mango? There is a problem: if one hour is like one mango, then 60 minutes is also like one mango. In Cebuano, *duha* represents two objects. You can see and hold *duha* objects in your hand, and you can add 2 + 2 objects to get 4 objects. You cannot see or touch time, even though you can see and touch a clock that represents time. You cannot add 2:00 a.m. + 2:00 p.m. to make 4:00 of anything. Nor is 1:00 p.m. 1/12th as much as 12:00 p.m. In fact, 1:00 p.m. is just a different time of day. Cebuano speakers have no trouble adding two hours to a time such as 2:00 p.m. and answering that two hours from now it will be 4:00 p.m., but they know that you cannot add two objects to a time of day.

My Cebuano friends who spoke English had no trouble using numbers correctly in both languages. When they spoke English, they used the word “two” for two objects and two p.m. That was not a problem, because they did not transfer the concepts as used in one language when speaking the other language.

**Incorrect transfer and wrong conclusions**

Incorrect transfer can be dangerous physically, and it can slow down our learning. For example, a child learns that it is interesting to touch something bright and glowing in a mirror or
on a television screen. The child often transfers this to mean that it will be interesting to touch a red-hot stove element or a flame.

Even unimportant transfer errors can be remembered a very long time. I still remember a silly transfer error I made at age seven in 1964 when I heard a new song, and was told it was by the beetles. I remember being laughed at when I said, “Beetles can’t play music.” (I was then told “It’s not beetles. It’s a band called ‘The Beatles,’ dummy!”). While the event was painfully embarrassing for only a short while, I still remember my transfer error of literal meanings for band names.

We often logically base our errors of transfer on what we know. One of my favorite examples of completely logical but incorrect transfer is from Dr. Marguerite Mason. She researches how children understand mathematical concepts. In one of these research tests, she gives children of various ages cutout paper triangles of different kinds to sort into groups. Many children group together all of the right triangles (a triangle in which one of the vertices is a right angle). However, some children separate some of the right triangles into two groups, depending on which way the hypotenuse faces. When Dr. Mason asks these children why they sorted the triangles into these groups, these children say they sorted the shapes into “right” and “left triangles.” Of course, there is no such thing as a left triangle, but their decision is a perfectly logical transfer. We learn the concepts of left sides and right sides, and children are often asked whether something is on the left side or right side. In fact, right triangles can be set down with the hypotenuse facing either right or left. If there are right triangles, then there ought to be left triangles.

The missing information for these children is that the concept of right in a right triangle has nothing to do with right-handedness and left-handedness. Rather, the right in right triangles comes from the same Latin word root that forms the word ‘upright.’ A telephone pole or wall is upright and creates a 90° angle, a right angle, with a sidewalk or floor. However, there are no right- or left-handed telephone poles—only upright or not upright telephone poles.

When we carry out transfer on our own, without instructions, and perhaps with incomplete information, the chances that we are incorrect tend to be much higher than the chances that we are correct. Incorrect transfer is risky. Consider people who transfer the idea of the harmlessness of an American milk snake (having attractive colored rings and being good-natured and nice pets if you like snakes) to the similar-looking attractive but venomous and deadly coral snake. Every year, the death cap mushroom kills people with incorrect transfer. In some locations, people collect and eat edible mushrooms that look somewhat like the deadly poisonous death cap mushroom. In those places, the death cap mushroom is not present, so there is no risk to collecting and eating mushrooms that look a little like the death cap. When people move to a new area that has death cap mushrooms it is deadly to transfer their concept for the kinds of mushrooms that are safe to eat.

Incorrect transfer can be risky, but often we need skill at transfer in order to solve new problems. To minimize the risks of transfer errors, we can learn methods to minimize mistakes, and we can test our results for the possibility of errors.

Transfer improves from learning with understanding

In an early study on learning with understanding (Judd, 1908), two groups of children were directed to throw darts at an underwater target. The challenge with this task is that water
refracts light, which means that the target appears to be in a different location than the actual location. Throwing at the apparent location of the target results in a miss. One group of children was given an explanation of refraction, while the other group practiced without the explanation. Both groups became equally good at hitting a target 12 inches underwater. However, when both groups were given a chance to throw darts at a target only 4 inches underwater, the group that had learned about refraction adjusted quickly and hit the target more often. Understanding the abstract principle of refraction helped them transfer their skill to a new situation.

Students who only memorize may master a specific skill as fast or even faster than students who memorize with understanding. However, those who only memorize will be much worse at transfer to any new situation. Over time, this problem builds up. Students who memorize must approach each new piece of information as if it is entirely new, and they must memorize everything. Students who memorize with understanding (hopefully with FRUCO) gradually pull further and further ahead. More and more learning tasks take the form of Oh, this new concept D is very similar to concept A, and related to concepts B and C. When I put them all together, D is obvious. All I need to do is remember that D is somewhat similar to A but follows from B and C, and then I don’t have to memorize D.

In another study, two groups of students were taught either a rote method to calculate the area of a parallelogram or a method with understanding for the same problem. Later, when both groups were given additional area problems with parallelograms or other geometric shapes, the students who learned the method with understanding performed much better. Those who had learned the rote method responded to the new questions by saying, “We haven’t had that yet.”

Transfer and context

We learn anything new in some context. We first learn the word “vessel” in some context, such as “She was given a vessel of water to drink” with just one definition and one context: a container for water used for drinking. Gradually, with learning the definition of a boat and the connotation of large size we know we can apply the word vessel in more contexts and with more connotations, such as “The 200 men sailed in that vessel to an island in the Mediterranean Sea.” With each new use, we use transfer to create new connections between the word vessel and the various definitions and contexts.

We also learn procedural rules in a specific context. Think again about the study on children using a formula for the area of a rectangle in different contexts. What they learned in only one context (the area of a rectangle drawn on paper) could NOT be applied in a different context (the area of a real object that was somewhat like a rectangle when viewed in one way). It is quite literally true that their brain cells did not have the connections to apply the formula for a rectangle in a different context. Too much application of a concept or procedural rules in only one context makes it difficult to transfer the concept or procedural rules to a different context. Children who practice geometric formulas ONLY on ideal rectangles, triangles, and circles on paper cannot transfer to a new context–similar shapes in the real world. For these children, word problems about the area of an envelope or a tabletop are impossible. Children (and adults) must practice word problems in multiple contexts in order to make their knowledge most useful.

If you learn something and study it in only one context, you will make it harder to develop expertise. Unless you continually try to connect new knowledge to old knowledge (transfer, in other words), your knowledge will be limited to that single context. You may be right more of the
time because you avoid transfer errors. However, you slow down your progress in learning toward becoming an expert.

Flexible transfer requires practice. Often it requires that you be active in seeking connections for yourself. A study in 1980 showed this very nicely. College students were given a passage that needed the same concept to solve two problems. In one case, related to an army invading a town, the solution was provided. In the other case, related to the use of x-ray beams destroying a tumor, the solution was not provided. Few students were able to solve the tumor problem on their own. However, when told to think about the information in the problem of the invading army as they solved the tumor problem, 90% of them succeeded. The few students who solved the problem without the hint most probably did one extra step: they asked themselves, “Why was I given these two passages to read together?” and answered, “The first passage probably has information to help solve the problem in the second.”

A real example of contextualization comes from the problem of a real person needing three-fourths of two-thirds of a cup of cottage cheese. Let us imagine a man who understood fractions and multiplication of fractions from school mathematics but who had never applied mathematics to measuring cottage cheese. Using grade school mathematics, we can solve the problem by multiplying 3/4 x 2/3 to get 1/2 cup (3 x 2 / 4 x 3 = 6/12 = 1/2 cup). Instead, the man filled a cup to the 2/3 marking with cottage cheese, emptied it onto a plate, patted it into a circle, and removed 3/4 of the circle for the recipe, putting the other 1/4 of the circle of cottage cheese back in the container. This kind of practical solution to problems is common: people who learn mathematics in school often apply different tools and tricks to do everyday mathematics in a store or at home. The contexts in which we learn tend to be the contexts in which we apply our knowledge.

To improve transfer, try mind mapping.

I wish I had some magical way to make my students skilled at correct transfer. Some people argue that transfer skills cannot be taught; they just happen as expertise develops. I don’t agree. I think that I had courses and professors who helped me understand how to make new connections for myself and use those connections to solve problems. First, I had to learn when not to give up. My professors had to show me that even when I thought I had no way to solve a problem, that if I didn’t give up I might find one.

Second, I had to learn that successful transfer requires seeing a connection that I hadn’t noticed before. Those connections are not yet in our memory. When we make memories, they are physical: cells in the brain and the connections between those cells. The only way to make a new connection is by creating new physical connections between cells. Those new connections don’t happen automatically; connections between neurons have no way to know that there are other, related concepts encoded by other memory traces. New connections shouldn’t happen by themselves, or else we would be forever making connections that make no sense, such as asking ourselves what time are two apples. Useful new connections for transfer need to happen because you think of two or more things together, and you notice the possible connections.

One way to make new connections you’ve never seen before is to sit and think of every chunk you have, testing the jumbled chunks you pull up for connections. But that’s not a very helpful or useful way. The best way I know is to make what are called mind maps. In mind mapping, you start with any chunk you have, written or sketched in the middle of a piece of paper. Then you think of any other chunk, and see if it has a connection. If so, you connect it
with a line, and maybe put a label on the line. On and on you go, adding chunks in a spider web of connections, and checking each new chunk to see how many places it connects. In the process, some will be new connections you've never noticed before.

Usually, I recommend mind maps to students for a different reason: to develop and improve FRUCO. Students can use mind maps to practice the connections and organization among chunks that they already know, building FRUCO. Of course, each time anyone checks in his or her head about a chunk and possible connections, that person is also doing retrieval practice for each chunk and related chunks. That retrieval practice (or recall practice) is one of the most effective ways to strengthen memory traces, so mind mapping helps improve fluent recall with understanding as well as develop connections with organization. Each time my students make a new mind map, they are practicing their old connections and previous memory traces.

There's another way to use mind maps that might help develop transfer. When I write a difficult transfer problem for an exam, the students who get correct answers often tell me that they had noticed the "new" connection before the exam, in some kind of mind map during studying. For my students who are frequently missing the correct answers on transfer problems (especially multiple choice transfer problems), mind mapping as part of their studying before exams seems to make them better able to answer those transfer problems.

I can't promise you that mind mapping really will improve your skills at transfer. I just don't know, and I don't have good evidence. The experts who argue that you cannot teach or learn transfer might be right. The best I can tell you is that mind mapping might help.
The bacterial ruler

In everyday life, we determine the exact sizes of things by measuring them—a slow process that requires at least a ruler. Usually, an estimate is enough. (Does this button fit through a buttonhole? Will this shirt fit? Is this glass or plate too small? Will that car or bicycle fit through a tight space?) We make these estimates automatically by comparing any new object to something related in our mind: That photograph is shorter than my hand, and so it is less than 6 inches/15 cm long. In science as in everyday life, estimates are often good enough.

Whenever you need to solve novel problems of some kind, you need two things. First, you need to have related chunks in fluent recall with understanding. Second, you need to have practiced procedural rules to solve that kind of problem. In this case, the novel problem is that we are estimating the sizes of things that are too small to see or to measure with a ruler. If I asked you to estimate the size of mouse, a goat, or a bush, you could do that easily by comparing them in your mind to a ruler. For the very small cells, microorganisms, and molecules, we can see sketches, movies, or magnified photographs, but we cannot see or measure them directly. Without a ruler, and without anything for comparison, we have to give up or guess.

The procedural rules we will use are the same ones you use to estimate size of something in a home photograph or a painting: comparison to an object whose size you do know. If you see a bush or a dog next to an adult person, and the bush or dog is a little more than half the height of the person, you would estimate that the bush or dog is about three feet/one meter in height. That part of these procedural rules at least seems simple: comparison of any novel object to something you know.

The chunks you need are in two categories. One category is the units of measure, because centimeters, millimeters, inches, and tenths of inches are all far too big. The second category is that of familiar objects to use for comparison. You need fluent recall of the chunks. You need appropriate connections between the chunks. You need organized connections between the chunks. You could learn the chunks you need in many ways, but most are poorly organized for efficient learning. The bacterial ruler is the fastest way I know to organize and learn the necessary chunks. It is based on the common bacterium from human intestines: Escherichia coli. This species of bacterium is approximately 1 micron wide. One micron is 1/1000th of a millimeter. One millimeter is about the smallest length it is easy to see when you hold up your thumb and forefinger just slightly apart to indicate a distance. One millimeter is also fairly close to the thickness of a toenail or thumbnail.

We’ll start with this question: How big is a typical human intestinal cell? You might have in fluent recall an answer to this question. We’ll still solve it using the bacterial ruler in order to check your memorized answer for accuracy. To solve this problem using the *E. coli* ruler, you need fluent recall with understanding of these facts: an *E. coli* bacterium is 1 micron wide and 2 microns long. In figure 6.4, I show you an *E. coli* ruler, with a width scale bar (1 micron) and a length scale bar (2 microns), two flagellae for movement (they actually have a few more flagellae), and the symbol for micron (which is another word for micrometer). To start developing fluent recall of these chunks, close your eyes and try to picture the important parts of this figure: the E. coli, the lines with scale bar for width and length, and the words and symbol for micron. (Please do this now—you’ll need it for later!)
Figure 6.4. The “ruler” part of the bacterial ruler is a bacterium, specifically the human intestinal bacterium *Escherichia coli*, or *E. coli* for short. *E. coli* make a useful imaginary ruler because they are about 1/1000 of a millimeter, which is one micrometer, also called a micron. In order to have it feel like a real object, it is useful to sketch one occasionally, with the scale bars next to it as well. We use this ruler to compare up and down to things that are larger or smaller. In this drawing, you might notice the bacterial virus sitting on top of the *E. coli*, shown at about the right size, about 1/1000 of a micron.

To get a sense of how large a cell is, you need to memorize an image of what an *E. coli* looks like next to a cell. This tells you the relative size. In Figure 6.5, I have sketched an *E. coli* ruler next to a typical human cell. You can see that the human cell is approximately 10 times as long as our *E. coli* ruler.

![Bacterial Ruler](image)

Figure 6.4

**Bacterial Ruler**

*Escherichia coli*

<table>
<thead>
<tr>
<th>Micron (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 µm</td>
</tr>
<tr>
<td>2 µm</td>
</tr>
</tbody>
</table>

Figure 6.5 An *E. coli* ruler next to a typical human cell, including the nucleus (which holds the genetic material of the cell). If we can see or imagine an *E. coli* next to some object, then we can estimate how much bigger or smaller the object is.

Here’s how we apply procedural rules for transfer to estimate size of new molecules, cells, or parts of cells:

1. **What do I already know that is similar?** Answer: I have in fluent recall with understanding a chunk showing an *E. coli* next to a cell. I also have in fluent memory with understanding that an *E. coli* is about 1 micron in size (more precisely, about 2 microns long and 1 micron wide).

2. **Are any of the similar things enough alike that I can use the same procedural rules to answer a question or solve a problem?** Answer: yes
(3) **Attempt to get an answer with one set of procedural rules.** Answer: *an intestinal cell is approximately 10 times longer than an E. coli. 10 x 2 microns = 20 microns.*

(4) **Check your answer to test whether it contradicts anything else you know.**

Answer: *(in my case) I think I remember correctly that a typical human cell is about 20 microns in diameter.*

So how is this better than memorizing the words “a typical human intestinal cell is 20 microns long?” Memorizing the nine words is much easier than memorizing those images and terms and the procedural rules! If the goal was just to learn the size of an intestinal cell, then memorizing those words is much easier. However, our goal is much bigger: I want you to be able to estimate the size of any biological cell, structure, or molecule. You could start memorizing all of them, but there would be far more than a million things to memorize. It will be much faster to learn to estimate any of them. In addition, memorizing these two sketches and the terms improves your Fish-version for the concept of micron and your concept for sizes of biological structures. With just a few more chunks associated with the *E. coli* ruler, and by connecting and organizing those chunks well, a student can estimate the size of any of these millions of kinds of cells, micro-organisms, and molecules. As soon as my students can close their eyes and see the *E. coli* next to the human cell in working memory, they have connected chunks on relative sizes. Even this small amount of information on relative sizes helps them solve other problems, such as how many *E. coli* or other bacteria might fit inside one infected cell. The image immediately suggests that far more than 100 *E. coli* bacteria might fit inside one infected human cell. This image also helps solve new problems, such as determining the width of the nucleus of a typical human cell.

Every cell has a cell membrane around it, much like the rubber of a water balloon or the plastic of a plastic bag full of water. When we ask a completely new question, such as how thick the cell membrane is, we need some new chunks in fluent recall with understanding. First, we need a chunk that is not related to size estimation: *a lipid bilayer membrane surrounds all cells, including bacterial cells.* That chunk allows us to make a first guess for the thickness of the membrane, phrased as *the cell membrane must be thinner than a bacterium, and so the cell membrane must be less than 1 micron thick, and probably less than 1/10th micron thick.* While you cannot know for sure, from just these two images, you can probably tell me that the cell membrane is less than 1/10th of a micron. You need another chunk: *1000 nanometers equals one micron.* Therefore, 1/10th of a micron is 100 nanometers, and your first estimate is that a cell membrane is less than 100 nanometers thick. That isn’t correct yet, but it is more than you could say without the bacterial ruler.

In size estimation, it is useful to approach the estimate in more than one way. In this case, you can learn new chunks that allow you to check your first estimate. Look back at Figure 6.4 to find a little bump on the top side of the *E. coli*, a little to the left of the middle. That’s a virus. Specifically, it is a type of virus that infects a bacterium. A new image for you to learn (fluent recall with understanding) is the virus next to or on an *E. coli* ruler.

If you look closely at the bump on the *E. coli* ruler, you might be able to tell that it is about 1/10 as tall as the bacterium is wide. If I blow the virus up in size so that you can imagine it more clearly (Figure 6.6), this particular virus looks like some strange space ship, or perhaps a
Bacterial Virus
('bacteriophage')

Figure 6.6

A bacterial virus, or bacteriophage, is shown next to an E. coli and then blown up to larger size. A typical virus is about 100 nm in size.

spider with a long neck. Whatever it looks like to you, this virus is about 1/10th of a micron—or 100 nanometers long (or tall). The hexagon at the top is the cap or capsid, and the capsid carries the genetic material of the virus and a few proteins. If you could see it close up, the capsid would look like the wall of a very small building made out of building blocks or Legos. (Notice that I’ve given you a Fish-version for a capsid here, using chunks I hope you already know: building blocks and Legos.) In this case, each Lego or building block is one protein molecule. You can’t easily see the individual protein molecules unless I show you a larger image of another kind virus shown in Figure 6.7.

A simple human virus

Plasma membrane
(stolen from a human)

Figure 6.7

A simple human virus has a capsid and a cell membrane stolen from a human. A cell membrane might be about 1/10 of the 100 nm, or about 10 nm. A typical membrane is actually about 6-8 nm, but 10 nm is a great first estimate and good enough most of the time. Also in this figure, I show the protein building blocks of the capsid at about its real size. A typical protein molecule is about 5 to 10 nm.

How do these chunks help us check our answer for how thick a cell membrane? You need another chunk: viruses that infect humans and other animals have a cell membrane around the capsid. That is something you may or may not remember from high school or middle school biology—viruses of animals have a capsid surrounded by some cell membrane that they steal as they leave the animal cell in which they grew. In Figure 6.7, I show a simple human virus with the stolen plasma membrane and the protein building blocks of the capsid wall.

So, is it possible that a cell membrane is 100 nanometers thick? No, not according to our use of the bacterial ruler. The entire viral capsid is about 100 nanometers, including the membrane surrounding it. According to our image and our ruler, the thickness of a plasma membrane looks like it might be about 1/10th of the length of the viral capsid—10 nanometers. That’s a good estimate, because typical plasma membranes range from 6 to 8 nanometers thick. If you have developed fluent recall with understanding of the full bacterial ruler, you could go on to check our 10 nm estimate, using other parts of the bacterial ruler. When I make my students develop fluent recall with understanding of the bacterial ruler and procedural rules to use the ruler, they KNOW that this is close to the correct answer.
Applying the bacterial ruler to estimate size seems like it might be a very simple task, but it is not. Students can make wrong answers week after week. They have to make connections with transfer that they have never made before.

Here is another problem I give my students, and it’s a good one for you try if you want to. How large is one of the amino acids in an enzyme? That is hard because my students have all learned about enzymes, but they didn’t learn their size, which is usually not very important. My students have learned that enzymes are proteins and that proteins are made of amino acids in a chain. My students may know which atoms form part of amino acids (usually only carbon, hydrogen, oxygen, and nitrogen), and maybe learned the way these atoms are connected to form an amino acid. They may remember that amino acids can be negatively or positively charged or to remember that one end has an -NH₂ (called an amino group) or to remember that amino acids in proteins are joined by peptide bonds or to remember that an enzyme converts one molecule, a substrate, into another molecule, the product. None of those facts or concepts associated with amino acids and proteins helps solve size problems. When those facts enter working memory, we need to test them for usefulness. We must push useless facts out of working memory to make room for review of other facts.

What my students do not have in fluent recall is (1) a tiny ruler, (2) fluent recall of the sizes of some small biological structures, and (3) practice with the rules to apply the bacterial ruler. Here is one useful set of procedural rules they often use:

First step: find one thing on the ruler that is certainly larger than X (in this case, X is the amino acid, but you could also do this to estimate the size of an enzyme).
- Since amino acids are the parts of a protein, then a protein must be larger than an amino acid.
- Preliminary conclusion 1: An amino acid should be smaller than the length of a protein.
  - A protein on the bacterial ruler is about 10 nanometers across, so an amino acid should be shorter than 10 nm

Second step: find one thing on the ruler that is certainly smaller than X.
- Because the elements carbon, nitrogen, and oxygen are part of amino acids, then an amino acid must be larger than an element (and longer than a chemical bond between two elements)
- Preliminary conclusion 2: An amino acid should be larger than the length of an atom or a chemical bond.
  - Because a bond between two carbons is about 1/10 of a nanometer, an amino acid should be longer than 1/10 nanometer.

Third step: try to find something else that is certainly larger (or certainly smaller) than X.
- Preliminary conclusion 3: Perhaps we can’t find one, in which case we just go on.

Fourth step: Choose a length between our two estimates. A good rule is to guess that X might be as many times bigger than the smaller thing, as X is smaller than the larger thing.
- In other words, an amino acid might be 1/10 the length of a protein and might be 10
times the length of a carbon-to-carbon chemical bond.

**Final conclusion:** An amino acid is about 1/10 of 10 nanometers (which equals 1 nanometer), and an amino acid is about 10 x 1/10th nanometer (which equals 1 nanometer). An amino acid is about 1 nanometer long. This is quite close.

When a student has the procedural rules, these size estimation problems begin to be possible. They can become easy for you with more work and practice. It takes three things: (1) practice applying the rules, (2) fluent recall of enough facts about biological molecules, biological structures, chemistry, and units of small size, and (3) previous transfer that connects information about different molecules and structures to each other. For example, to find the size of an amino acid, you would need to remember that somewhere you learned that a protein might be made of around 100 or more amino acids connected together like links of a chain. You would need the fact that in a protein, the long chain of amino acids is twisted around into a sort of blob, like piling a chain on the floor or twisting and scrunching 12 inches of string (or 25 cm of string) inside your hand. In addition, these two facts need to be connected already by previous transfer. Finally, you need to drop from working memory any information that is not useful. Students who have these chunks for an amino acid and a protein as fluent recall with understanding still cannot solve the problem unless they have learned and practiced the procedural rules.

**New chunks about transfer**

Here are seven new concepts with terms that are new chunks to remember from Chapter 6:

1. As a Fish-version, transfer occurs when you make a new connection between two or more chunks.
2. New transfer is hard and slow (memorizing is easier). Incorrect transfer causes mistakes.
3. It is possible to learn how to make new connections when we need them.
4. Transfer improves from learning with understanding, connections, and organization -- FRUCO.
5. Mind mapping is a method of making new connections that can help develop transfer.
6. Procedural rules for novel transfer are to checking for parts of a chunk that are similar or related to other chunks. When you notice a possible new connection, it can be tested to see if the connection makes sense and fits with other connections. You can also check whether a new connection is contradictory with old chunks and connections.
7. Skills at solving one kind of problem often don’t transfer to other kinds of problems.
Chapter Seven: Information Reduction

Chapter Seven

Information Reduction

To learn something new, you need to be able to turn it into a chunk. As you learn, you can only use the spaces in your working memory to hold the old chunks you are combining to learn as a new chunk. That means that the new chunk must be made up of no more than seven things in working memory. The fewer spaces you have to use, the easier you should be able to learn the new chunk.

Often, a new chunk is presented to you as an explanation with terms, examples and a diagram. All of these are important as you begin to understand the concept. However, to think of them all at once, you often need more than seven spaces in working memory. That's not possible. Fortunately, developing a new chunk does not often require that most of the information be in fluent recall and sometimes not even in recognition memory. The problem is figuring out what you need in fluent recall with understanding (the FRU of FRUCO). I call that process information reduction.

I'll give you some examples, starting with a Fish-version:

(1) Fish, Fish, Fish, Fish, Fish, Fish, Fish, Fish, Fish, Fish
If you remember it just as I presented it, you need 10 spaces in working memory.
Information reduction: “Ten Fish” = 2 spaces in working memory.

(2) 1234567891011121314151617181920
If you remember it just as I presented it, you need more than 20 spaces in working memory.
Information reduction: “numbers 1 to 20, in order” = about 4 spaces in working memory.

(3) “The large cat went up a tree, out on a large branch, but failed to catch the squirrel she was chasing. She noticed a bird nest and waited nearby. When the female bird returned, she leaped up and caught the bird. However, she missed the branch and fell to the ground. She was not hurt when she landed, but when she opened her mouth, the bird escaped.”
If you remember it just as I presented it, this child’s short story needs about 16 spaces in working memory, if you retain just the key words.

**Information reduction (words):** “cat, branch, squirrel escaped, bird nest, jump, caught female, fell, unhurt, bird escaped.” = about 11 spaces in working memory.

**Information reduction (sketch):** If you tried right now to remember the story in the form of my sketch, as a sequence of stages, the sketch is easily held in working memory, making it easy to remember the story.

**Is information reduction helpful?**

Try it. Right now, find a stopwatch or a phone that can show time in seconds. Time yourself reading my story, neither rushing nor going slowly, but thinking about it as you read. *(It takes me about 11 seconds, but I wrote the story.)* Then time yourself going through the events in my sketch, neither rushing nor going slowly, but thinking about it as you go. *(It takes me about 4 seconds, but I made the sketch.)* Now try recalling the entire thing with your eyes closed, and imagining the story. *(It takes me about 5 seconds, if I imagine all of the events as pictures in my mind from the sketch.)*

I’m guessing you didn’t try my exercise above, because I probably wouldn’t have. Please do it anyway. It’s important and it will only take about 30 seconds. What was your result? I cannot predict which way will be faster or better for you, though I know what happens with most people. You have to test for yourself. Becoming good at information reduction can improve learning and reduce time for most people, but not for all. (By the way, no other person can do this for you, because you have to reduce the information to what you need for any concept, fact, or event. No one can read your mind to find out what it is you need.)

If you can study the same thing in a half or a third the time, is that useful to you? If studying is more interesting, would that be useful to you? If you find that you get bored while trying to change understanding into recall with understanding, information reduction might help. Memorizing by re-reading books and notes is one of the most boring things to do, and you
shouldn’t be surprised to learn that it is among the slowest and least effective ways to study. Information reduction is a lot faster and easier for me, but of course I’ve had practice.

**Trying information reduction**

In your next study session, try carrying out information reduction on one thing that you need to learn. You should make sure it is something that you cannot hold easily in working memory. Once you have reduced the information to essentials, check to make sure that nothing important is missing. Finally, do two things. (1) Time yourself reviewing the original material in your notes or a book in comparison to reviewing your version with just the important things. (2) Close your eyes (or stare at a wall or window) and compare how well you recall each version.

**Some procedural rules for information reduction**

These are not the only rules possible, but they will get you started:

1. List whatever you think might be important from your chapter or day or week(s) of material.
2. Pick the three most important. Start with those.
3. List the terms you need to know with fluent recall with understanding in order to understand the three most important concepts.
4. Start information reduction for each. This often begins with sketching or visualizing in your mind. Get ideas for sketches or mind pictures from (a) the book, (b) a lecture, (c) other people, (d) previous sketches or mind pictures you may have made.
5. Simplify.
   - (a) Are you using the absolute possible fewest lines and marks or letters?
   - (b) Have you included every essential chunk either in a sketch or because the sketch has enough to remind you of every essential part?
6. Redraw a final sketch version in which all terms and sketches fit on half a page and which has no words. Your words should all be off to one side. Even if you use mind pictures, this sketch is useful, because it gives you a quick way to review many weeks, months, or even years later. This final sketch and terms should contain **ALL** essential parts needed to understand the concept, either because the parts are in the sketch/terms OR because your sketch and terms automatically remind you of everything else you need to know. The final sketch and terms should include **NOTHING** that is not essential.
7. Practice the most important things first. A possible goal: practice until you have FRU of all of the most important topics on each of the three days before an exam.
8. If you have time, decide whether you should add additional important topics.

**An example of a very complex paragraph before and after information reduction**

It doesn’t matter whether you actually understand the following example very well. I chose, on purpose, an example that most people won’t understand. What I expect you to understand is that after information reduction, something that you cannot understand becomes easier to get. **The point is that the pictures really do contain all of the essential information, and I want you to see how much simpler the sketches are!**
Muscle cells normally have many more positively charged sodium atoms (sodium ions: symbolized \( \text{Na}^+ \)) outside than inside the cell. As a result, the inside of the cell is negative compared to the positive outside of the cell. A neurotransmitter chemical from a nerve cell can attach to specific proteins on a muscle cell. The attachment opens protein channels that allow \( \text{Na}^+ \) to enter the muscle cell. \( \text{Na}^+ \) enters partly because the positive charges are repelled by other \( \text{Na}^+ \) outside and attracted to negative charges on the inside. Any proteins inside the cell that have a charge change shape if more \( \text{Na}^+ \) are nearby. One of these proteins is a closed channel that allows the passage of calcium ions (\( \text{Ca}^{2+} \)) when opened. The \text{Na}^+ near the calcium channel protein causes the calcium channel to open. When \( \text{Ca}^{2+} \) enters the cell, it attaches to another protein. That protein causes the cell to shorten. (The cell shortens because of molecules we will describe later.) When muscle cells shorten, the entire muscle shortens, or contracts. The result is muscle movement.

As is, this takes at least 30 spaces in working memory and probably more. It is impossible to hold in your head in working memory at one time. Unless you already know about how muscles are controlled, this is probably impossible to understand. However, you can start information reduction on this topic.

**Information reduction (key words):** Muscle cell, negative inside, \( \text{Na}^+ \) outside, neurotransmitter chemical, proteins, channel, neurotransmitter attachment opens channel, \( \text{Na}^+ \) enters cell, \( \text{Na}^+ \) opens \( \text{Ca}^{2+} \) channel, \( \text{Ca}^{2+} \) enters, \( \text{Ca}^{2+} \) attaches to negative charge on protein, cell shortens, muscle shortens

These need about 22 spaces in working memory.

**Information reduction (chunked in sentences, each 3-5 spaces in working memory):**

- **Chunk 1:** Muscle cell, \( \text{Na}^+ \) outside, negative inside
- **Chunk 2:** Neurotransmitter chemical attachment protein channel for \( \text{Na}^+ \)
- **Chunk 3:** \( \text{Na}^+ \) enters cell, attracted to negative charge
- **Chunk 4:** \( \text{Na}^+ \) near a \( \text{Ca}^{2+} \) channel opens Calcium channel
- **Chunk 5:** \( \text{Ca}^{2+} \) enters cell and attaches to negative charge on a protein
- **Chunk 6:** Cell shortens, and so the whole muscle shortens

**Information reduction (sketches):** You can take the set of six sentences, and turn each into a simple sketch (or diagram or flow chart). That gives you a sequence of six sketches, each needing about 3-5 spaces in working memory, together telling a story.
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1. Sketch one has a muscle and a line from it showing a single cell. There is sodium with + charge outside and negative charge inside.

2. Sketch two shows a diamond that represents a neurotransmitter chemical from a nerve cell. While you may not know what a neurotransmitter chemical is, you do know that a chemical must have some shape. A diamond shape will do as well as any. This diamond happens to stick to a protein 'channel' on a cell.

3. In Sketch three, the neurotransmitter diamond has opened the channel, and sodium enters the cell. Why? Because the + sodium is attracted to the negative charge in the cell.

4. In Sketch four, the sodium has in turn been attracted to another channel, this one for calcium (Ca$^{2+}$).

5. Sketch five shows the calcium channel opened and Ca$^{2+}$ entering the cell. Why? Ca$^{2+}$ is repelled by the positive charge outside and attracted to the negative charge inside the cell. In addition, Ca$^{2+}$ apparently sticks especially well to one particular protein in the cell. That protein is shown as a line twisted onto itself.

6. Sketch six shows the Ca$^{2+}$ attached to the protein in the cell. Arrows show the cell shortening. Since the cell is part of a muscle, then the whole muscle should also shorten.

If you are learning about the molecules of muscles for the first time, the description of the events in words above gives you a Fish-version. The sketches I drew would also be a Fish-version. You could have drawn something like the sketches above based on the description.

Test whether information reduction was helpful for you

An exercise: Find a stopwatch or a cellphone that can show time in seconds. Time yourself reading my initial sequence of events in the paragraph about muscle contraction. Think about it as you go, and try to understand what is happening as well as you can, neither rushing nor going slowly, just thinking about it as you read. Unless you already understand muscle
contraction, the words alone won’t make much sense, I’m guessing. However, if you remember a few basic science facts [opposite charges attract each other, same charges repel, a cell, atoms such as sodium and calcium, and proteins have a shape that can change like opening and closing a door] then the words plus the sketches should be understandable. Here’s the important point: once you’ve read the text while looking at the sketches, you might never need the text again. You can probably just look through the sketches and remember everything important that was in the word description. (You might have to go back and check a few things.) I predict that the sketches are much, much easier for you to remember than all the text.

**Another exercise:** Stop reading and think back. Close your eyes or stare at the ceiling, and try to describe my story about the cat. Ask yourself, what is in my mind as I do this?

**Another exercise:** This time, think about what causes muscles to contract. Close your eyes again, and think about the steps and events to start muscle contraction. What’s in your head?

Which way of thinking about these examples was faster: the words or the sketches? If you compare the time needed to read with the time needed to look through my sketches, neither rushing nor going slowly, and thinking about it as you go, the sketches are probably faster and maybe much faster. (The sketches are probably also less boring.) Write down the number of seconds it took you to read my description, while thinking about it, and the number of seconds it took you to go thoughtfully through the sketches, in order, and thinking about each step. We’ll come back to these results later.

What I have been doing is showing you examples of the process of information reduction. You cannot hold a paragraph with 30 chunks about muscle in just 7 spaces in working memory. If you read it over and over, you will not even begin to understand this until you start making it into smaller chunks with the essentials. That’s information reduction.

**Information reduction to develop FRU (and why re-reading doesn’t work)**

If you have fewer things to put into memory as FRU, it’ll be easier. That should be obvious. Information reduction takes things you need to learn and turns them into the essentials that you need. That makes whatever you want to learn easier to remember. Information reduction also gives you a simple way to practice recalling the memory. That’s good, because recalling memories is what makes memories stronger.

My students often come to college believing that reading something over and over will help them remember it better and better over time. Unfortunately, re-reading a book or your notes or your highlights over and over is one of the slowest, poorest ways to develop FRU. Research studies show this. In one recent study, students were asked to read a chapter’s worth of text and practice recalling what they read, after which they reviewed (not just rereading) and practiced recall again. Another group of students was asked to study the chapter, with no instructions to practice recall. Two things happened. First, those who practiced recall did much better (more than double the number of correct answers). Second, those who practiced recalling what was in the chapter predicted that they would do worse than those who used other methods. For some reason, practice recall of our memories makes us feel like we are learning poorly, even though the memories strengthen when we recall them.
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Here’s what I think is happening. When you re-read a chapter or your notes, do you ever make a mistake? No. You get it right every time. How wonderful! Each time you re-read a chapter, it feels even more familiar, because you recognize it better. It feels like progress, but all you’re getting is recognition memory. In fact, because it is boring to read the same thing over and over, our minds tend to wander. We aren’t building memories. Now think about what happens when you practice recalling new chunks. You are building memory. However, what you notice is that you make mistakes. You forget. You can’t help noticing all your errors and flaws. That’s uncomfortable, and it makes us feel dumb. Even though recall practice is building fluent recall, doing recall practice makes us feel unprepared. In contrast, when we re-read we make no mistakes, and we always feel comfortable. We are fooled into choosing the wrong way—re-reading—to develop fluent recall.

Information reduction does three things for you. First, it simplifies anything new to the essential chunks you need. Second, it allows you to check your understanding, because if you don’t understand the new material, you cannot reduce it to essentials. Third, it gives you an easy way to do recall practice or “retrieval practice.” After information reduction, you have the new information in a form that you can practice easily, check quickly for errors, and know when you’ve practiced enough. How do you know you’ve practiced enough? You’ve practiced enough, today, when you can recall it. Go on to something else until tomorrow.

Why I suggest you should learn procedural rules for information reduction

Learning can happen only when you break any complicated topic into smaller chunks that you can hold in working memory. That is the major goal of information reduction. You start with a long and complicated paragraph or image in a book that needs more than 7 spaces in YOUR working memory. You break that topic into a sequence of one or more chunks that you can close your eyes and visualize or talk through in your mind. If you can visualize it in your mind or talk through it, then you are not overloading working memory. If you have a simple sketch that includes all of the important points and a list of key terms above or on one side, then you also have a fast way to review it whenever you need it. I have had students who were in medical school or doing research in graduate school tell me that they still refer back to sketches like this from years before in college. (My step-daughters could have made sketches like these in high school that I know would be useful to them in college classes, but they have not been enthusiastic about having me tell them ways to study.)

Why am I telling you to try information reduction? Because neither a book nor a teacher can do information reduction for you. Teachers can help, but we can only guess what might work for you; we cannot know. Only you can tell when you understand something at a first Fish-version level. Information reduction that you do for yourself will not be exactly the same as the best information reduction done for someone else. My sketches above are good information reduction for me, but my sketches are probably NOT the best way for you to do this information reduction! Of the many students who have adopted methods of information reduction, all tell me that, “My own sketches are always the best, though seeing the sketches made by you or by friends helps a lot.” No student has liked my sketches better than their own.
One last exercise

Please do two things. First, carry out information reduction for yourself on my cat story and on my muscle story. Your results might be very similar to mine, but try to improve on my versions. Second, try one additional step that is important in information reduction. Underline or circle any term that you do not already have in fluent memory (or effortful recall) with understanding. (*Recognition memory is not enough.*) If you were trying to learn this new information about muscles for a class, you would need to look up that term, develop a chunk for it, and begin to practice it.

Chunks about information reduction

The six new chunks for Chapter 7 are:

1. Information reduction is taking any information and reducing it to the essentials. Simplifying new information to just the chunks and connections you need – the essentials – makes it much easier to learn. Recalling the essentials allows you to explain it or solve problems.
2. Information reduction saves times when you are practicing memories (retrieval practice).
3. In order to do information reduction, you have to decide which parts of something new are essential, and which are not. That takes practice.
4. The essential chunks are those that, if you forget them, turn everything else into nonsense. The nonessential chunks are the ones that, if you forget them, have little or no affect on your understanding of the whole concept.
5. Sketching can be a useful method of information reduction. The final version of a sketch should include only the essentials – only enough to remind you about all the pieces you need to remember.
6. Rereading the same text over and over is a poor way to develop memories. First, you are not doing retrieval practice to develop memories. Second, you can’t do information reduction.
Chapter Eight: Sketching and Visualization

Chapter Eight

Sketching and Visualization

Why visualization works

In your science classes, and probably in many other classes, you have had to memorize many words and definitions stated in words. In fact, teachers encourage and develop this use of words so well that many of my students (and me, at one time) resist doing anything else. That’s a mistake, and in this chapter I’ll try to explain why. I will encourage you to develop and use your ability to sketch and visualize in mind pictures. (Even if you happen to be blind, the same skill is important, though it would be to imagine a physical shape as if you could touch it and hold it in your mind. In fact many people who are blind seem to be extremely good at this.)

Fluent recall with understanding of many, many words is an essential skill for learners. Though fluent recall is essential, in this chapter I want to convince you that it is not enough. In the sciences especially, most of what we learn has physical reality. In history, people, events, and conflicts all have physical reality. For things that have physical reality, we can think about them and understand them by seeing the things and events directly or by illustrations that show the things and events or by descriptions in words. Good descriptions in words are often called word pictures, because that is what good descriptions do. They bring up a picture in our mind.

How about abstract concepts that do not have physical reality? Abstract concepts can be presented as connections between real people or real things. We can show abstract concepts with examples that have physical reality. In fact, we usually develop our first fish-understanding of an abstract concept through explanations of things that have physical reality.

This brings up an important point. Words are abstractions. The word for “lever” is not a lever. The word “lever” does not look like a lever, feel like a lever, or sound like a lever. The word “lever” is an abstraction that we connect to the concept of a lever. We can connect the word lever to a definition of a lever: a rigid bar resting on a pivot, used to help move a heavy or firmly fixed load with one end when pressure is applied to the other (a definition I took from Wikipedia). We could connect the word “lever” to long written explanations about types of levers and the way levers are used. Written well, those explanations will give us a word picture about how a lever works.

The use of words has one serious limitation. We cannot use words alone to solve any physical problem EXCEPT one for which we have already memorized the answer. Imagine that we are given a situation in which we have to move a load. The only way to apply the concept of a lever to solve the problem is to have images in our head about levers and how levers are used. If the problem is to lift a heavy object with a lever, mind pictures showing ways to lift a heavy object can help. The words cannot. Let’s try this: Place the rigid bar beneath the firmly fixed load, while applying pressure on the pivot at the other end of the bar. My sentence is grammatically correct. It uses all the correct words. But the statement is wrong. Our load will not move if I push on the pivot. We can tell that the sentence is wrong only by imagining what sentence means. The words alone don’t make the problem obvious, but an image does (Figure 8.1). In order to solve a problem involving anything with physical reality, you have two choices: You can memorize the solution in words beforehand, or you can check an image.
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Figure 8.1 The concept of a lever shown correctly (top left) and incorrectly (lower three images). The bottom three images all match my sentence: Place the rigid bar beneath the firmly fixed load, while applying pressure on the pivot at the other end of the bar. In the sketches, it is easy to see problems. In the words, it is not.

My students who are good with words often resist this message. They argue that they are verbal or auditory learners and their way of learning is enough. They suggest that they do not need to improve their visualization or sketching skills. I argue back that it is great to be good at any kind of learning (and to keep that skill), but that is not nearly enough. To solve problems and do things with your knowledge, you need to be able to visualize what the words represent.

Box 8.1 Experts often think with images. Beginners usually don’t.

I have an assignment for you. Find a novice and an expert in their fields. Ask them to close their eyes, think of something difficult in their subject or job, and then explain it to you, still with their eyes closed. As they start explaining, watch their hands. The hands of a novice usually don’t move much. The hands of most experts are often moving as they explain, shaping imaginary objects and moving around them, often without even noticing that they are doing it. Next, stop their explanation, and ask, “What is in your mind?”

When I do this with physicians, scientists, and many others, they nearly always tell me that they are imagining the thing(s) that they are describing. Some start by describing an image or images they say they have in their mind. Most of the rest will confirm that they had images in their mind, but sometimes only if I ask, were you seeing anything? The exceptions are quite interesting—mathematicians, for example, often have quite different things in their mind (not images), and so do experts in philosophy. I haven’t tested many lawyers or literature professors on this, so I’m not sure what they would say.
What does this mean for you and your learning? Is visualization of mind pictures or sketching an essential skill? Is it worth your time to practice visualizing (and maybe sketching)? If all of your exams in classes and if all of your work in a job requires only that you give memorized answers to problems, then you might not need to work on visualization. If your tests only require you to memorize the answers in advance, or to solve problems that are just slightly different from problems that you have memorized, then you might not need visualization skills. However, if you have a lot to learn, and if your classes and your real life require you to solve problems you’ve never seen before, then you will need visualization skills. If your life requires that you know how to move an object you have never seen before, in a location you have never seen, and using a lever that you have never seen, you can’t just rely just on words.

Experts in any area of science or in practical trades (plumbers, electricians) seem to be very good at visualizing and, often, sketching. They solve new problems all the time by visualizing what they know and trying solutions on images in their head or sketches that show their ideas. Electricians, plumbers, computer experts, scientists, and physicians all move fluently back and forth from images to spoken words to printed words. People who don’t do use visualization are more likely to make a mistake, such as place the rigid bar beneath the firmly fixed load, while applying pressure on the pivot at the other end of the bar.

A great deal of experimental evidence shows that visualization and sketching skills are useful for learning in science. (That seems likely to be true for learning many other kinds of things, but I haven’t seen research on learning those other kinds of things.) Finally, I can tell you what has been most useful to my students who have improved from C, D, and F students to B and A students. In my own experience, developing skill at visualization and representing real things in simple sketches and drawings has been the single biggest thing to turn an ordinary or struggling student into a smart, fast learner. Will this work for you? I don’t know, but I do know that it isn’t that hard to begin.

Minute sketches as a tool for problem solving

Minute sketching is a method to turn any concept, structure, or event into a simple sketch that you can easily practice and recall. These sketches can also solve problems or make predictions in science. As you read, I hope that I will also convince you that this is how scientists work and think. Whether you plan to be a scientist or not, this way of approaching learning will, automatically, give you a straightforward method to solve problems.

A minute sketch is designed to teach students how to simplify a new term or concept to a sketch that has everything necessary to capture the concept for them. It is designed to be drawn quickly (in less than a minute; my actual rule is less than 30 seconds) so that you can reduce a concept or term to essential elements and hold it easily in your mind once you have learned it as a single chunk. (You can always capture anything too complex for a single minute sketch in a series of two or more connected minute sketches.) Each minute sketch is intended to be a chunk that you will learn if you practice it enough times with enough interest. Learning to use and create your own minute sketches is training in the chunking that develops expertise.

It takes time to learn to do visualization and sketching well. My students who sketch already, at least some of the time, can improve a lot, sometimes very quickly, once they realize that it is worth their time to practice. My students who have not practiced sketching and visualization very much (most of them) take months to start getting good at it. It seems to be
much like learning a new sport, musical instrument, or other skill. No one gets good without months of practice, but everyone always improves if they practice thoughtfully.

Many ways to do visualization and sketching take far too much time. Until you become good at drawing and visualizing simple sketches that represent EVERYTHING in your new concept, fact, or event, you will try to put far too much in your sketch or your imagined picture. Everyone does. Too much in your mind picture or sketch causes a predictable problem. You quickly overload working memory. To avoid overloading it as you try to develop manageable chunks, you have to create your own symbols, your own imagery, and your own ways to sketch. That takes time.

**Research on learning and minute sketches**

Minute sketching is an application of research on how people learn efficiently and how they use what they learn. Here are some conclusions from research that help us understand why minute sketching could be useful:

- Humans are highly visual, and use images, gestures, and symbols extensively in thinking.
- Different brain areas process images, written text, and spoken language.
- Humans have one focus of attention at a time; you can read text OR comprehend an image, but not both at the same time.
- Memory for physical skills and specific movement tasks (non-declarative skill memory) is independent and uses different brain areas from memory for words and observations (declarative memory). Skill memory is created by and stored in its own separate brain areas. (Other names for skill memory are motor memory, muscle memory or kinesthetic memory, all of which refer to the same thing.)
- Motor memory is far more permanent than memory for words and phrases.
- The fewer lines in a diagram, the easier it is to copy and remember.
- It is easy to recall a drawing that you can create in less than 30 seconds if you practice it just a few minutes a day over several days.

Minute sketches are intended to involve motor memory (or ‘kinesthetic memory’) in order to provide a second way of learning that is independent of word learning. This motor memory is also much longer lasting than word learning (or declarative memory). Words are banned from a minute sketch! This allows the brain to use only image-processing visual areas and motor areas when creating and using a minute sketch. When words are on an image, the brain has difficulty comprehending the image, because the image processing areas have to compete with text processing brain areas. Visual attention can be on only one or the other, text or image, not both at once. However, since associating the words with the correct terms is critical when actually using the concept, we can combine a second tool with minute sketches to make the connection between images and terms. This second tool, what I call the *Folded List*, is described in the next section of the chapter. It is a method to associate appropriate terms, key words, and phrases with sketches.

**Four steps for minute sketches**

You will have learned how to minute sketch when you can (1) create minute sketch diagrams and drawings that capture a definition or a concept and (2) use your minute sketches
for logical solutions to new problems. Below are four steps you can start with as procedural rules for creating minute sketches. You will probably find others that work better for you.

1. From lecture notes or a textbook chapter, identify an important process, concept or structure.
2. Write down the term for the process, concept, or structure, and then list the key words from the definition or explanation.
3. Create or find symbols for each key word or event.
4. Combine the symbols in a sketch that captures the definition or concept.

**Hint**: It is easiest for most users to start by studying with pre-prepared minute sketches for something they want to learn. Once students understand how to use them and can tell that they remember something very well surprisingly quickly, it makes more sense and is easier to learn how to create their own minute sketches, and do their own ‘chunking’ en route to becoming an expert.

**Step 1. Identifying important concepts or definitions**

Start with the most important item to learn, either in your notes or a book. As a beginner, you’ll just have to make an informed guess as to which is most important. It doesn’t matter if you’re not exactly right. With practice, you can figure this out: the most important topics are the ones that, if you don’t know them, will make it impossible to understand more of another topic. For example, if you’re studying molecular genetics, then DNA is critically important; you can’t understand anything else without it. The role of transfer RNA is less important; you can forget it, and still have a fairly complete explanation of many topics in molecular genetics, but you won’t be able to solve every problem that involves the growth of new proteins. The molecular structure of ribose sugar is probably unimportant; you can forget it and might still solve every molecular genetics problem you’re given.

Of course, if a teacher tells you which things are important, that will make this task simpler. However, it’s still incredibly valuable to develop this skill on your own. You’ll be making decisions on what is important to learn for the rest of your life. You’ll save a lot of time if you can decide that many things are not worth studying.

In the examples I give you here, we’ll create two minute sketches. The first, Example (A) is for some basic chemistry. Example (B) is the complex biological process of DNA transcription to RNA and RNA translation to protein.

**Step 2. Write down the term and key words from the definition or explanation**

Example (A) The key words for basic chemistry might include element, proton, neutron, electron, ion, specific important elements, water, crystal, covalent bond, sharing electrons, ionic bond, dissolved ions.

Example (B) Our second example involves DNA transcription and translation: the processes by which genetic material, a section of a DNA molecule, is first recopied as the related molecule RNA and then the RNA sequence is used to assemble amino acid molecules in the correct order. Here is a description of what happens, a description similar to what you might read in a textbook.
One or more transcription factors (or enhancers) plus RNA polymerase bind to specific sequences of DNA, allowing RNA polymerase to move along the DNA and make an RNA copy, including both exons and introns. Introns are cut out of the RNA strand, and the exons become the messenger RNA (mRNA). When mRNA encounters a ribosome, RNA begins to move through the ribosome. Transfer RNAs, each carrying their specific amino acid, bind to the mRNA in the ribosome, and their amino acid is added at the end of the growing chain of amino acids. Eventually, the ribosome reaches the end of the mRNA, and the chain of amino acids, now a protein, is freed.

The key words might include: gene, promoter, exon, intron, RNA polymerase, messenger RNA, ribosome, transfer RNA, and amino acid. There are other possible terms to include, such as codon, anticodon, start codon, and stop codon. You decide when you’ve included all of those needed for the problems you’ll have to solve.

**Step 3. Create or find symbols for each key word or events**

As you do minute sketches, you’ll start picking up a set of symbols that you’ll take from lectures or books or invent for yourself. If you can use symbols that mean similar things each time you use them, you’ll save time. It is important that the symbols in your sketch make sense to you. They do NOT need to make sense to others, but if you’ve got good symbols, other people will understand them. For example, you could indicate movement or time with arrows. Small symbols can indicate individuals (individual people, animals, molecules, or whatever). Different small symbols can indicate different people, elements, molecules, or animals.

Example (A): A circle with a plus might be a proton, an empty circle a neutron, and a minus sign an electron. (An electron is much smaller than a neutron or a proton.) Double arrows with a minus sign in the middle might indicate shared electrons, while double arrows that have a proton and an electron at opposite ends might indicate attraction of opposite charge without shared electrons in an ionic bond. Water molecules might have very tiny plus signs near the hydrogens in order to indicate that even though the electrons are shared, the electrons spend more time near the oxygen, which gives the hydrogen a slight positive charge and the oxygen a slight negative charge.

These mind images might give us the following minute sketches:
Example (B): For the more complicated example of DNA transcription and translation, some possible symbols include:

- DNA: double line to indicate paired strands of molecules with dotted lines across to indicate different parts of a gene (promoter, exon, intron).
- mRNA: a single line
- tRNA: a curved squiggly line
- amino acid: a small square
- ribosome, a small oval on top of a larger oval
- RNA polymerase protein: a solid or dashed circle
- Some other protein: a twisting dashed line
- Time or movement: an arrow

Here are the symbols, in the same order as the terms above:

Step 4. Combine the symbols in a sketch that captures the definition or concept

Example (A): I’ve already captured the concepts of basic chemistry in the sketch above.

Example (B): For our more complex example, we might start with DNA transcription: two parallel horizontal lines for DNA, a transcription factor plus RNA polymerase bound to the DNA, some messenger RNA starting to be produced, and with four segments of the gene. The four segments represent the promoter region, then the first of two exons, then an intron, and then the second exon. For a novice, this is a good sketch for a single chunk:

Below is the second part, new mRNA, out of which the copy of the intron is cut and broken down:
Chapter Eight: Sketching and Visualization

Here, I've combined the two parts in a single sketch showing the mRNA intron removal

Next (below left) the two exon segments of the mRNA have been reconnected and have encountered a ribosome (the two large ovals). The RNA is moving through and being translated into a protein (the string of tiny ovals) of amino acids (each little oval). I've also included a triplet codon (CGU) and transfer RNA coming in from the right. tRNA needs to have a correct amino acid bound to the tRNA, and then the tRNA-amino acid pair can move into the ribosome, where it binds to the correct codon gives up the amino acid to the growing protein. The sketch on the left was the first one I drew, but it was too complicated and too hard to picture. After practice, I realized that a simpler sketch (on the right) reminded me of almost everything.

A novice would learn each of these separately, each as a single minute sketch and each as one chunk. An expert might hold the entire thing as a meta-chunk (several chunks connected
to allow the group to be a single item in working memory)—the sketch below.

Realize that to create and use minute sketches, you first have to hear about and understand the whole process. Without an explanation, my minute sketch makes no sense at all. However, once you’ve read the chapter or heard the lecture, this sketch actually captures what happens in DNA→RNA→Protein:

Notice that there’s nothing in here that isn’t necessary; no extra lines, no colors, no shading (except that the proteins have more dots than needed; you could use fewer dots). That makes your minute sketch quick to draw and simple to think through (and keeps it the size of a ‘chunk’). And notice: there are no words on the diagram! At most, there are only single letters or initials, but no abbreviations. When you can, don’t even have letters on the sketch! Don’t ever break this rule. With practice and re-sketching, your minute sketches become even simpler:

While I’ve made the process seem simple, in fact, when you start, you’ll be slow to create new sketches. The hardest part is learning how to create good sketches, but that’s also an important part of studying. One of the reasons it is hard to create minute sketches is that you have to understand something before you can make a good minute sketch. Once you know the method, if you can’t create a good minute sketch for something, then you don’t yet understand the topic well enough. The correct use of minute sketching will force you to REALLY learn topics, not just memorize them. Once you’ve learned the method, you can create new sketches quickly as soon as you understand a concept.

Quite a few of my students have learned minute sketching just from these instructions. However, you’ll probably learn faster if you have someone who is good at it look at your early sketches and show you how to improve them. Most of my students learn the method faster when they get this kind of help.

**How minute sketches help**

A minute sketch shows all of the events in a way that is easy to remember. My students often scribble minute sketches on the margin of an exam to remind themselves. When I was a student, my teachers often let my use a sketch as part of an essay answer. Your teachers might allow you to use minute sketches in some answers.

Because you can only sketch one thing at a time, you sketch things in order. People start sketching at the beginning, and so minute sketches help you remember the order or sequence of events. I don’t even have to suggest that students sketch in a particular order. My students just do it automatically. They sketch a series of events from beginning to end.

Minute sketches help solve problems. They give you an image that is a tool to test possible answers. Imagine that a teacher (me) asks you how DNA transcription and translation might change in a cell if a person is starving. With a minute sketch, my students answer this question easily. Take a look at my sketch that shows transfer RNA and amino acids. A starving
person would have less food, so less protein in their diet and therefore fewer amino acids. With fewer amino acids, transfer RNA will take longer to bump into and bind a new amino acid. So there will be fewer transfer RNAs attached to amino acids, and it will take longer for a new transfer RNA with amino acid to attach to a ribosome. Once you see that, you have an answer: creation of new proteins should slow down, for reasons that you KNOW are logical. The important part is that with a minute sketch, you have an image that actually represents the real events. If a teacher tells you something has happened to X, you just look at your sketch to see what would change. (Here’s another question you might try for yourself: What might happen to the process if we added a drug that bound to and blocked the enzyme that cuts out introns?)

Memorizing only words describing a process is incomplete. You need a sense in your head of what’s actually happening. Memorized words alone won’t help at all. I might be able to memorize a Russian novel and I could “know” it perfectly, but that wouldn't help me answer any questions about the plot. (Why not? I don’t understand Russian….) My students can “know” biology in great detail and still fail an exam that asks them to solve problems. Those students have memorized all the words, but that’s only one step in problem solving.

Minute sketches help you think like a scientist. A minute sketch is a hypothesis: a model for a structure or a function or an event. In the sciences, new models (new minute sketches) are not yet known to be correct—we have to test them. In most of science, we do that by changing one part of our model or minute sketch—taking something out, adding a new piece, or doing something to change it. We then predict what SHOULD happen, based on our model—our minute sketch. That’s our prediction. Then we test our prediction in a real experiment. If our prediction is correct, then we have support for our hypothesis—our minute sketch. If our prediction turns out to be wrong, then there is an error in our model. Getting good at using minute sketches helps you get good at creating, using, and thinking with hypotheses and predictions in problem solving.

How long does it take?

How long does it take to actually get a minute sketch into our memory so that it will stay? My experience for most people is that redrawing a sketch 2 or 3 times a day, while thinking through the process, on at least three different days gets something fairly well into memory so that it sticks. That may seem like a lot, but it isn’t. Remember that minute sketches are small, and each can be redrawn in 30 seconds. Each time you redraw it you think through the process as you sketch (again, that’s important). Because you’ll find that you automatically recreate your sketch in order, from beginning to end of a process or structure, your motor memory helps you keep track of the order for you. Because you also use your motor or muscle memory in addition to your declarative memory brain areas, you’ll have more ways to remember the sketch. Often a student tells me that they couldn’t remember something until they decided to just start drawing, NOT YET KNOWING what they would eventually draw.

You are likely to find that you can use study time that was never useful before. It turns out that using your motor memory to draw while also using your declarative memory to think through your sketch makes it easier to concentrate. Most people find that they can practice and redraw their minute sketches in noisy crowds, on a bus or plane even when others are talking, or while other students are settling down just before class. You’ll be surprised the first time on an exam when you cannot remember something, and after starting to sketch in the margin, your motor memory brings it all back.
Chapter Eight: Sketching and Visualization

How long does it take to learn how to use and make your own minute sketches? If your brain already sort of thinks this way (in other words, if you tend to emphasize visual learning this general way, and if you like sketching), then you might improve very quickly. A very few of my students who try minute sketches go from C’s, D’s, or even F’s to A’s in a single exam if they work hard with minute sketches AND folded lists for several weeks. MUCH more often, it takes 3 months, 6 months or even a year to get good at using minute sketches as an effective study technique. Many of my students tell me, two or three years after I first showed them minute sketches, that they tried minute sketching, couldn’t get it to work, and so mostly gave up. BUT, every now and then they tried again, and by six months or a year later, they were using minute sketches in all or almost all their classes. Many also tell me that they’re able to learn things faster, with less study time than in the past, while also doing better on exams.

To learn how to make your own minute sketches, it’s good to do them as experiments. The experiments could test whether your minute sketches are useful. Your experiments could test your skill or speed.

Metacognition Experiment 8.1: Minute Sketch Speed

Purpose: To test whether I can get faster at making useful minute sketches

Methods:
1. Two times each week for 30 minutes create as many useful minute sketches as I can from the content of a class on that day or the day before. (Or 20 minutes? Or 15 minutes?)
2. If I cannot even get one useful minute sketch, I must stop trying at the end of the time. (I am allowed to go back and finish the sketch if I get an inspiration later.)
3. Continue for 15 weeks recording the number of useful sketches I make in each session. (Or five weeks? Or 10 weeks?)

How I’ll decide: The answer is yes if I can increase by four sketches above the baseline set in my first two sessions. (Or by two sketches above the baseline set in my first session?) Alternatively: The answer is yes if I can increase my number of sketches by two per session, even if the reason I increase is that I start to realize the kinds of chunks I can turn into a minute sketch, and the kinds of chunks I cannot.

Many alternatives…

Results and Conclusion:
Here, you would make your conclusion. You might write them on paper, or just scribble down some notes. It’s important to record whatever happened, unless you don’t care what you forget.

Why is minute sketching so important?

Scientists think in minute-sketches (though that’s not what we call them). Scientists think about their science using what we call “models” that look like the figures and flow charts and diagrams we put in textbooks. Those figures (or models or sketches) aren’t there just to help students learn. The figures are available for textbooks because that’s how scientists think about
the topic. For example, no scientist I know memorizes definitions only as words. We learn using mental models that describe the topic as an image. If I need a definition, I describe the sketch or picture I see in my head. (If I use a definition enough times, I can end up memorizing the words as well, but without trying.) Even scientists who tell me, at first, that they don’t think in pictures actually discover that they do. So far, for every scientist I’ve asked to, “close your eyes, and explain _X_ to me,” has found that he or she does indeed have images in their head, and the scientist describes the images to me like minute sketches. Exceptions probably exist, but I haven’t met them yet.

So how commonly do my students think in diagrams and pictures when they come into my classes? Most don’t. Very few of my students think in simple sketches and simple models, perhaps because they’ve never been taught an easy way to do so. They think in words, they memorize definitions, they read sentences in textbooks over and over again, and they learn which words go with other words, and which terms go with other terms. Most RESIST thinking in minute sketches.

Does it matter? Yes. When I ask most students to USE their science to solve a new problem or make a new prediction, they’re not good at it. The definitions don’t help them very much. It’s as if I taught them basketball only by having them memorize definitions, descriptions of movements, and rules. They might be able to explain basketball, but they couldn’t play a game. How do you get good at basketball? By practicing how to play on the court, by drilling the basic moves and plays, AND by learning rules and terms (free throw, lay-up, pass, basket, traveling, foul). If I want students to learn how to do science, I need to teach them the words and to practice the skills to play the game. If you want to develop your ability in science, you need to know terms and be able to explain concepts in order to work with others and use information from others. Scientists also need diagrams and models to think about their science and use their science to solve problems. For any problem involving structures, functions, or interactions of physical objects, diagrams are much easier to manipulate to solve problems than are words. If you want to be able to think about and solve scientific problems, then you need to be able to manipulate diagrams (on paper or in your head).

Of course, terms are necessary to describe what you’ve done and to communicate with other scientists or on exams—that connection is made with folded lists.

**Folded lists with minute sketches**

To learn anything important to you, try using a folded list with minute sketches. A “folded list” takes a little bit of practice, but not nearly as much as minute sketching. For some kinds of learning, some students find that folded lists are faster than minute sketches and give better recall and application of what they learn. It is worth trying for just a few things you need to learn, and then deciding when and if you want to use it more in your studying. The idea is to train your brain to visualize any concept as a model and connect it to keywords. The method might improve your learning while reducing study time and making study time more interesting.

**Why do you need a new/different study technique?**

You might not.
If you're satisfied with your grades, and you know that you're not wasting time with inefficient study methods, then a new technique isn't necessary. At one point, this section on folded lists was optional. I have found that not many of my students choose to use folded lists on their own, after my classes. This suggests that others reading this book will not use this method. However, almost anyone will benefit by a rational consideration of what methods help them learn a particular kind of material or skill the best or the fastest.

For many students, the single biggest advantage of the folded list technique is that it's FAST. Once you learn how to use it and get some practice—and it does take some practice, sometimes a lot—this is among the very fastest and most efficient ways to learn in many areas of science and some other fields. Once my students have learned how to use it, I've had many students conclude that they learned more, got better grades, and saved time with this technique. Of course, that takes practice and experience. Most students need to try it a number of times before they understand how to use it well. This isn't some magic wand to raise grades in just a few weeks. Just as in sports, when an athlete wants to learn a new move or shot or serve, they need practice and dedication to nail it, and sometimes an athlete is worse (briefly) as they begin to apply a new method that they haven’t yet mastered. This method is not something to try in order to learn better in a few weeks; it is something to try in order to be a much better learner and user of knowledge over months and years. (I don't think that any new study method works well without practice and intelligent adjustment.)

**How to make a folded list**

In this first example, I'll show you how to develop a folded list for the water cycle. The method is simple. Start with a blank piece of paper. Fold it lengthwise into 4 sections:

![Folded List Diagram]

Pull out your lecture notes or a textbook and start identifying the topics that are most important. The first column is a terms column. List your terms or events there. You are not allowed to put sentences or phrases in the terms column, just the important words or dates. List the events or terms that are part of an idea, concept, or set of events you want to remember. For the water cycle you might use words like water cycle, lake, ocean, evaporation, condensation, cloud, precipitation, runoff, groundwater, impervious layer.

In the second column, make a minute sketch of the idea you want to remember. You must be able to recopy the final version of your sketch in less than a minute, even if your first try takes longer. Your minute sketch should have only the simplest reminders of whatever you need to remember, so simplify your sketch. Remember, words are not allowed on the sketch. Symbols are allowed; you may put ‘H₂O’ on your sketch, but not ‘water.’ How do you know a good sketch? If you know that you can give a good definition or explanation from the sketch as you recopy it, then you have a good sketch. A good image in a book can help. Often you can simplify the book image so that you can redraw it quickly, easily, and in less than 30 seconds.
For my water cycle example, you can probably redraw the sketch in 25 seconds even while thinking through exactly how the cycle happens.

Review your sketch and your terms, with a book or your notes in front of you. Do you have all of the important words and dates? Do you have all the important parts in your sketch? Take out what you don’t need. Add anything you do need. The sketch doesn’t need to look pretty. All that matters is that you understand it.

Now, hide the word column by folding it under. While looking at the sketch and thinking through the sketch, rewrite all of the terms, in the 3rd column. If you can’t remember some terms, that’s normal. Never guess, though. Just quickly turn the words back up to check, and then write the missing words. Say the words aloud as you write them. In a place where you may not talk, just say the words silently in your mind as you write them. You may abbreviate terms, as long as you know the whole term.

Hide the sketch column. As you look at only the terms in column 3, redraw your sketch. Make sure you can draw it in less than 60 seconds. If you don’t remember part of the sketch (which is normal), don’t guess. Just quickly turn the first sketch back up to check, and then finish your new sketch. It’s okay if you have to check twice. Just don’t guess. Describe or explain the sketch while you draw, either aloud or silently to yourself. When you run out of columns, get a new sheet of paper and keep going.

On your first day, go through the whole folded list two times. Go back and forth from terms to sketch to terms to sketch, four columns in all. On the next day, draw and write your folded list twice again, and then again on another day. Even in a car or on a bus, you can practice by drawing on paper, in your mind, or on imaginary paper. Whenever it all comes easily, you’re done (for now). Practice when you need it.

Why does a folded list work? Because in less than two minutes you can review an entire concept, using vision, hearing, and movements of your hands and fingers for sketching and mouth for speech. The use of vision, hearing, and movement together keeps you from becoming distracted. Using all three makes you practice three different forms of memory. Repetition of all three fixes the memory in place, and any one brings back the others. Hearing or seeing a word will recall the terms and sketch. Drawing the sketch will recall the explanation.

More on folded lists with minute sketches

Here’s another example of a folded list for a concept in evolutionary biology called "allopatric speciation." In this process, a population is split geographically, which results in accumulated genetic change that then prevents interbreeding between the two separated
populations. Two species are formed from one. Allopatric speciation has four steps: a geographic barrier that splits the populations, accumulation of genetic changes over time, resulting eventually in enough changes that reproduction between groups becomes impossible, and, if the geographic barrier ever disappears, no possibility of mating. In your first column, write allopatric speciation, underneath it, you might write something that may help you recall it, like 4 steps.

Remember: the first column is for words, and the second is for images. If you must, you can use common short abbreviations, such as 'RB' for reproductive barrier or DNA, but symbols are always better. You should put key words or phrases in the word column, but never a complete definition anywhere. Your sketch is supposed to show you the definition; if it doesn’t, then you need a better sketch. Your goal is to identify any important idea or concept or term and to convert it to a very simple sketch that will capture the essence of the concept and be easy to remember and fast to draw/write. You want your sketch to be a chunk in the form of a minute sketch.

ONLY WORDS

<table>
<thead>
<tr>
<th>Allopatric speciation</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 4 steps</td>
<td>Geo Barrier</td>
<td>Accum Diffs</td>
<td>RB</td>
<td>Even if back, no breed</td>
</tr>
</tbody>
</table>

Especially when you first use the technique, you may find that you really want (and think that you need) more text. For example, an alternative would be:

ONLY SKETCHES

1. Geo Barrier
2. Accum Diffs
3. Repro Barrier (chance!)
4. Even if back, no breed

This second alternative might be easier to invent, but don’t do it. Use numbered sketches and arrows and diagrams instead. Using the figures is faster than the words. Try timing yourself or competing with someone else to see which is faster, reading through the words (in your head) or thinking through the logic of the sketch (in your head). When I do time trials with students, the image almost always wins. Try drawing the image above for yourself twice, and then close your eyes and try to imagine the image. Then close your eyes and try to remember the words—usually much harder.

Keep in mind that your goal is partly to remember the concept, but also to have your memory of it represent the concept. If you use only words and study only words and memorize only words, then you'll remember only words. Remembering only words is fine if you need simply to regurgitate a definition or a term on an exam, but if you actually need to use the concept to solve a problem, you'll need a deeper and non-textual understanding! (If you’re trying to learn about basketball for a class, and you know the test will be a written multiple choice test in which you match terms with descriptions, then you should read about basketball and memorize words. But if you know that the examination will be to play a basketball game, then
your studying should be practice with the ball and playing basketball! When you know that an exam—or life—will require comprehension, not just memorization, you must adjust how you prepare for it. Practice and study the things you know you'll need to do on the exam. The same goes for learning tasks you face in the rest of your life.

The version of the folded list with sketches actually captures what happens in allopatric speciation, and that sketch illustrates most of the events in a way that is easy to remember, easy to scribble down on the margin of an exam (or even use as part of an essay answer), and helpful if you need to decide whether a particular new example is allopatric speciation. The version with the lists of words will help you memorize words, and if you think through the idea while writing the words, that might be enough. But if you need to use concepts to do problem solving on an exam, memorized words alone won't help at all. I might be able to memorize a French novel and “know” it perfectly, but that wouldn't help me answer any questions about the plot (since I don’t understand French…). A student can “know” biology in intricate detail and still fail an exam that requires solving problems.

Back to our list. Keep adding words in one column and sketches in the next, until you’ve filled the page. Below, I’ve added another concept: costs of territory defense.

![Folded list with sketches](image)

Once you have a full page, you can start studying. Fold the first column behind the paper so that you can see only the second column and the empty third and fourth column. THIS STEP IS EASY AND FAST!

Now, in the third column, go down the page and write the term (and any quick reminder you're using to help) next to each sketch:

![Folded list with sketches](image)
Now fold the next column behind and redraw your sketches:

Fold the final column behind, and now start a new piece of folded paper, writing the terms, and so on … continue copying and recopying from memory, checking back when you need to, until you have the material memorized (and understood), eventually very well.

Think about the concept (or the term) while you're writing. Go through the cycle a couple of times on one day, then do it again a day or two later, and by a third day you should find that you're starting to understand and remember those concepts very well. If you're doing this correctly, you should see improvement every day, even with only three minutes per concept going through each concept twice, using four columns. (Well, unless you're badly sleep deprived; severe sleep deprivation blocks memory consolidation.) Some concepts will be easier than others, and sometimes you'll find you MUST to go back to your book or your notes to think through a concept better or to get a better sketch or to get a better explanation.

DON'T give in to the temptation to pack too much into your lists or sketches. Absolutely not! That defeats the purpose. You're trying to reduce a concept to the essentials, and to make those essentials be enough to enable you to think through the full idea. You shouldn't be trying to get a complete description on paper; rather, you just want enough to jog your memory for a complete understanding. ALSO, don't think you can get away without repeating the writing and the sketching parts by hand! Actually recopying and thinking about it as you do is how you're getting your attention fully on the material, and—VERY IMPORTANT—how you're engaging your motor memory (somatosensory cortex, motor cortex, and their link to memory) as well as your visual cortex in this material. That gives you three times as many brain areas with which to recall the information later. IT MATTERS!

When you find that you don't need to keep writing/sketching any more, then you can start doing quick reviews of an entire page at a time (one column only). Scan your eyes down the column, and for each item you might then close your eyes and try to visualize your sketches or the terms, and perhaps even explain it aloud (or in your head) in words. If you can't remember everything, flip the paper over for a quick check. One great advantage of this technique is that it is very easy to carry a few sheets of folded lists with you and you can quickly review for even a few minutes in a noisy classroom before a class begins. (Very few people can concentrate enough to do much of this with a textbook or written notes.)

For most class lectures, you should be able to fit all of the essential material on the top half of one sheet. Truly. Force yourself to keep to a limit like that, because that will force you to identify the most important material as your first step. You can always go back and add more material and sketches, or reread more of the text and notes once you feel that you've mastered the essentials. In most classes, of course, you'll need to combine several study methods. Folded lists are great for the most essential material.
Folded lists do a lot of good things for you.

Using the folded list method with sketches makes you learn things as sequential events. While this may not be good for all areas of knowledge, it is almost always good in biology and chemistry—chemical and biological things happen in a sequence over time, so it's good to learn them that way. You can only make a sketch or write out a list in a sequence as you can't write or draw two things at once. If your sketch or lists follow the same sequence as the real event, then not only do you learn it that way, but as you redraw your sketch, you're also thinking through the procedure in order.

Folded lists with minute sketches are a way to approach any learning task (such as preparing for an exam) with a set of specific simple tasks that you can go through on a schedule. As you practice, you know what you know, and you know what you still need to practice. (In contrast, if you're just reading and rereading your notes and the book, it is very hard to know how much you've learned and how much you still need to learn.) With this method, you can schedule a day by which you want to have lists made, another by which you will have redrawn them all by memory twice, and so on. Also, you can set a goal for yourself for each study session. For example, tell yourself, "When I can accurately do 90% of the items on three full pages, then I know I've learned as much as I need today, and so I can quit and go do something fun." You may find that you are less likely to put off studying when there's a clear objective and a reward at the end of the task. (It works for me, and I'm a serious procrastinator….)

Folded lists with sketches allow you to review material surprisingly fast, even in distracting conditions.

You can extend it to use in other study methods. For example, when you know a concept well—both the words and the sketch—try and make up your own example, explain it to yourself, and then think what you could change to make it incorrect. (That's one way I and other teachers write exam questions, so you would be practicing a skill we want you to have, and something we're testing you over.) Go down your list, making up examples and thinking about them for each one.

You can use your sketches or words as part of “concept mapping” (a useful method developed more than 20 years ago and described many places on the web; I also have an explanation on my web site). Concept maps help you connect ideas. How is that useful? I'll give you an example. On one exam, I had a question that described how regulatory genes might control the growth of antlers. Some of the possible multiple-choice answers had to do with the control of genes for regulatory proteins. However, one choice stated that this protein could act by causing an allometric effect (and it was a true answer). For this, you needed to be able to connect your knowledge of genetics with another concept—allometry (differences in proportion of body parts caused by different rates of growth of cells), that we covered in a different context (as a concept connected with macroevolution) and in a different week of the class. A concept map could have easily shown you that connection. Without a concept map you had to make that connection for the first time during the exam.

A final comment about folded lists

Making folded lists can be a little intimidating when you first try it. It is new, and you have to learn new things that take time and are frustrating at first because you don't yet know what you're doing. In contrast, the same old method of reading the book (or your notes) over and
over is very reassuring, because you know you won’t miss anything. However, learning only by reading and rereading the ever-larger amounts of material we teachers (and ultimately your bosses) give you just won’t keep working. The learning tasks you face keep getting harder and harder, and the problem solving keeps getting more and more complex. A potentially better and faster method should be important to you. It helps to start with focus on a manageable few important concepts, and then build them together to create more and more complete and complex interconnected ideas. This is what experts do in any field in the process of “chunking” their knowledge. With time and practice you should get better and better at applying the method, and also better at knowing when you truly need it. It can be daunting to try something new, especially since new things do not work perfectly the first time. As with anything in learning, practice makes you better, and much practice makes you an expert.

**Chunks about sketching and visualization**

The six new chunks for Chapter 8 are:

1. For much of what we learn, terms represent real objects, processes, or events. We cannot have FRUCO for these real things unless we can hold them in our mind. Visualizing them is one common way to hold chunks in our mind, and so visualization is a useful skill to practice.

2. Sketching is one way to practice visualizing. In a sketch, we often can see solutions to problems that we would not discover from the terms and definitions in our mind. In a sketch, it can be easier to notice a mistake.

3. A minute sketch is a method of making and practicing fast sketches. It can become easy to visualize your minute sketches after just a few practices on each of a few days.

4. Different brain areas process images, written words, and spoken language, and so a sketch can help develop memories in new ways.

5. Memory for physical skills and movement (non-declarative skill memory) is formed separately and in a different brain area than declarative memory. It seems that this motor memory can help remind you of chunks when your declarative memory may have partly faded. Motor memory seems to last longer, once made, than declarative memory (you remember how to ride a bicycle for many years after your last bicycle ride, but declarative memories often fade within months.)

6. Minute sketches can help in problem solving. An answer that you cannot find from the words you can sometimes ‘see’ in a minute sketch.

7. In some of my students, good minute sketches practiced in ‘folded lists’ sometimes develop faster memory with understanding than just looking over the same chunks for the same amount of time. Students who use them also find that their practice before exams – especially final exams – is easier. (However, minute sketches with folded lists have not been carefully tested. You’ll have to check for yourself.)
Chapter Nine

Study Strategies

I have written and rewritten this chapter over and over because I have a problem. The problem is this: the best way for you to study and learn depends upon how well you understand your own learning and how well you understand methods of studying. As you understand your own learning and discover the strengths and weaknesses of different methods, you will change what you do. That will make your learning faster, better, and easier—at least, that’s what I watch happen with my students. There are best ways for you to study, but you have to discover them.

This section is best read about midway through this book because that allows me to refer to terms such as FRUCO (fluent recall with understanding, connections, and organization), chunks (each thing you know), information reduction, metacognition, and transfer from other chapters. In this chapter, I’ll talk about the research on studying and the methods that my students tell me have worked for them. I’ll also warn you: don’t expect instant changes. It takes practice and self-testing with metacognition to improve. Most of my students can feel that they are improving their learning fairly soon, but it usually takes months or longer to change their grades. Once they do improve, they often improve a lot. You might be faster.

Using metacognition

Remember that metacognition, in its simplest Fish-version, is thinking about your learning. To apply metacognition as you search for the best ways to learn, you need procedural rules. They can be as simple as a set of questions to keep asking yourself.

Here are three:
(1) *Do I know a reason for X, or have I empty-memorized an answer?*
(2) *What chunks am I missing that are necessary for understanding this new concept?*
(3) *How do I know I will remember this at the time of the exam?*

You can create any questions you want to use.

Some more:
(a) *Do I have FRUCO for X?*
(b) *Have I been focused for the past 10 minutes?*
(c) *Am I interested?*
(d) *Am I sleepy?*

It might help to place your list of questions where you’ll see it often. Your questions may, and probably will, change. My point is that you need to start asking yourself questions about your learning. Practice, practice, practice, asking yourself the questions and getting answers.
Chapter Nine: Study Strategies

Research on study methods

I think that everyone benefits from exploring how he or she learns best. I also think that the results of research on studying are important. Methods that have worked for a lot of other people are probably more likely to work for you than the methods that don’t work for most people. What does the research suggest?

Don’t study by rereading and highlighting.

First, I’m going to tell you what not to do. The two most common study methods my college freshman use are rereading (notes or the book) and highlighting. Research on studying says that these are poor study methods. When I was in high school, those were my two favorite study methods. OK, it is true that you can learn from them, but nearly every other study method is as good or better. All these methods do is tell you, “Yes, I’ve seen this before, it looks familiar and I think I understand it.” Unless you add in some recall practice, that’s all you get: recognition memory.

Rereading and highlighting feel good for two reasons. (1) They’re easy. (2) You never, ever, make a mistake. The procedural rules for rereading and highlighting are very simple, so they’re easy to apply: Read it again. Mark things that seem important with a highlighter. These are as simple as rules can be. What novice students all like about rereading is that we never make a mistake, which makes us feel good. In fact, it isn’t possible to make a mistake; whatever we read is equally correct each time we read it. Whatever we highlight is equally important each time we read it. Mistakes are not possible. (Yay!) But I never notice what I don’t understand. (Oops!). In fact, the only time we can discover what we don’t understand is when we miss those questions on the exam. Think about it: when would you rather discover what you don’t know: before the test—when you can still fix it—or during the test?

There are harder but better procedural rules for developing fluent recall. We make and strengthen memories by remembering them. If you want to remember something, practice remembering it. It seems so obvious when I write it this way, but it took a lot of research to show that it’s true. The better-but-more-complicated-procedural-rules for developing memory all include practicing and testing each memory you want to learn.

Study Methods to Use

Below, I’ll go through some procedural rules for study methods that are known to work. Both the research and my experience in coaching individual students to improve their studying say that they work. You’ll still need to learn and test them for yourself. Until you do that testing, you can’t be sure they’ll work for you.

Test your memories, understanding, and procedural rules

Good procedural rules for studying include testing your memories after practice. You need to test for fluent recall (FR) by testing whether you remember your chunks. When you don’t, you practice and test again the next day. You need to test your understanding (U) by checking to see if you remember reasons for what you know. Those reasons have to make sense. You need to test your memories for connections and organization (CO) with some form of mind mapping. (You might be able to find another way than mind mapping to check
connections and organization, but every useful method I’ve seen includes some sort of mind mapping). Together, those are FRUCO for recall and procedural rules.

Testing your memories is about recalling them and seeing if they are correct, and correcting them when they are not. Here’s an important point: It’s not about guessing! Guessing reinforces what you guessed, right or wrong.

In order to make memories that will last through an exam (or longer), test yourself in advance. If you remember, then you’re done for the day. If not, practice them two or three times. A day or two later, test yourself again. If you remember, you’re done for that day. If not, practice the chunks two or three times again. For most chunks, a few days of this will hold the memories for at least another day (through the exam), and if you ever need it again for another exam, you can practice those old memories a few more times. In other words: on multiple days, test yourself, practice if needed, and repeat tomorrow. Folded-lists with minute sketches are a fast, useful way to test yourself and to practice remembering.

You may have noticed that we’ve gotten rid of one problem—rereading and highlighting—and created another problem: you cannot practice and test yourself on every word, sentence, and image in a book or your notes. How to decide what to study? Later in this chapter I’ll tell you more, but what you’ll need are procedural rules for information reduction.

Testing your understanding means checking to see that you understand reasons and haven’t just memorized stuff without thinking. If I memorize a Russian novel and know it perfectly word for word, that wouldn’t mean I understand it. I don’t know Russian. It would be a huge amount of work, and I might even be proud of it, but my perfect recall would be empty memorizing. Empty memorizing isn’t understanding, and it isn’t useful. If you understand reasons, you could explain why something has to be the way that it is or why events must happen as they do. Like a row of dominoes, each fact or step must connect, each domino knocking over the next in a chain. You could memorize $2 + 2 = 4$ without understanding what the shapes and symbols mean, or you could connect those symbols to your understanding that two pens from a bag added to two pens on a table gives four pens.

Testing your procedural rules means practicing them from memory on new problems. Usually, at the beginning, it helps to practice enough time to memorize the rules with one sample problem. However, you can’t just stop when you’ve done the same problem over and over until you’ve memorized the problem. New procedural rules are only useful to you if you can apply them to a problem you’ve never seen before. To do that, you need fluent recall (FR) of your procedural rules, you need to understand (U) your rules, and you need to be able to connect those procedural rules only to the right problems in the right situations (CO). That’s FRUCO for procedural rules. If you practice your procedural rules on new problems that you’ve never seen before and get good answers on each day for several days, then you probably know them well enough for an exam. If you ever find you cannot recall them easily, practice again for a few days.

Test yourself and practice over days: distributed practice

If you want to remember things for more than just a day, practice and test yourself over more than just a day. This is another thing that seems obvious when I write it, but it took a lot of research to show. This is called distributed practice, because you distribute your time over more than one day.
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When you have so little to learn that you can practice it on one day (or all night) and still remember it the next day, then cramming the night before the exam works. It only works for that day, though. In a week, it’ll be mostly gone. Unless you find it interesting enough to recall it later, you won’t build any lasting memories for chunks. The same amount of time spent usefully over several days will build longer-lasting memories.

As soon as you have a course for which cramming doesn’t work, you have a problem. Either there is too much to review in one night, or you need to build chunks at two or more levels, such as trying to read the word “γατ” before learning (right now) that I want you to treat “γ” as a c, “α” as an a, and “τ” as a t. You can’t build FRU for the complex chunk until you’ve got FRU for the simpler chunks. You can’t start learning other simple words (“αγτ”) using these simple chunks until you have FRU for them. The further we get in school, and the more challenging the courses become, the more likely it is that we’ll first have to build simpler chunks before building complex chunks. You can’t build complex chunks with FRUCO in one cramming session. (Maybe you can, but I can’t.)

Eventually, if you’re in good classes, you’ll start having tests with too much to cram. It happened to me, and it may already have happened to you. At that point you’ll need to study over many days. You’ll need procedural rules for distributed practice. You’ll improve best if you test your procedural rules for learning. You’ll be applying metacognition about your learning.

Metacognition as you learn

Over time, an expert develops automatic application of procedural rules for metacognition. Most experts would automatically apply most of the metacognition questions below, even if they are not actively aware of doing so. As you develop expertise, you can begin to develop automatic application of these rules by asking yourself some of these questions as you learn:

(1) Do I have interested, focused attention? (If not, how might I become more interested or focused?)
(2) What should I learn first? What should I learn second? (And so on…)
(3) Do I need recognition memory, recognition memory with understanding, fluent recall, fluent recall with understanding, fluent recall with understanding and procedural rules, or fluent recall with understanding and procedural rules and transfer? Each of these requires different learning methods and different kinds of practice.
(4) Do I know this well enough yet? (And, later, do I still know this well enough?)
(5) How do I know that I know this? How can I tell if I know this well enough?
(6) What is the most efficient way to learn this as well as I need to learn it?
(7) Have I finished the learning tasks that are useful today?
(8) Am I doing empty memorizing? Should I be?
(9) Might there be better or faster ways to learn this?
(10) Will learning this also help me learn many other things, later?
(11) How important is this? Does it connect to many other facts, principles, or kinds of problems?

The list above is a good list, but it won’t be the best for all people all the time. You should change them and add or remove questions to fit your own learning. In fact, a good learner will ALWAYS consider whether my suggestions, or anyone else’s, can work for himself or herself.
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Make it feel real. Imagine it as real

We are often told to relate our studying to our life. That can help, because it is easier to learn something that connects meaningfully to us. When you can do it, great! For me, that was often hard. I wasn’t doing algebra, learning grammar, or talking about history with my friends and parents. A strategy that is easier to learn and works well is to make it feel real. (Sketching can help, which is one reason I suggest using minute sketches.)

If you can make something feel real, it is easier to chunk and recall. You can imagine it in your mind as if you can see, touch, or hear it. You do this all the time, automatically. My favorite example happens when we listen to a terrifying story or watch a creepy movie. Think back to watching some movie or reading a book at a tense, scary part. Remember that feeling of creepiness in your skin, your muscles getting tense, the hair rising on your neck, and the urge to look behind you? You made something feel so real that you imagined it right there with you. You couldn’t actually see it, hold it, hear it, or smell it. But it felt real.

You can learn to make things feel real as part of your procedural rules for learning. You can learn to make anything that COULD be real feel real. Right now, you’re reading (or maybe hearing) this chapter on a very ordinary thing: a computer, a book, or a stack of paper. Whatever it is, you can reach out and feel it. You can see it or pick it up. You can click it or tap it to make noise. You might even be able to hold it near your nose and smell it. You can close your eyes and set the chapter down so that you cannot touch, hear, see, or smell it. Even with your eyes closed, you can imagine the shape. You can picture it in your mind. You can imagine touching or hearing it. Now answer this question: can you make it feel real? Can you close your eyes, picture it, and run your fingers over an imaginary version, imagining what it would feel like? Close your eyes and try now.

Really – please stop and try now. If it worked, then you have made it feel real.

Let’s try it with a coin. Close your eyes, and imagine there is a coin in front of you. Imagine how it feels—the hard edge, the bumps and ridges, the words. The feel of it sliding against your fingers. Imagine that you can see it, focusing on the edge, the circular shape, the raised letters and words, and the head of a person. If you need to, you can find a real coin. Practice with it. Then set the coin down, and try to imagine the same things without touching or seeing the coin. When you succeed, you made it feel real.

If a chunk is abstract, like friendship, how can you make it feel real? That’s a problem, but not as big as you might think. We can make abstract concepts feel as real as the relationship between two concepts. We can make the concept of friendship feel real using examples of the behaviors between two real people. Friendship results in behavior that doesn’t happen between strangers or enemies. Laws are another abstract concept. They can feel real because laws change the behavior of people. Most of us are less likely to do the things that are against the law. So we can represent the abstract concepts of friendship and laws with real events and real people (or objects). Abstract mathematics is a little harder, but we can represent even abstract mathematics as real changes in diagrams or graphs. The more real you can make it feel, the easier it’ll be to learn.

Why does making it feel real help you learn?
First, things that feel real usually also feel more important than things that are unreal to you. Memories form faster and more strongly for things that feel important.
Second, the focus required to make something feel real blocks distractions. You’re not able to think about anything else. This focus is important for learning.

Third, when you make a concept feel real, you are building understanding with connections and organization (. . UCO). You are not just connecting words with other words or with lines on a page. You are connecting them with analogous things and organizing those things into categories. Too often my students think they have FRUCO, when all they’ve really done is connect one set of memorized words with another (FR for words). If you just recall words, then the memories you have are just for the words. To recall words, you don’t even need a Fish-version of facts or concepts. That is empty memorizing. In order to make it feel real, you must have at least a good Fish-understanding. If you practice visualizing (or imagining in other ways, such as sketching), then you practice understanding each time you practice making it feel real.

Metacognition experiment 9.1 Making it feel real

Imagine that I have discussed snignups. Close your eyes and picture a snignup. Make it feel real. Try this now, and then read on. (Please stop and try.)

Unfortunately, you cannot make a snignup feel real, because I have never described snignups. However, imagine that I provide more information: a snignup is a strange beast that combines a butterfly, a puppy, and an octopus. With that information you could begin to make it feel real. Try that now. You might want to make a sketch for yourself with some puppy parts (head with ears?), octopus parts (feet?), and butterfly parts (body and wings?). Close your eyes, and try to picture a snignup as a combination of a puppy, an octopus, and a butterfly, and do your best to make it feel real. (I mean it! Close your eyes…. ) This time, you really can do it!

Making snignups feel real helps to develop fluent recall with understanding. If, for example, you sketched your simple Fish-version of a snignup from my information, and then tried hard to make that exact version of a snignup feel real three times a day for the next week, spending just 15 seconds three times each day, then you would gain a strong memory for snignups that would probably last for weeks and maybe longer. You would develop that memory even if you don’t have any interest in snignups, even if you find snignups dull and silly. You would develop that memory even if you cannot find any other connection between snignups and the rest of your life. It works because it feels real, because you are focused, and because you are connecting a new term to something other than just words.

You may doubt that what I am telling you is true. I have a rule not to trust everything I read, so you can test this for yourself with a metacognition experiment—an experiment on your own learning.

Purpose: To test whether making something feel real helps me remember it.

Methods:
1. Spend 30 seconds making a stick-figure sketch of a snignup.
2. Set aside 15 seconds three times a day for a week. Each time, for ONLY 15 seconds, glance at your sketch, close your eyes, and try to make snignups feel real. Once you’ve done this a few times, 5 seconds would probably be enough for each practice time, and you could do all three one right after another, as long as you clear your mind for a few seconds between each time.
3. In order to test whether “making it feel real” actually helps, we need a comparison (a control exercise). As one kind of control, read the following sentence for 15 seconds (about twice) three times a day, either before or after your 15 seconds on snignups. Do not try to make a millsnig feel real. Just read the sentence over and over, as if you were empty memorizing. Do NOT try to picture what a millsnig might look like.

A millsnig is a strange beast that has the appearance of the combination of a beetle, a kitten, and a starfish.

4. I have added another control, because I am concerned that some of you will try to make a millsnig feel real, even though I’ve told you not to. So, read the following sentence for the same amount of time three times a day.

A pulktwip is a strange beast that has the appearance of the combination of a swerple, a clentiff, and a musgit.

**How you’ll decide**  
**ONLY IF YOU DID THE EXPERIMENT, CAN YOU DECIDE WHAT WORKED BEST BY ANSWERING THE FOLLOWING QUESTION.**

**If you skip the experiment, do not read the question below.** I mean it. Don’t read the next paragraph unless you did the experiment. I’ve printed the question in faint gray text so that it’s easy to skip over.

Now that your week is up, try to answer the following question. (A) Which is more dangerous, a snignup, a millsnig, or a pulltern? (B) Which would you prefer to have as a pet? (C) Explain specifically how each might be dangerous to a baby or small children.

Just as importantly, decide if you remember any of these better than others, and decide whether one way of studying was more interesting, or less boring.

**Conclusions**

I don’t know what your conclusion will be. You might remember better by making it feel real, and you might not. You might enjoy practicing and studying more when things feel real, and you might not. That’s why I hope some of you do this experiment on your own learning. If you do, you are not just thinking about your own thinking. You are doing more: you are comparing three different ways to learn on yourself. The entire experiment on your learning will take you only 3 minutes of each day for a week. I don’t know what your results will be, and neither do you. That’s the point.

If you discover that one method works better, you can use that method to learn faster. If it turns out that none of these methods makes any difference, you’ll only have lost a small amount of time. Even if nothing else happens, you will have learned and practiced an experimental method to test how you might be able to learn better or faster. You will have practiced metacognition, and you will have improved your Fish-understanding of metacognition. Again, I don’t know what will happen if you do this experiment on your learning. I do know that you’ll be smarter at the end of it.

Information reduction to essentials
Remember that information reduction is a study skill. Information reduction saves time and keeps you focused on whatever is essential. When you watch a great movie or read a great book, it takes minutes, not hours to explain it someone who has never seen it. That’s information reduction. It isn’t the same as seeing the whole movie or reading the book, but your summary is everything you need in order to recall it. We do information reduction all the time when we describe important or interesting things to other people.

With my students, I demonstrate information reduction using examples from my classes. We typically find that something I took 15 or 20 minutes to explain in class can be reduced, with a little practice, to essentials that they can review in a few minutes or even less than a minute. Information reduction requires practice. The first time you reduce a new concept to essentials requires a lot more time than after practicing the skill for several days. As an example, think about when you learned division or multiplication of large numbers. It probably took an entire class period to go through a procedure that you can explain to yourself now in under a minute.

Information reduction to essentials is important because no one can do retrieval practice on every word they read, every word they hear, and every image they see. (Well, maybe somebody can, but I can’t.) There’s far too much. One of the most common study problems my students have is that they try to memorize everything (FR or FRU). They don’t decide that some chunks are more important than others, and often they don’t work on connections with organization (CO). They have no sense of which chunks are valuable to practice more and which chunks do not need much practice. They don’t develop any ordering, such as learning the simpler chunks first and then combining them into more complex chunks. In a hard class with a lot of reading and many, many chunks, their study tasks become impossible. Before I understood how to reduce information to essentials, this kind of class made me panic and avoid studying.

Mind mapping for connections with organization (CO) and recall practice

As I mentioned in Chapter Six, mind mapping is a well-known study method with many versions, including “concept mapping.” A lot of good research shows that various ways of mind mapping can be very useful. Mind mapping is also fast. A set of procedural steps are:

1. In the middle of a blank piece of paper, write down any term for any chunk.
2. Think of other chunks and terms to which it connects. Write each one down or put them in as a simple sketch.
3. Add lines for the connections. Put notes or sketches on the lines to explain the connections.
4. Repeat, until every chunk and term you need to know is on the paper. (You may need to tape multiple pieces of paper together at the edges to have enough space.)

I recommend mind mapping at either or both of two stages. Mind mapping is most useful once I’m starting to have important new chunks as FRU and I need a way to practice, as well as make connections with organization, CO. Some of my students also use mind mapping at another stage of studying: they rely on a mind map as they are reading new material, trying to figure out how the new things map onto what they already know. They say that the method is useful if they are sleepy or just bored with the reading, because it keeps them focused.

Mind mapping as you are developing FRU does helps you see connections that you were never told, and it helps your mind organize what you know. Teachers cannot make every
connection for you—there are far, far too many connections, plus it is exciting to make connections on our own. Once you find these connections, they help you get better at transfer. Connections that you find for yourself suggest that chunks you know in one way may help solve problems and be useful in other ways. Making connections sometimes helped me on exam questions, because I had already thought about a question that ended up being on the exam. To see new connections and organization, it is often helpful to use minute sketches for some of the concepts.

Mind mapping is a fast, easy, and more interesting way to do recall practice. Each time you think of a concept and try to think of all the connections, you have to practice recall of your chunk for that concept plus all of the chunks that might connect. You quickly discover which chunks you don’t recall very well, so you can spend an extra minute or two practicing those. If you cannot figure out a connection, you don’t understand it well enough yet. If you know there is a connection because you read or heard it, but cannot explain it, then you empty-memorized it. Mind mapping forces you to check your understanding. With mind mapping, you can do retrieval practice on dozens of chunks many times, including all of their connections, in an hour.

Mind mapping helps you see which chunks are truly most important. Any chunk that has many connections is probably essential. If you forget that chunk (or don’t understand it well), you won’t correctly understand many other chunks. Any chunk that has only one connection is probably not very important; if you forgot that chunk, you would lose only that one connection and that one concept. This can help you identify the most important things to start studying first.

The value of mind mapping comes from making the map, not having the map. Don’t just make a map once and memorize it! That would turn mind mapping into empty memorizing. Each time you start to make a new mind map on the same material, you are making and practicing connections with organization, checking your understanding, and doing retrieval practice. There’s nothing wrong with having a mind map handy for quick reference and review. However, the real value in a mind map happens when you make it. I remember being surprised that each version I made of a mind map looked different from prior ones. Looking more closely, however, I would find that the structure of the map was the same. The same connections existed even though I put some of the concepts in different places. Sometimes, though, when I drew the map a different way, I would see new connections I had never noticed before.

Learning methods that cause students to get poor grades in college

As I am writing this chapter, my younger daughter is taking 9th grade biology. At the same time, I am teaching college freshman biology at the College of William and Mary. Often, my daughter is trying to learn exactly the same information in 9th grade that I am teaching to my students in college. Even though they have had the content before, many are earning poor grades. How can that be? There are two reasons. First, my 9th-grade daughter is getting a first Fish-version of introductory biology. College students are usually expected to solve more complex problems with their knowledge than my daughter needs to solve with hers.

Second, most of my college students have lost even effortful recall (and sometimes even recognition memory) of most of the chunks from their high school biology. They have to learn most of it again. In many cases, it feels as if they are starting over from the very beginning because they never learned it well in the first place. Most of these students have no useful study materials from their first time, and so they have no quick ways to practice their old chunks. Often, their Fish-version did not go far enough. They practiced only a few times. They often
practiced in ways that never developed their memory pathways very well, such as engaging what I call “use once and forget memory”. What is “use once and forget memory?” Many things are important to remember only once: “Where did I leave my keys?” and “What do I need to tell mom?”. Once we use the information, we NEED to forget it, so that we are not distracted the next time. Our brains seem to actively hold this kind of information until we use it, and then actively remove it. Imagine what happens if you are thinking, as you study, “I just need to get through this exam! I just need to remember this for the test.” You are assigning those to “use once and forget” memory. I don’t know if this is truly a category of memory, but I know that thinking this way makes memories that won’t last. The memories for concepts learned in this way are so weak that students will never get them back.

My students poor grades are not because these students don’t have the potential to earn high grades. The poor grades are because of poorly developed recall for biological concepts and procedural rules along with a second problem: not having the learning skills to catch up. These students often remember less because they have poorer learning skills. If they have strong learning skills, then they can catch up, but it takes extra work. If they have too few chunks in recall with understanding, they often don’t have strong learning skills. If they don’t have strong learning skills, they may not have enough time and may not be doing the right things to catch up.

How do I know that most students who get weak grades (even F’s) are able to develop smart learning and high grades? Because over and over again, if those students are interested and focused, if they start learning in better ways, put in the time, seek good coaching, and never quit trying to be better learners, they gradually change to being better and better students. These students catch up as they improve their learning skills. It isn’t fast. They don’t get better on the next exam or maybe even in the same semester or year. However, they can tell that they are learning better (and so can I). Over 1-2 years, their grades become gradually better. If they start early enough, if they are interested enough and focused enough, and if they put in the time with effective study methods, the students who do this often graduate from college with A’s and B’s.

For students who need better learning skills and practice on earlier chunks, first they have to understand chunks and chunking. I have them practice recognizing when they need to learn the OLD chunks in order to learn the new chunks. For example, my college freshmen need to learn about genes and transcription and translation. Some of my students do not remember or do not understand the difference between DNA, RNA proteins, lipids, and carbohydrates which keeps them from getting past the simplest Fish-version of genes and transcription and translation. In fact, when I give new information to students without these chunks, they develop even WORSE Fish-versions because they don’t have the old chunks in fluent recall with understanding.

Empty memorizing doesn’t help students much, because more advanced exams never have a question that asks, “What is DNA (or RNA or a protein or a lipid or a carbohydrate), and how is it used in a cell?” Advanced exam questions are often like “How would soap or another detergent affect specifically DNA (or RNA or a protein or a lipid or a carbohydrate), and would this affect the function of the cell? Explain.” In my classes, for example, I don’t ask specific questions about the definition of DNA, RNA, proteins, or lipids. Because they don’t see those questions, students often decide it would be a waste of time to review and practice these fundamental chunks. In fact, FRUCO of these chunks is where they have to start. They cannot understand or learn correctly NEW chunks without the OLD chunks. Solving problems with any of these chunks requires FRUCO of the old chunks. Just because the old chunks won’t be on an
exam doesn’t mean the old chunks are not important! Your high school English teachers never tested you on the printed alphabet or short words, but that doesn’t mean you didn’t need fluent recall with understanding of the alphabet and short words!

I try to get my students to understand that whatever you are learning, learn it in a way that makes it easy to review when you need it. You’ll save time. Minute sketches with key terms are the fastest way I know to learn and review old chunks and new chunks. If you save your minute sketches for anything important, it is much faster to go back to them than it is to go back and reread a book or your detailed class notes.

**Five study strategies NEVER to do (don’t work well OR work well but are very slow)**

1. Empty memorizing. Dangerous, because it can get you through a text or a class, but it won’t make you smarter. You might get a better grade, but you aren’t learning.
2. Highlighting. Nearly useless as well as dangerous. It makes you THINK you are learning well.
3. Rereading over and over. Dull. Usually makes a person LESS interested and LESS focused on learning. Dangerous. Kills enjoyment. *(Rereading specific sections in order to develop understanding is fine! Once you understand, though, rereading a book or your notes is one of the least effective study methods.)*
4. Recopying notes over and over, or writing and recopying a summary of readings over and over. Works well, when done well using retrieval practice of memories. However, usually SLOW and time-consuming. Often kills enjoyment.
5. Flash cards. Flash cards are a method that is sometimes useful. They’re not bad. However, someone who has practiced other methods is faster at learning than with flash cards. Flash cards are in my list of “things to do” AND in my list of “things NOT to do.” You have to use your understanding of your own learning to decide if and when to use them.

**Three strategies that might be good but are easy to do in poor ways**

Good methods can be applied in ways that aren’t useful.

1. Summarizing in your own words. The research on this surprised me a little, because I used to think this ought to work. In fact, the research says it isn’t very effective. I think that’s because people often summarize in the words they’ve just seen, without thinking too much about them. It’s easy to not notice your errors, and you aren’t doing retrieval practice. I suspect that summarizing as information reduction, in which you MUST understand each concept in order to reduce it to essentials, might be more effective. I don’t know for certain, though. That hasn’t been tested.

2. Visualizing what you just read for the first time. The research says it doesn’t tend to be very effective. I think that is because it when you first read something, you have to visualize and memorize with just a Fish-understanding. In addition, visualizing isn’t helping you make new memories unless you practice recalling that memory. In other words, it isn’t that visualizing is bad. The problem may be that trying to visualize as you read is happening too soon, before you really understand. Your Fish-versions of images aren’t very useful yet. To use visualizing well, you need to have images that capture the concept without errors, and you have to do retrieval practice. As you develop FRUCO, recalling and practicing useful images can be part of checking your understanding. Just make sure that you aren’t empty memorizing.
(3) Drawing without thinking about what your drawing means. If students are just told to imagine as they learn and draw what they’ve learned, their drawings often aren’t very good at representing the concepts. Even if they have useful sketches, students are unlikely to remember them without practice. Not surprisingly, just telling students to sketch doesn’t seem to help them learn. To use sketching effectively, you have to work to make sure your sketches represent the chunks well, without errors, and you also have to do retrieval practice.

Box 9.1 Reducing stress and staying organized: the two-list method

Though this book is not about managing your stress and being organized with your study time, stress and organization have a huge effect on your studying. I cannot possibly know what will work for you. I can suggest one method that you might try: the two-list method. I learned it in college (I have no idea who taught me, but I’m forever grateful to them). I was an anxious, often panicked college student. Big planners with detailed weekly plans took a lot of time, and it was discouraging when I couldn’t follow my plans. Instead of feeling well organized, I felt like a failure. The two-list method was easy, and it reduced my stress. If you want to try it, here’s what you do. Keep one master list in your room. Every day, carry a second, day list in your pocket or a purse. At the end of the day you’ll update your master list, throw away today’s list, and make a new list for tomorrow.

Either at the beginning of the day or before you go to bed at night, you’ll spend a few minutes making your new day list of study tasks for the day, filling in realistically what you need to do. Include the whole day—even the 10 minutes that you’re going to be waiting for a bus or for a class to start. You can leave that time empty if you want, but include it in your thinking. As you go through the day, cross off everything you complete (including going to classes). No matter how small it is, cross it off. If you get any new assignments, add them to a “new assignment” section at the bottom of your list. Don’t worry about new assignments now, because you’ll think about them when you update your master list.

At the end of the day, transfer changes from your day list to your master list. Cross off everything you’ve done. Add in new assignments. Break up the new assignments to things you can do in maybe 10-minute to 30-minute chunks of time. Plan to do most parts of big assignments over time, in pieces that you can cross off your list. That’s it. If you try this for a while, over time you’ll find that you adapt it to yourself.
Box 9.1 Two-list method (continued)

Why did this work for me, and why does it work for many people? First, it doesn’t take much time; five minutes a day was enough for me to plan out what I was going to do each day. Second, it is surprisingly rewarding to cross things off the list. For me, when I’m stressed and overwhelmed, which still happens a lot, it always feels great to be able to cross something off the list. Sometimes I forget to put something on my list, but then do the task anyway. I laugh at myself because I write it on my list after I’ve done it, just so that I can cross it off. Third, I stopped having to think about everything all the time. It was relaxing to know that if I just followed today’s plan, everything would get done. I only had to worry about today. If I didn’t do something on one day, because something came up or I was too busy, I just added it to the list for the next day. If someone tried to get me to do something fun, I could look at my list and decide whether I had time. Finally, when I had finished everything on my list, I was done. I tried hard to make lists that I could finish before the end of the day, just so that I could feel finished.

The more I used the two-list method, the better I got at breaking up assignments into pieces. I learned how to finish something within a set amount of time, and I would decide that whatever I did in that time would have to be good enough. I discovered I had been wasting a lot of time.

Putting it all together: study strategies

Fish-version\(^6\) of study strategy:

**Study Strategy 1. Each day:**
1. Go through the reading and in-class material and pick out the three most important things from class. Start with a list of the things you covered, and mark importance with stars. Save your list, but you’re going to start on the three most important things. Here’s a rule: You are not allowed to put effort into learning the less important things until after you have fluent recall with understanding the three most important things. That means you need to start early enough to have time to go back for less important things.
2. Make a list of your missing chunks: terms in the reading that you don’t recall or don’t understand.
3. Carry out information reduction to essentials for each of the three most important points. To do that, do one or more of the following.
   (a) Make it feel real in your imagination. Write down (or sketch) just enough to make it easy to practice making it feel real.

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\(^6\) Why do I call this a Fish-version of Strategy 1? Because when you first try this, if you do, you won’t understand it completely, and you won’t do it perfectly well. You’ll be more like a Fish-bird than a real bird. You may want to fly, and as a Fish-bird you’ll fly better than a fish, but you’re not yet a bird. You’ll gradually replace your Fish-version with a better one as you learn.
(b) Turn each new chunk into a minute sketch with key words on the side. This is most important for the concepts you can tell are going to be hard to learn and remember; you won’t do this for all concepts. Your minute sketch should hold the explanation. (In other words, it should easily remind you of everything that is important.) It should have no words on it. (Symbols are OK.) Later, you should be able to redraw your sketch from memory in less than a minute. (Better: less than 30 seconds.) Every line and dot in your sketch should mean something essential. If not, simplify the sketch.

(c) Mind-map your three things, drawing connections to every other chunk in that course to which they can connect. Mind mapping can help you do information reduction, because you include on your map only what you need for the connections.

4. Check your understanding: Can you picture it, see the connections, explain it, and mind-map it?
5. Practice each one until you have fluent recall with understanding. Repeat tomorrow.

Here’s another version of a study strategy:

Study Strategy 2. For each exam period:
1. Decide what you need to learn and why it matters. Make a list, and rank it.
2. Decide what you need for fluent recall with understanding.
3. Chunk and learn the most important things first. There are four categories:
   (a) essential
   (b) important
   (c) maybe important
   (d) unimportant
4. Transfer and practice, spending most time on category (a), and then (b). Don’t practice anything from (d). You should skip (c) and maybe (b) UNLESS you have mastered everything in category (a) and then (b).

Study strategies in the rest of this chapter

The rest of this chapter has more details about study strategies. Some are strategies that work well once a student learns them. Others are strategies that students use but that do not work well. I wrote these various strategies in response to students in my class asking for more options to consider as they decide how to study. Since I don’t think there is one best way for all students to study, I can’t write a section that tells you exactly what to do. If you apply them well, there are multiple strategies that can work. One way to find out is to try metacognition experiments. While I cannot tell YOU what to do, I can describe study strategies that seem to have worked for many students in the past.

Metacognition Experiment 9.2 Practicing a study strategy

Purpose: To test different study strategies.

Methods:
(1) Imagine that this book is your class, and each chapter is one day of class. For each day of class (each chapter), GO BACK and apply Study Strategy 1 above. To start, be as fast as possible making your lists and picking the three most important things for each chapter. Your goal is not to pick the three things that I think are most important. (I haven’t done that, and I don’t even know what I would pick from each chapter.) Your goal is just to make the decisions.
When my students do this, for any book I use or course I teach, all of them pick three things that I agree are among the most important or next to most important. Most of them have at least two of the three that I would agree are among the most important. Your real goal here is to have a place to start and to start learning how to decide on the things that are most important to learn first.

(2) Next, apply Strategy 2, imagining that you have an exam coming up on Chapters 1-8.

How you’ll decide: The day after your last practice session, you might list the things you recall from each chapter. Compare how well you recalled the chapters.

Results and Conclusions

Unless you are reading this book as part of a course, you probably won’t do this experiment on this book. It probably won’t feel important enough. You might have some exams soon in classes. You could test these for one of those exams.

Picking out the “most important” things

Students who try these two strategies always get stuck trying to pick out the most important things. It feels hard; how can you tell what is most important. Try it anyway. Even for beginners with this strategy, their most important three are almost always in my most important five. That’s pretty good. In fact, sometimes I discover that their ‘most important’ three are better for them than the three I would pick for me. Because students have not mastered all of the same chunks, and because understanding is not identical for all students, the ‘most important’ three on which to start can be different for different people.

My most important three are always the things that have the most connections to other parts of my class. Because of those connections, the ‘most important’ three are always the most useful for understanding other topics and solving problems. Because my students don’t usually see the same connections that I see, our most important three can differ. Here’s an important point, though: with enough practice, they are not wrong in their most important three, just different. With enough practice, every student gets good at this.

A Fish-example of “most important” things using reading

Imagine that you are a skilled learner but a pre-reader, and you have to start learning reading as a new skill. You don’t know the alphabet. You don’t know about consonants and vowels. You don’t know how to combine letters into words and words into sentences. How could you know what was ‘most important’ to learn first about reading?

Imagine that on our first day I talk to you about the concepts of (1) sentences are combinations of words; (2) words are combinations of letters; (3) letters are either vowels and consonants; and (4) the alphabet. Remember, I specified above that you are a skilled learner; you just don’t know how to read. As a skilled learner, you would know that you need fluent recall with understanding of the alphabet before you can develop fluent recall with understanding of anything else. Why? Because if you cannot remember the alphabet fluently with understanding, then you cannot recognize all consonants and vowels, you cannot recognize some words, and you cannot recognize some sentences. If you saw my letter \[\text{\textparagraph}\] but
could not remember what it was, could you decide whether this strange letter is a consonant or a vowel? Could you read any new word that contains my letter? A skilled learner would know he or she needs to start by developing chunks with fluent or automatic recall, with understanding, for the letters used in words.

Let’s jump to our second day of learning. You are practicing the 26 letters of the alphabet (and hopefully, not my invented letter). You spend equal practice and study time on each letter. On your third day, I start showing you some simple words that are combinations of two or three letters. You cannot read the words yet, but you notice that some letters are used in many words. Other letters are used in very few words. You decide that the common letters (vowels and some consonants) are most important at first. You decide that three letters (Q, X, and Z) are not very important yet.

At each stage of learning to read, you could identify things that are most important to learn next. As you begin trying to chunk words, you could discover that each letter of a word you read must be held in working memory as you try to identify that word, and you also need to remember the sequence of letters in the word, as well as the consonants and vowels. You could decide that two-letter and three-letter words were more important to learn than five-letter or six-letter words, and that seven-letter to ten-letter words would be impossible until you have chunked many shorter combinations of letters. You could decide that some three letter words must be important to practice often because you see them all the time (the, you, see, get), and others you see so rarely that must not be essential (gnu, ply).

After going through my example above, I want you to notice two categories of “most important” to learn.

• **First**, some things are “most important” to learn first because they are fundamental. You cannot understand chunks at higher levels unless fundamentals are in fluent or automatic recall with understanding. The alphabet and concepts of vowels and consonants are in the category of fundamental. Some short words are not fundamental (gnu & ply). Later, as you begin to read sentences, the concepts of sentence, subject, and verb would become new fundamentals for learning to read sentences.

• **Second**, some things are “most important” to learn first because you need to practice simpler chunks in order to learn more complex chunks. Words of two or three letters are in this category. Two- and three-letter words are not more fundamental than four- and five-letter words. Could you tell me if the word ‘up’ is more fundamental than the word ‘down’? You can easily decide this for yourself. **Go through this specific sentence, word by word, and tell me if the short words are more fundamental than the long words.** We need them all! However, until you develop memory pathways for short words, you cannot learn long words. It is “most important” to learn short words and single syllables first because you need those memory pathways to learn longer words.

Many short words of two or three letters are important to learn first because their letter combinations are chunks that are used in longer words. It is easy to think of examples. Think about an and and. An and and are in: land, bland, landing, candy, sand, sandy, hand, handling, sanded, resanding, hand sanding, and the phrase handling hand-sanded candy on sandy land. A very large number of two- and three-letter words are parts of many other words, often with a completely unrelated meaning. Most of the chunks you develop for short words are combined with others in longer words. Over time, as your reading skills progressed, the “most important” things to learn would be four- and five-letter words. By then, as you were beginning to read
sentences, you could decide that that it is “most important” to learn and practice short, simple sentences before learning and practicing long, complex ones.

A Fish-example for mathematics

Imagine that you are your current age, you’ve read this book, and you are starting over in something you know nothing at all about: mathematics. You do not even understand the concept of numbers. Here we are, and I am your new teacher. I set out in front of you every concept in mathematics that a typical student will learn before college. I explain that I will give you tests, so please learn all of this. However, I do not tell you what is most important. I do not tell you where to start. I give you no hints on how to learn.

Even in this situation, you might do pretty well, based on what you know now about learning. You would start in complete confusion. You would be angry at me, I’m sure, and frustrated. However, you could notice that there are symbols that show up over and over: 0, 1 2, 3, 4, 5, 6, 7, 8, 9, =, +, -, x, \slash. You could easily decide that these must have more connections than anything else, because they show up in almost every topic. They look like fundamentals. If you conclude that these are “most important” to learn first, you would be right.

How would you learn them? Based on the strategy that you need to “practice simpler chunks in order to learn more complex chunks,” you would start with development of fluent recall with understanding of these symbols. As you master these (fluent recall with understanding), you would begin learning procedural rules to solve problems. You would begin with problems such as $2 + 5 = \_\_$ or $3 \times 6 = \_\_$. You would not start with problems like $578 \times 4392 + 56 / 2275 = \_\_\_$.

As you are learning mathematics in this way, you would sometimes discover that you have forgotten earlier chunks. Earlier chunks that were important and that you once had in fluent or automatic recall with understanding are now becoming hard to recall. You would need to go back and practice those fading chunks.

This shows a third strategy of learning most important things first. If you lose fluent recall of any “most important” topic, especially if it is a fundamental, it becomes most important to go back and review. You must review fundamentals when you need them. I don’t care how well someone ‘knows’ geometry, algebra, or calculus; if he or she has forgotten basic addition, the person cannot have fluent recall with understanding of any of these more advanced concepts. (This need to review and practice never goes away! As a professor teaching different courses, I must always review and practice each course’s most important topics that are no longer in my fluent recall with understanding. If I choose not to review and practice them, I will make mistakes in class.) Identifying lost or missing chunks and practicing for fluent recall with understanding is essential for skilled learners.

Choosing the “most important” from any new reading or class session

No matter what the subject is, you can at least guess what is most important. Most of the time, in order to make this decision you need, (1) fluent recall with understanding of OLD knowledge, combined with (2) the simplest Fish-version of understanding of the NEW information. Together, these let you decide what is probably most important. You usually need
fluent recall with understanding of the old knowledge because otherwise the old knowledge takes too much working memory space. If you can only barely hold a necessary concept using all seven spaces of working memory, then you cannot ALSO consider the importance of something new, let alone learn that new thing. When a student understands the rules for “most important” things, but still cannot decide what the most important things are, it often means he or she does not have fluent recall with understanding of the necessary OLD knowledge.

Have courage! At first, it may feel like you are just guessing the “most important” topics to learn first. With experience and practice, any new method gets easier and easier. You will develop expertise at knowing the “most important” things for your learning. As you practice, your metacognition skills will improve.

**Metacognition as you learn**

Over time, an expert develops **automatic application** of procedural rules for metacognition. Most experts would automatically apply most of the metacognition questions below, even if they are not actively aware of doing so. As you develop expertise, you can begin to develop automatic application of these rules by asking yourself some of these questions as you learn:

1. Do I have interested, focused attention? (If not, how might I become more interested or focused?)
2. What should I learn first? What should I learn second? (And so on…)
3. Do I need recognition memory, recognition memory with understanding, fluent recall, fluent recall with understanding, fluent recall with understanding and procedural rules, or fluent recall with understanding and procedural rules and transfer? Each of these requires different learning methods and different kinds of practice.
4. Do I know this well enough yet? (And, later, do I still know this well enough?)
5. How do I know that I know this? How can I tell if I know this well enough?
6. What is the most efficient way to learn this as well as I need to learn it?
7. Have I finished the learning tasks that are useful today?
8. Am I doing empty memorizing? Should I be?
9. Might there be better or faster ways to learn this?
10. Will learning this also help me learn many other things, later?
11. How important is this? Does it connect to many other facts, principles, or kinds of problems?

The list above is a good list, but it won’t be the best for all people all the time. You should change them and add or remove questions to fit your own learning. In fact, a good learner will ALWAYS consider whether my suggestions, or anyone else’s, can work for himself or herself.

Remember that an important part of metacognition is testing your own learning. Below are two more examples another example of a metacognition experiment to test a study method (Experiments 9.3 and 9.4).

**Metacognition experiment 9.3: Testing mind maps with sketches**

**Purpose:** To test whether mind maps with sketches make me less confused than my best alternative method.
Methods:
1. Find two concepts or sample exam problems about which I feel confused or uncertain. The two should be or at least feel equivalent in difficulty.
2. Flip a coin to decide which to sketch.
3. For one, develop a mind-map, which might include identifying missing chunks. For the other, do my usual things to try to understand it.
4. Spend an equal amount of time on two different days for each. (1 hour? 2 hours? 30 minutes?)

How I’ll decide: The best method will be defined as the one that … (It’s not easy to come up with a good decision rule here! The obvious choice is the one that makes me feel least confused. However, that might be because one method or the other just makes you feel less confused, even though you are not!). You’ll have to be thoughtful about objective decision rules.

Results and Conclusion:
The results were →

Metacognition Experiment 9.4 The fastest way to review for an exam

Purpose: To test whether mind maps with sketches, folded lists, or rereading notes and/or the book is the fastest way to review material for an exam.

Methods:
1. For the same number of concepts, time myself looking up and reviewing material;
2. Stop the clock when I feel that I understand it as well as I did originally.

How I’ll decide: The best method will be defined as the one that takes the least time.

Results and Conclusion:
The results were →

A summary of ten strategies to do (these are more and more effective with practice)

(1) Retrieval practice. What does retrieval practice mean? Read or review, then close your eyes or stare off into space, and try to remember the important parts. Repeat, once or twice per day for each important concept, over a period of days and weeks. Repeat whenever you need to review. (Flash cards can be useful as a trigger for retrieval practice, but so is a list of terms.) By the way, I usually think of retrieval practice as recall practice, even though the correct term in learning research is retrieval practice.

(2) Minute sketching. Use information reduction to produce a sketch or diagram that represents any structure, concept, or event. The sketch should include simple symbols for things you have already chunked and have in fluent recall with understanding. The sketch should include only what you need to remind you of all of the important pieces in the concept. The sketch many NOT include any words, because words are distracting on a sketch. Practice redrawing your sketch or diagram once or twice per day while thinking
through the entire concept. *(Minute sketching is a method described in more detail in Chapter Eight.)* Make your sketches feel real.

(3) **Connect** new terms to new concepts. Instead of memorizing definitions, make a **folded-list** and practice with it. Practice rewriting your column of key terms from your sketch and redrawing your sketch from your terms. As you write the words, describe the concept or event to yourself (aloud or in your head) using the terms. As you draw the sketch, practice describing what you are drawing. *(The folded list is a method described in more detail in Chapter Eight.)*

(4) **Develop** transfer and problem-solving skills. 
   (a) For every new thing you learn, **make an imaginary change** (on paper) to one part of your sketch. Consider what would be different. Predict how your imaginary change would alter the structure, event, or concept. 
   (b) Look out the window, at a photograph, or at anything else. Whatever it is, try to **find a connection** to chunks you are practicing. (For example, if you are studying the concept of heat, you might look out the window or around a room and imagine what each object would be like if it was one of a group of molecules that was hot or cold, and how molecules are moving in a hot object versus a cold object. You would be making it feel real.)
   (c) Find **word problems** in your book or anywhere else to practice solving. (Word problems that feel hard are usually hard because they require transfer. Therefore, word problems are a great way to practice transfer.)
   (d) Look for **procedural rules** for problem solving. Sometimes these are in your book or come from a teacher, and sometimes you have to find them for yourself.

(5) **Develop** transfer skills with **concept maps** or **mind maps**. For any of these, start by writing or sketching any concept or event or structure in the middle of a sheet of paper. Think of every chunk that directly connects to that chunk. (For example, the concept of a “chunk” connects to working memory, to seven spaces in working memory, to the concept of a piece or part of something else, to fluent recall, and to understanding). Add these, with lines making the connections. Next, add connections between these new things. (For example, the concept of fluent recall connects to understanding, but not to seven spaces.) Next, think of new chunks that connect to any of the chunks on your paper. Add them, and draw the connections. I recommend that you use at least some sketches, but you can use any method you want. Sometimes you will want words or sketches on your connecting lines, and other times the connections will be obvious to you. Make these feel real.

(6) **Set goals** for each learning session (for each study session). Decide that you are going to do one specific thing, such as information reduction to sketches, or practice with any method until you understand a concept or a list of terms. Then stop and reward yourself.

(7) Use **drilling games** but only for concepts and connections you want in **automatic recall** (not just fluent recall) with understanding. Drilling games are for things like the alphabet or Spanish or French verbs. In mathematics, drilling games are for things like your 1-9 multiplication tables, or pi and e. In chemistry, these are for things like the elements, electron shells, and parts of the periodic table. In biology, these are for things like cells, organelles, DNA, genes, and membranes. **Be careful!** It is easy to let useful drilling become terribly **awful** empty memorization. You always should know exactly why you want those things in automatic recall. Useful drilling is for things you need to hold as a
Chapter Nine: Study Strategies

single chunk in working memory very, very often. (Imagine trying to read without remembering the alphabet in automatic memory. Imagine trying to do almost anything in chemistry without having carbon and hydrogen and oxygen and electrons in automatic memory. Imagine trying to learn anything in biology if every time the teacher or book says “cell,” all you think of is a jail cell.) Drilling games include the alphabet song or having a classmate yelling out “What’s 5 x 7?” “What’s 4 x 8?” and “What’s 6 x 9?” or having a friend yell “cell,” “DNA,”, or “protein” while giving you just a short time to sketch or imagine or describe each (while making it feel real), including every essential part.

(8) **Write exam questions** for yourself, in the style of word problems. Then try to answer them. This is much, much harder than it sounds, but it becomes easy with practice. It can be especially useful to try to write exam questions in the style of your teacher or professor. While my students tell me they almost never predict a question that I have on an exam, they find that trying to predict my questions makes it much easier to answer my questions. When you do this, you need to know that you might ask a question that is impossible to answer. That is okay. Your job is to write a question for yourself, decide whether or not it can be answered, and answer it if you can. If it seems impossible, just try again. Learning to see that a question is impossible is actually a useful transfer-building and problem-solving skill.

(9) **Save good study materials!** Especially when you have done information reduction, it is much faster to review and relearn material from your sketches or other materials than from a textbook or detailed notes. In many subjects, you will want to review quickly in several months, a year, or even years later! You can have fluent recall with understanding for an entire course, but if you haven’t retrieved and strengthened memories for a few months, you will lose it. Good study materials can help you reinforce exactly the memories you need very quickly and get them back into fluent recall with understanding. I have seen students in my college classes use good materials they prepared as long ago as 9th grade. My students who have gone to graduate school for a doctorate or to medical school often tell me that they reuse good study materials from college over and over! This year, some of my college freshmen in this class (Memory and Learning) have shown me good sketches and summaries from their high school chemistry that they are using in a college chemistry class.

(10) **Have a sense of wonder.** Find ways to enjoy your learning

(11) **Should we add a number 11?**

Anyone can develop memory skills using a method called the memory palace technique. This is a very old method that dates back at least to the ancient Greeks. The basic idea is to link any series of things you want to remember to an imaginary walk through a building or street that you know well, placing each thing in order in your mind along your way. With practice (not as much practice as you might think, but still quite a lot), people can develop the ability to remember sequences of dozens to hundreds (and even many more) words or numbers almost as fast as they can read them. With a little more time, people have memorized sequences of 50,000 random digits. These are not people with extraordinary memories. When tested in other ways, their memories are usually just average. What they have developed with practice is the method and skill to form such memories quickly and hold them for a long time. The method works well, but it has two problems. (1) It does not make useful connections. (2) The sequences of words or numbers you learn are not organized EXCEPT in that sequence. In other
words, you can put things into fluent recall very, very quickly, but you cannot use them well EXCEPT to recall the original sequence. Very few experts use this method. That might be because it takes most people months of regular practice to get good at it, and you don't gain any organization.

So the answer is: No, we won’t add this as number 11.

**Changing your study methods: don’t expect instant changes.**

One mistake students make is that they try to do too much too fast. They try to change from inefficient studying to efficient studying in just one day or a few weeks. They try to completely stop procrastinating. There may be a few people who can make huge, sudden changes any time they want. I usually can’t, and neither can most of my students. It usually takes steady practice, trying again when something doesn’t work.

As far as I know, there is no single thing that you can do to become smarter and learn better. There is no simple trick and no simple technique to becoming a better student overnight. Better learning, better problem solving, and better grades don’t usually come fast. Just as with learning to play basketball or a musical instrument or anything else, you have to practice many different things, and you have to practice in the right ways. Beginners get it wrong much of the time. It takes practice and coaching to become skilled. No one suddenly becomes a great basketball player, scientist, or pianist in just a couple of weeks, but a year of interested, focused study and practice with good coaching and increasing challenges will bring results.

**New study strategies start out being hard, but become automatic with practice.**

When you look at the long lists of steps and multiple study strategies, it feels confusing. As you go through a textbook to pick out the “most important” things or make simple sketches, you may feel you haven’t even started learning yet! That is not true. You have started learning as soon as you start deciding on what is most important and what to chunk as a sketch. The process of deciding what you need to know, the ways in which you need to know it, and how to learn it IS part of learning anything new.

Through the process, you are developing memory, developing transfer skills, and increasing your own interest. When you decide that one thing is more important to learn first than another, you cannot help but be a little more interested. In order to prioritize the importance of chunks, you have to test them for new connections with your old chunks. The act of prioritizing helps develop your memories and make them stick.

My lists of study methods to try looks long, complicated, and slow, even to me. With practice, though, any strategy becomes fast and automatic for a student. Think about the ten seconds before the end of a nearly even basketball game. Explaining the last ten seconds, including a detailed description of in-bounds throw, followed by description of a play to score the winning basket also seems long, complicated, and slow. With practice, though, it’s doable in 10 seconds. Without practice, people mess it up and miss the basket nearly every time. It’s a lot like studying. With enough practice, the right things happen very fast.

Students who have practiced these methods eventually tell me that they couldn’t imagine studying without them. Over time they can become easy and natural.
Chapter Nine: Study Strategies

Box 9.2 Study Strategy 3 -- another optional method

1. Ask yourself, “What do I need to learn, and why?”

2. How do I chunk this?

3. Do I have the necessary chunks for new knowledge already in fluent recall with understanding?
   
   If not, then drill and practice the chunks you need.

   In biology, you can’t learn about genetics and genes with understanding if you don’t understand DNA or alleles.

4. Learn the most important things first.
   
   - A rule I often give to my students is: for each lecture (or class day), start by finding the three most important things to put into a minute sketch along with key terms to learn. If you don’t have a way to choose the three most important things, then guess. Practice putting those things into fluent recall with understanding. You are not allowed to study anything else from that lecture or section UNTIL you have the three most important things in fluent recall with understanding.
   
   (A practical rule for identifying “the most important things” is that they are the terms or concepts or procedural rules that come up most often. They aren’t necessarily going to be directly on an exam, but if you don’t know them, you’ll make many mistakes on exams.)

5. How to learn them?
   
   - Take the three most important things, and turn each into a chunk you can learn using 7 or fewer chunks you already know.
   
   - Minute sketches with folded lists for fluent recall with understanding

   - Retrieval practice

6. Information reduction. Every new chunk I teach can be simplified to a minute sketch. Every hour of lecture I give, or night of reading I assign, can be simplified to about 3-7 minute sketches. Those 3-7 minute sketches contain EVERYTHING essential for those 3-7 facts, events, concepts, or procedural rules to solve a problem. When I say they “contain” everything essential, I mean that they will remind a student about everything they need about that fact, event, concept, or procedural rule. Students can review and practice those 3-7 minute sketches completely in about 3-7 minutes. Truly. Then why can’t I just give them the minute sketches? Because for understanding something the first time, we humans need a lot of detail. The details connect new chunks to old chunks. You have to have the extra details. Once you understand it, though, you can simplify to essentials. In fact, you MUST simplify to essentials, or else you overload working memory. You cannot memorize everything. (Even if you could, it would not be organized well.)
Box 9.3 *Study strategy 3 (continued)*

Here’s the sequence of events:

Use your readings and your in-class lecture or discussion time to understand the new chunks you want to learn.

Identify the three most important new chunks to learn as fluent recall with understanding.

Use information reduction to turn them into chunks that contain ONLY the essential elements for the new chunk. You cannot do this until you understand the new chunk. (You usually cannot do this for someone else. A teacher cannot do this for you, because they do not know the chunks you already know, and they do not know the connections you already have between chunks. The correct information reduction for you is probably going to be different than the correct information reduction for someone else. The best minute sketch for you is not the best minute sketch for someone else.)

7. By the time you are in high school, if you plan to go to college, you are learning chunks that you will need later. In other words, the chunks you are learning will be necessary to build more complex chunks later. Most students forget most of what they learn in high school, and need to relearn it later. IF you learn high school information in ways that are easy to review and rechunk later, college will be much easier.
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**Box 9.3  Study strategy 4**

1. When you have a new learning task, start by analyzing it.
2. Always skim the notes or text you have to read. Write down key words for concepts. (Do **not** copy any definitions yet; just note where in your notes or readings the concepts occur.) Do this fast. If you cannot, then you are thinking too hard about it or including too many terms and concepts in your list.
3. In a problem-based class, such as mathematics, chemistry, or physics, go to the problems you have to solve, list the key words and topics, and then find the pages that cover that kind of question.
4. Rank the facts, terms, concepts, and problems by importance. You may have as few as two groups (or rankings): “Most important” and “Next-most important.” You should always have one more category for “Not important now.” None of the “not important now” terms should stay on your list. How do you decide? Sometimes a teacher gives you advice on this. It’s best to think for yourself: “How often will I use this again in this class OR in classes I take later OR in my life outside of school?”
5. Plan what to learn for each thing in your “most important” group. In other words, if you just need to recognize and understand something, plan to learn to that level but no further. For example, I have never used the word “defenestrate” myself, but I have on occasion read it somewhere. While recognition memory with understanding for “defenestrate” might be necessary for me, fluent recall of the word is not. I have never needed to recall the word. I have needed to recognize it. If you need fluent recall with understanding, decide how you will develop that kind of memory. If you need transfer with that concept or term, decide how you will develop transfer memory using the concept.
6. For each, what chunks are a necessary part of the fact, term, concept, or procedural rules?
7. For each, which of these necessary chunks do you already have in fluent recall with understanding?
8. Decide how to learn each term or concept or set of procedural rules. If you do not already know each of the necessary chunks, start with those before trying to learn the new fact, term, concept, or procedural rules.
Chapter Ten: Nerve Cells and Memories

Chapter Ten

Nerve Cells and Memories

What is a memory?

We must build new learning on the chunks we already have. Knowledge can only be built out of what we already remember and understand. In this chapter, I want you to begin to understand the cells of memory and learning. Using chunks you already have, we'll start with a Fish-version of a memory.

My Fish-version is this: a memory is a row of dominoes ready to knock each other over. When something triggers the memory, it pushes over the first domino, which hits the second, and the second hits the third, on to the end. Most of the time, you are NOT thinking about most of what you know. Those memories are like a standing row of dominoes with nothing happening. Stop a moment, right now, and close your eyes. Think of a fact or of something that happened to you recently. (Pause here, while you close your eyes and think. I'm doing the same thing.) Whatever you remembered is a memory. Before you recalled it, the memory was there in your mind like a standing row of dominoes. It has the potential to be remembered, but it isn't being remembered right now. When you recalled the memory, you knocked over the first domino, which then knocked over all of the others. Knocking over the row of dominoes is remembering. That is what it means to remember something. The row of dominoes is the memory, and knocking it over is you recalling that memory.

How does that work? We will start with the simplest version that I can call a “memory” (actually a reflex). Imagine that you are sitting on the edge of a table. Your leg is hanging down, but your foot is not touching the ground. Your knee is bent and your leg hangs loosely. A doctor taps just below your kneecap with a small soft rubber hammer. (A friend can do this with the edge of their hand. You can even do this to yourself, with practice. You have to hit just the right spot, and hard enough but not too hard). The hammer hits a tendon—a strap of tough material that connects your kneecap to your lower leg. Your leg kicks (Figure 10.1).

Figure 10.1. When sitting with your leg dangling, tapping you knee just below your kneecap makes your leg kick.
Why does this happen? The whack to your tendon is the push on the first domino (A). The first domino falls into a second domino (B) that falls onto a leg muscle as shown in Figure 10.2. The muscle makes your leg kick.

In memories, dominoes are the nerve cells (or neurons). That's the memory: A to B to muscle. You were born with this memory. Your memory from birth for a leg kick changes only with disease or damage. In Figure 10.3, I've added neuron A and neuron B. The lighting bolt represents the small electrical charge when the muscle contracts.

No neuroscientist would call this a memory. When it is not something you learned, they call it a reflex, not a memory. However, a reflex has only one difference from a memory. You are born with a reflex and cannot easily change it. To get a memory, you have to have an experience or practice something. However, once you have a particular memory, there is no simple way to tell the difference between a memory and a reflex. A reflex is a row of dominoes you were born with. (An instinct is also a row of dominoes you were born with—just more complicated and with more dominoes than a reflex.) A memory is a row of dominoes you invented for yourself, from your experiences. Each row of dominoes is a row of nerve cells—a row of neurons—ready to be knocked over, as in Figure 10.4.
As a Fish-version of your brain and memory, you should think of everything you do and think, every movement and every thought, as rows of dominoes as shown in Figure 10.5.

Every reflex, instinct, and memory is a row of dominoes. Knock over the first domino, and the whole chain falls over, one by one. When the whole chain falls over, something happens. Perhaps you recall a memory. Maybe your leg kicks. Maybe you say, “Ouch!” like in Figure 10.6.

What would happen if one domino were missing? What if there was no connection from one domino to the next? The chain stops (Figure 10.7). If there never was a nerve cell making a connection, then you never had that reflex or memory. If injury or disease removes a connecting domino, then you lose that memory or reflex.
Figure 10.7. If the row has a gap—if a neuron is missing—then everything stops at the gap. You fail to say “ouch” or have the complete memory. Often with these gaps, the neurons or dominoes are not missing; they’re just too weak or too small to knock over the next domino in the row.

Chains of neurons, just like rows of dominoes, can branch. You can knock over one domino, and later split the chain, and end with two (or more) falling dominoes. You can start with one neuron and end with more than one movement. You have one reminder trigger more than one memory. For example, what happens if I hit your knee in the right spot, but too hard? Your leg will kick, but there will be other branches from the chain. As you kick your leg, another branch of neurons might make your mouth open and then exclaim, “Ouch!” Knocking over one domino, like domino A in Figure 10.8, can connect to branches that have more than one result. Domino E opens your mouth, H makes you yell, “Ouch!” and M makes you leg kick like in Figure 10.8.

Figure 10.8. Knocking over a single domino (or neuron) can cause new branches to fall, with a domino falling at the end of each branch.

Your brain has a lot of chains of neurons. The chains connect and twist in your brain. Each chain is a reflex, an instinct, or a memory (Figure 10.9).
Figure 10.9. Branching rows of dominoes are like the chains of neurons in your brain. Different starting points in the same chain can sometimes cause some of the same results. In this figure, there are at least three ways to knock over the domino at the top right. There are two ways to knock over the domino at top left.

Some movements or memories require more than one domino to start. Imagine that you are hungry, and food is on a table in front of you. Will you ALWAYS start eating? What if you can tell that the food is uncooked? To eat the food, you need to observe it on the table and know that it is cooked. A row of dominoes can make that happen by using two small dominoes that must fall together to knock over a single large domino. In Figure 10.10, Domino C in the chain toward “Eat” is larger than the others. Domino C is too large to fall from just one falling domino (domino B, which falls when we see the food on the table). It takes two dominoes: we have to see the food (domino B) and know it is cooked (domino H).

Figure 10.10. Some results might require more than one event to start them. Here, the large domino C is too heavy to be knocked over by a normal domino. C will not fall unless both B and H fall against it. Domino E falls onto “Eat!” only if you see food on the table and you can tell that the food is cooked.

In your brain, more than two dominoes may need to fall against C. Before you eat the food, you need to know if the food is for you, if you like it, if you are hungry, and whether or not the food smells bad or spoiled. Many small dominoes may need to knock over one big domino. Many chains of neurons sending impulses to one other neuron may be required to start a new nerve impulse.
As you make a memory, you are setting up new chains of neurons, just like you have to set up rows of dominoes on a table. The dominoes in your brain are new connections between neurons in your brain. Those new connections need to be grown and strengthened. Each fact or concept you learn is a chain of dominoes, and you have to make these new memories starting with the chains you already have. For example, think about learning this historical event: “Christopher Columbus sailed in 1492 to Central America.” In order to develop a new memory, you had to connect the name “Columbus” with the year 1492, the concept of sailing in a ship, and the geographical location of Central America. Before you developed this memory, if you saw the name “Columbus,” it connected with nothing else as on the left side of Figure 10.11. Columbus was just a word. When you heard or read the word “Columbus,” a row of dominoes for the letters C o l u m b u s knocked over a domino for “Columbus,” but that was the end like in the middle of Figure 10.11. Finally, on the right side of Figure 10.11, you learned this historical event when your nerve cells had made the branching chain of dominoes to connect Columbus with the other concepts. With that new chain, just seeing the word “Columbus” causes the whole memory: “Christopher Columbus sailed in 1492 to Central America.”

We are fooled by how long it takes to make a lasting new memory. That’s because working memory can understand something new very quickly. However, working memory holds your seven chunks only for about 30 to 120 seconds. You can read that “Christopher Columbus sailed in 1492 to Central America” to start making a memory. But it takes time and repeated re-use of a memory to make it last a long time. To change something from working memory to long-lasting memory you have to strengthen connections and grow connections between neurons for every part of every fact, concept, and connection.

A simple rule of memory is the more times you recall a memory (the more you practice), the stronger the memory gets. It is like setting up chains of dominoes that are weak, small, and temporary. Each time you knock over the dominoes and recall the memory, it sets the chain back up a little stronger—a little easier to recall the next time. However, if you wait too long, you will lose connections. The connections become weaker; the dominoes become smaller. In Figure 10.12, with practice the initial memory has the entire set of facts all equally strong (left side of Figure 10.12). However, over time, dominoes K and L might get smaller because of insufficient practice (middle of Figure 10.12). When thinking of “Columbus,” this particular person on the right side will still remember that Columbus sailed and that the year was 1492, but not where Columbus went (right side of Figure 10.12).
Figure 10.12. A memory may be strong at first, on the left, but without practice two connecting dominoes, K and L, become smaller and weaker. As a result, on the right side, the word Columbus now recalls only 1492 and sailing, but not Central America, because domino K is no longer large enough to knock down domino L.

When you learn something new, you add new dominoes here and there to make new rows or new connections between rows of dominoes. Each new chain is a new fact or new concept. Each connection might connect two ideas by joining two rows you already have. The connections between rows are your connections, for example, of the word ‘hot’ with hot fire, hot sun, and hot chili pepper. However, unless you practice—unless you use those new dominoes day after day, over and over, you dominoes of memory disappear. It is possible to learn a new fact or concept in a class, understand it completely, and then lose it. Unless you practice using your rows of dominoes, they shrink and fade away. Each day that you practice recalling that memory causes the connections to become a little stronger and long lasting. Eventually, with enough practice, memories can last a lifetime.

I will use the words “neuron” (or “nerve cell”) instead of “domino” from now on, most of the time. However, you may still think of neurons or nerve cells as connecting much like dominoes (Figure 10.13).

Figure 10.13. A chain of nerve cells (neurons) drawn like a row of dominoes.

Keep in mind that this is a Fish-version for reflexes and memories. If you keep reading and learning, you’ll steadily get closer and closer to fluent recall with deep understanding and transfer for the concepts and structures of memory.
Reflexes, learning, memory and neurons

I want you to picture a new reflex. This one also has two nerve cells, just like your knee jerk reflex. Imagine that you are standing facing me, reaching out your hand toward me. I stick it with a pin (sorry). I’ve shown the pinprick in the left side of Figure 10.14. What happens? The pin stabs into nerve cell A. Neuron A causes a nerve impulse in neuron B in your spine near your shoulder. Neuron B sends that impulse to a large muscle in your upper arm, which is indicated by a lightning bolt to a muscle (your biceps). That connection makes the muscle contract. When your biceps contracts (becomes shorter), your lower arm and hand jerk up and away from the pin like on the right side of Figure 10.14. You have used another reflex.

Figure 10.14. When stabbed with a pin, a nerve impulse in neuron A is sent to neuron B. Neuron B sends a nerve impulse to a muscle in your arm that pulls your hand away from the pin.

With this new reflex, I want to add a new concept. Though the idea of rows of dominoes is very much like neurons, neurons don’t fall like chains of dominoes. Instead, neurons are like tubes. The tubes have charged ions in them, especially sodium, chloride, and potassium ions. Remember that table salt—sodium chloride—dissolves in water. Each single molecule of sodium chloride separates into one sodium ion, with a positive charge, and one chloride ion, with a negative charge. (We call them ions because they have a charge—that’s what makes them an ion.) Potassium salt dissolved in water releases a potassium ion (with a plus charge) and another ion with a negative charge (often a chloride ion). In each neuron, positive charge pushes in one end and out the other, like water through a hose (Figure 10.15). Here, you need to remember some basic physics: positive charges repel. They push each other apart, spreading evenly in a tube, like + charges P and Q in Figure 10.15. Next, if we push a new + charge in at one end, charge R in Figure 10.15, then charge R repels charge P. In turn, charge P moves and repels charge Q out of the end of the tube. A real neuron has far more charges—millions of trillions more charges—but the idea is the same: if enough + charge comes in at one end, it pushes + charges from the far end out of the tube. This is another Fish-version of how neurons work. It gets us close enough to work with.
Figure 10.15. In a Fish-version for how neurons work, positive charge enters at one end of a neuron and repels other positive charges already in the neuron. When positive charge enters, it pushes (repels) positive charge out the other end.

Figure 10.16. A domino falling is like a positive charge passing through a neuron. At the top of the figure, nothing is happening: Domino 1 is standing, and Neuron 1 just has all the charges spread out along the neuron (repelling each other). In the middle, if we add positive charges A and B into Neuron 2, then the + charge repels other charges. At the far right, two other charges, S and T, are pushed out of Neuron 4. Shown as dominoes, at the bottom, positive charges A and B cause Domino 2 to fall, and eventually Domino 4 falls, with positive charges S and T pushed out.

Figure 10.16 shows neurons connected to each other by passing + charge, just as if they were dominoes falling onto each other. Some + charge coming out of one neuron can cause + charge to enter the next neuron in a chain. This is just like one domino falling to hit a second domino, causing the second domino to fall. In neurons, the fall of the domino is the positive charge moving through the neuron. A real neuron has many more + charges, but in my example in Figure 10.16, I kept track of only enough + charges to show the result. Notice that in Figure 10.16, I made the last neuron in the chain, Neuron 4, branch. The two branches of Neuron 4 could connect to two other neurons. In our rows of dominoes, we sometimes had one domino knock over two, and neurons can also branch. Connected neurons in memories are not
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...exactly like rows of dominoes, of course, but this visual image helps us understand how memories work.

In my example of food on the table, two dominoes had to combine to knock over one larger domino. In the same way, two neurons (5 and 6 in Figure 10.17) might need to combine to put enough charge into another neuron (7) to push + charge out (Figure 10.17).

Figure 10.17. Positive charge from two or more neurons is often required to cause a nerve impulse in another neuron. (Recall that it can require more than one small domino to knock over a larger domino.) In this figure, Neuron 7 will not move positive charge out unless both Neuron 5 and 6 pass a charge.

In your reflex response to a pinprick (Figure 10.14), what makes + charges enter the first neuron? How does this all start? In my example, stabbing your finger with a pin caused damage to cells. The leaking material from inside the damaged cells open channels for + charge to enter one kind of neuron. (We often call these "pain neurons".) Opening channels for + charge in a pain neuron is the same as knocking over the first domino in a row. In Figure 10.18 below I show how the pin stabbing your cells causes leaks from the cells (the gray leak in the middle image). Then those molecules reach the pain neuron, which opens channels for positive charge to enter (shown on the right side).

Figure 10.18. How does a pin sticking your finger start a nerve impulse? In this Fish-version, I show a pin stabbing through your cell (the gray blob) near a pain neuron. I’ve drawn these much larger than real cells, and the neuron is also much larger than a real neuron. When molecules from the inside of the punctured cell ooze out (the gray ooze) and get to the pain neuron, those molecules attach to and open a channel for + charge. With the channel now open, + charge from the fluid around cells enters the pain neuron.
If we go back to your reflex when I stabbed you with a pin, we can redraw the reflex showing the neurons as tubes with + charge (Figure 10.19). (You might want to jump ahead to look at Figure 10.22, in which I show the neurons where they really are in a person.)

Figure 10.19. Here we see the reflex that pulls your hand away after I stab your finger with a pin. Positive charge moves into Neuron A, sending positive charge to B. Neuron B causes positive charge to move into the muscle. The positive charge makes the muscle contract, pulling your hand away.

Neurons truly are long and flexible tubes that move + charge from one end to the other. Neuroscientists draw chains of neurons to show reflexes, memory, and learning. Most simply, they draw each neuron as a circle with a line coming out and a broad sideways V on the end (Figure 10.20).

Figure 10.20. Neuroscientists often draw a neuron as a circle with a line and sideways V. The circle is meant to represent the body of the cell, holding the nucleus, genes, and most molecular machinery of the cell. The lines with the V represent the tubes through which positive charge is moving.

I can make this drawing a little more realistic for you, though later, we’ll use the simpler style of Figure 10.20 above. In Figure 10.21, thin tubular parts of neurons called dendrites move + charge into the cell body, and thin tubes called axons move the charge out at the other end. The tube carrying + charge away from the cell body, the axon, can branch to go to tens, hundreds, or thousands of other neurons. Connections to the next neuron are usually made at the cell body or on dendrites leading into the cell body. The connections are called synapses.

Figure 10.21. Positive charges (from the left) move into the dendrites or cell body of Neuron A. From the cell body positive charges enters the axon. The axon may branch hundreds or thousands of times to send positive charge to other cells, including B. The connections between axons and dendrites or cell bodies are called synapses.
Some new chunks about nerve cells and memories

Even with these new chunks, neurons are still like dominoes. The synapses between axons and dendrites or the cell body are where a neuron is “hit” by other neurons. Synapses are the locations where one domino falls into another. For the last part of this chapter, you will need to have these concepts as well as the terms for different parts of a neuron as fluent recall with understanding, connections, and organization (FRUCO). With these new chunks you have most of what you need for a beginner’s understanding of learning and memory. Here are the nine new chunks you need:

(1) Reflexes and memories are like rows of dominoes.
(2) Rows of dominoes on end can knock each other down in a chain.
(3) Each row of dominoes is a reflex or a memory.
(4) Rows of dominoes can split into two or more branches, and two branches can combine into a single row. Sometimes it can take two or more falling together to knock down a single target.
(5) Neurons are like rows of dominoes. They can branch and combine in the same way as a row of dominoes.
(6) Neurons move + charge instead of knocking each other over.
(7) The places where one neuron “hits” another (passes + charge to it) are synapses. A synapse includes the end of a branch of an axon and part of either a dendrite or the cell body.
(8) + charge comes in to neurons at synapses on dendrites.
(9) + charge moves out of neurons at synapses on axons.

Please practice to convert these new chunks into memories before reading the last part of this chapter. Please stop a minute or two now, and think back through each of these new chunks. One at a time, reread them, starting with number 1. Close your eyes, and try to recall a key sketch and explanation for the concept. If you cannot recall it, go back and review. Then look at or think about something else for 30 seconds—just long enough to clear out your working memory. Again, try to recall the key sketch and explanation.

I really mean this. Do it for each! I just did this for each concept as I was writing. I needed to review to make sure that you really do need all nine of these chunks. The answer is: yes, you do. So, please stop and take the time to do it. If you were interested and alert as you read this chapter, it’ll probably take you only 1-2 minutes for the entire review of nine chunks.

If you do not spend the time to strengthen your memories for these chunks, you will be wasting time and energy. If you do not recall and understand these chunks, you will have an incomplete and wrong Fish-understanding.
Memories and behaviors as a result of neural circuits

With the nine new chunks above, you can imagine connected neurons for reflexes (your response to being pricked with a pin) and for memories you’ve learned. In fact, you have all the chunks you need to predict neural circuits for reflexes and simple movements. If you want to try this, sketch a neural circuit for moving your finger (starting at a neuron or neurons in your brain), feeling a touch on your nose, or slapping at a mosquito when you feel a mosquito bite. (An example is below in Figure 10.22.) Will your neural circuits be exactly correct? No, but they will be a lot closer than you might think.

I will start referring to things you remember as a “memory.” I will refer to things you do as a “behavior.” A behavior is when you move some part of your body using a muscle. A behavior might be as simple as a wink of an eye, or it might be as complex as a spoken sentence or a dance. A memory is when you are remembering something. To a neuroscientist, though, learned behaviors and memories are just slightly different ways of learning. Behaviors and memories both involve rows of neurons like dominoes. Knock over the first, and the whole chain goes over. In both cases, experiences forced your brain to make and strengthen synapses. The synapses are the connections for your new learned behavior or memory—connections that make new branches and rows of your neurons. If you push on the first neuron for a memory, such as “Columbus,” then you recall the memory: “Columbus sailed in 1492 to Central America.” This neural circuit is your memory. You recall the memory when you send positive charge through each neuron and branch. What happens when you retrieve a behavior? In your neurons, the same thing, except that the end of each branch is a muscle contracting. Think about two people racing each other. Someone yelling “GO” is the push to that first neuron for a behavior. The behavior is all the muscle movements to start running. The neural circuit is your learned behavior for running.

Below, in Figure 10.22, let’s look at what else would have happened when I stabbed you so unfairly with that pin. This neural circuit is much like the dominoes in Figure 10.8. In this neural circuit, I’ve numbered the Neurons 1 to 5. For each neuron, positive charge at the synapse causes positive charge to move into and through the new neuron. At the end of the synapses from Neuron 2 and Neuron 5 are muscles. On the left side, I’ve made all the synapses gray. Nothing is happening until the positive charge from the pinprick reaches the end of Neuron 1. The left side of Figure 10.22 is like a memory that you are not currently recalling; the memory is there, but not active.
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Figure 10.22. Neuron 1 received positive charge from the pinprick. Neuron 1 has synapses on Neurons 2 and 3. Neuron 2 caused positive charge to move into your biceps muscle. When the biceps muscle contracted, your hand jerked up and away, which is a good thing. Neuron 3 moved positive charge through the axon up to your brain. Neuron 3 caused positive charge to enter Neurons 4 and 5. Neuron 4 is in a “pain center” in your brain, and so you felt the stab as pain. Neuron 5 has axons to some muscles of your mouth. Positive charge entering those muscles caused contraction that opened your mouth. Neuron 5 has another branch of the axon to the vocal cords in your throat. Contractions in the muscles of your vocal cords caused you to say. “Ouch!” The real circuit is more complex than this because it takes many muscles to open your mouth and to say, “Ouch!”

If you were a very tiny insect, your reflex neural circuits would be this simple. One neuron could detect the touch and cause one neuron to make a muscle contract. However, you have many tens of thousands of individual muscle cells in your biceps muscle. In Figure 10.23, I have shown these muscle cells looking like bricks in the muscle. In fact, the real muscle cells would be even smaller, but they are actually arranged rather like rows and stacks of bricks. In order to contract a muscle, you contract these individual cells. When each cell shortens, the muscle shortens or contracts. To control your biceps, axons must branch. The branching axon from a single neuron may control hundreds of muscle cells. You actually use hundreds of neurons to cause the tens of thousands of muscle cells in your biceps to contract at one time. The real neural circuit actually does start with only one neuron, which I showed as Neuron 1. Neuron 1 got some + charge when I pricked you with the pin. The axon from that one neuron branched to reach the many neurons that control your biceps.
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Figure 10.23. The neural circuit from your finger to the muscle is like a very short chain of dominoes, with one initial domino knocking over many of others. Neuron 1 has axon branches to many Neuron 2s. I’ve shown four of these Neuron 2s. Each Neuron 2 controls hundreds of muscle cells. Together, all of those Neuron 2s cause your whole biceps muscle to contract. Each of these second dominoes (Neuron 2s) causes only one part of your biceps muscle to contract.

Let’s go on up into the brain. My neural circuit in Figure 10.22 had only one Neuron 3 going up into the brain. In fact, there were probably many—a few to maybe dozens or more—but one is enough to show. The branches of Neuron 3 we followed went to parts of the brain that sense touch and pain. In my neural circuit, that connection to touch and pain was Neuron 4. In your real brain, Neuron 4 would also have been many neurons. To open your mouth and say, “Ouch!” (Neuron 5), you also needed many neurons. You used many different muscles to open your mouth and then move your lips and tongue and vibrate your vocal cords to say, “Ouch!”

I want you to know that the complete REAL neural circuit is more complicated. However, you don’t really need all those details. We can get a very good Fish-version of reflexes, memory, and learning even with these simpler neural circuits. You don’t need to know or remember the complicated version (at least not until you become a neuroscientist). Happily (for me), neuroscientists do their best to use these simpler Fish-versions of neural circuits as they trace neural circuits of reflexes, memory, and learning. They want the sequence of neurons to be accurate, but they usually do not need every single neuron. If we know that every single one of the many Neuron 2s does the same thing in different muscle cells, we don’t need to show more than one to get the idea.

Parts of the neural circuit in Figure 10.22 are reflexes and are not learned—from 1 to 2 to 3 and 4. You do not learn these parts of the circuit; they are innate. However, another part of your response to a pinprick was learned. You had to learn to say, “Ouch!” instead of some other word. In fact, some of you may have used some other word. If you happen to be a native Spanish speaker, you probably would have learned to say “Ay!” instead of “Ouch!” In other languages, it might be “au”, “darro”, “ai-yah”, “ita”, “ah”, or “ai”. You learned to move the muscles of your tongue, mouth, and vocal cords differently depending upon your native language. Which word you yell depends upon a learned neural circuit for that word.

In one convenient way, neurons are not like dominoes.

Neurons are NOT like dominoes in one other important way. Dominoes fall over and won’t set themselves back up, but neurons do reset themselves. Neuron pass their + charges like very tiny jolts of static electricity very quickly but then are ready to pass more + charges.

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very soon. Just 1/100th of a second (or faster) after passing some + charge, neurons are ready to do it over again. In the domino version of reflexes and memory, each domino falls into another, knocking it over. The difference is that when dominoes fall over, someone has to set them back up (boring). Neurons reset themselves. It is as if we knocked over a row of dominoes, and almost instantly the row popped up again.

The neurons in your brain, spine, and limbs twist and branch around each other, forming many, many branching chains. How big are these neurons? The very biggest neurons are about as large and long as a human hair. Most neurons are much smaller, much shorter, and much thinner. As a result, your brain has room for many more neurons than you have hairs on your head. You probably have about 100,000 hairs on your head. You have around 10,000,000,000 neurons. That’s a lot of possible rows of dominoes.

You need a lot of rows of dominoes, because, for example, you need a different chain of dominoes to recognize every letter or digit or symbol you see and every word you read. Even then, many neurons are used in more than one different neural circuit. Still, you need a different set of connections of neurons to recognize every different sound you hear, every smell you smell, and every different touch that you can feel. You need a different chain for every concept you know. You have to learn these circuits to recognize shapes, smells, and concepts! When I was a kid, I used to wonder why it took so long to learn and grow up. Now, I find it astonishing that it only takes twenty years, instead of a thousand.

In our Fish-version of the human brain, you can think of many, many rows of dominoes in the brain. Each memory or movement happens because the first neuron in the row was knocked over. If you could see all of the neurons individually, they would look like a very complicated pattern of strands of hair, connected in rows and many, many branches. Some neurons would be very short, some intermediate in length, and some very long. A row of dominoes might have as few as two dominoes in a row, for a simple reflex. Almost always for us humans, even these short chains would have many branches. Slightly more complex reflexes such as your eye-blink reflex and learned processes such as identifying the letter A might be three to ten dominoes long (again with many branches). Complex behaviors such as speaking one short sentence aloud, or making just one move in a dance, might use rows of neurons that are tens or hundreds long, with many branches at many places.

More new chunks about nerve cells and memories

Earlier, I gave you nine new chunks to master. Now I want to add five more. These are essential, if you want to get past a Fish-version of memory and learning. You need to practice these until you get them into fluent recall with understanding. Here are the new chunks:

(10) New memories are new chains of neurons (new chains of dominoes).
(11) You learn by growing or strengthening connections between neurons.
(12) We can show a reflex, a memory, or a learned behavior by a neural circuit.
(13) Real neural circuits include more branches than we usually show in a sketch.
(14) Everything you know, recognize, or can do is a row of dominoes (a row of neurons). Knock over the first, and you will remember something, recognize something or do something.
In the last chapter, I gave you new chunks about neurons. To understand those new chunks, you either needed to build on other chunks you already.

To get the most out of this chapter, you need all of the 14 or so new chunks from Chapter Ten in fluent recall with understanding. If your goal is simply to understand as you read, and you don’t really care what you remember next week, then you probably don’t have to practice. However, if you hope to remember the new information about learning and memory in a week or a month or a year, you have to practice these chunks. It is easy for us to be unwilling to practice new knowledge. Soon, it is as if we never saw it. As you read this chapter, you’ll start understanding why that happens.

**Learning the alphabet**

You are an expert reader. Your expertise came from developing new neural circuits (new rows of dominoes) for every single thing you do as you read. In some cases, we know how you did it. We’ll start at the beginning: the letter A. Learning the letter A is more complicated than it seems. Figure 11.1 shows just a very few of the ways to combine the two slanted lines and one horizontal line that make an A. Each of the twelve versions in Figure 11.1 has exactly the same lines. You could make many more combinations. Only one is an A.

![Figure 11.1](image)

Figure 11.1. Twelve ways to combine the two slanted lines and one horizontal line used to make an A.

To recognize any letter, you had to develop a neural circuit triggered only by the correct shape. It took you months of near-daily practice to get each letter into automatic recall and automatic recognition with understanding. Understanding the neural circuit you developed will help you understand memory and learning.
Your eye has cells that detect light, like spots on a page. As a Fish-version, each cell detects a spot of light OR a spot of black. Because print is usually black on white, we'll look at the way you detect black letters on a white background. Figure 11.2 shows a black letter L that you see. (I chose L instead of A because L is easier to diagram as a neural circuit.) On the right side are the spots of black on a white background in the back of your eye. (The spots are on your retina, but you don't need to remember the retina.)

Figure 11.2. On the left side of this figure is an L, in the middle your eye, and on the right side is the image on the back of your eye. (Because of the way your eye's lens bends light, it should be upside down and backwards, but we don't care.) What is on the page as an L becomes converted to a pattern of dark and light dots.

Those same cells can receive any other image as dots of light or dark, including things you recognize, such as the house, sailing ship, or the letter H in Figure 11.3.

Figure 11.3. A drawing or image of a house, sailing ship, or an H become patterns of dark and light dots in the back of your eye.
Your eyes have far more cells for white or black spots (or colored spots) than I’ve shown. The few cells I show here are enough for understanding. In fact, you can and should chunk this concept of an image of dots of dark or light even more simply, with even fewer spots as in Figure 11.4-a, for example.

Your brain has to learn to recognize each pattern you know—in other words, to decide which of the sets of lines in Figure 11.1 is an A. In Figure 11.4-a below, I have shown these spots. On the left, I show the simplest way you detect an L. This is the smallest L that you can see: L, L, L, or... Light from the page—white light around the edges but dark with little or no light from the L—enters your eye. The cells of your retina detect the light as black dots in the shape of the L surrounded by light dots. On the left, the image of L on the retina is three black dots in a vertical row plus one black dot on the bottom right side. To show you the neurons connecting to the retina, I have taken my sketch of retinal cells and have turned it out toward you as if the sheet of retinal cells is tilted at an angle out from the page. On the right side of Figure 11.4-a, I show the ends of axons connected with the cells in the retina. Each cell in this part of your retina connects to a neuron.

In Figure 11.4-b, I have drawn four of these neurons—the ones that get + charges if the four specific cells shaded in black in the retina in Figure 11.4-b have a black dot. Each of the four neurons in Figure 11.4-b is like a single domino. Each domino will fall over if a black dot is at that spot on the retina. As you look at an L, black dots will be in the shape of an L, and so each of these dominoes falls over. In other words, each of these neurons gets + charge. The plus charge is passed through axons to synapses, and at the synapses, + charge enters the next neuron.
Figure 11.4-b. The cells of your eye connect to a neuron that produces action potentials depending whether it is dark or light. Behind those cells that detect the light, I've shown four neurons, 1a, 1b, 1c, and 1d that would receive positive charge. You can think of these four neurons as four dominoes, as in the top right, with each domino falling because of a black dot.

The next part of the neural circuit connects to a domino that can be knocked over only by a short vertical row of black dots (Figure 11.5). If Neuron 2 receives + charges from all three, then it passes along + charge. This domino falls only when hit by three others.

Figure 11.5. Neurons 1a, 1b, and 1c must combine in order to cause a nerve impulse in Neuron 2. You can think of this as three small dominoes that can push over a large domino only if all three fall at the same time as in the top right.

In this circuit, Neuron 2 is called a “bar neuron” or “bar cell.” The name comes from the fact that Neuron 2 will fall—will pass + charge—only if the cells in your retina have a dark vertical bar. Now, we have a neural circuit to detect the upright arm of our L, but we don’t yet have a neuron to detect the short line that is the bottom of the L. You could probably guess what that part of the neural circuit will be. Your neural circuit for an L uses another bar neuron, Neuron 3 in Figure 11.6. Neuron 3 passes + charges only if a dark spot is at two specific cells in the retina. Bar cells such as 2 and 3 are called “simple neurons” in the brain because they pass positive charge in response to very simple shapes: just bars that are horizontal, vertical, or at different angles.
Figure 11.6. Neurons 1c and 1d from Figure 11.4-b must combine in order to cause a nerve impulse in Neuron 3. You can think of this as two small dominoes that can push over a large domino only both fall at the same time as in the top right.

Our neural circuit needs only one more cell in order to detect an L. Bar cells 2 and 3 both connect to a neuron that passes positive charge in response to a more complex shape called, conveniently, “complex neurons.” Cell 4 in our neural circuit falls—passes + charge—only if it receives + charge from both Neurons 2 and 3 shown in Figure 11.7. In the upper right of Figure 11.7, I show the complete neural circuit as a row of dominoes. Cells 1a, 1b, and 1c all need to pass positive charge to Cell 2 to make Domino 2 fall. Cells 1c and 1d need to pass positive charge to Cell 3 to make Domino 3 fall. Only the combined + charge of Neurons 2 and 3 make Domino 4 fall. This neural circuit is a memory for the letter L. This neural circuit is what allows you to recognize an L when you see it. Figure 11.8 shows the same circuit to recognize an L more simply.

Figure 11.7. The complete neural circuit to detect an L. Notice that Neuron 1c has to branch to both Neuron 2 and Neuron 3. In the row of dominoes on the top right, Neuron 1c falls against both Neurons 2 and 3, and Neurons 2 and 3 together knock over Neuron 4.
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Figure 11.8. Neurons from the eye detect spots of black (or white). They combine to cause nerve impulses in simple bar neurons. In this circuit for an L, two bar neurons combine to cause a nerve impulse in the L neuron. The L neuron passes nerve impulses only when the eye cells in this location view an L.

As an exercise right now, draw a neural circuit to recognize the letter H. (Please do this! It will help you develop fluent recall with understanding of the concept of neural circuits. You need both the understanding and the fluent recall.) Next, draw another neural circuit to recognize the letter X. In the circuit for X, your bar cells will be diagonal lines instead of the vertical and horizontal lines we used for L.

If you think further about this, you will realize that recognizing the letter L is more complicated than my single neural circuit. How is it more complicated? What if there are letter L’s in different locations (for example, LAD versus ALL)? If so, they would affect different neurons. If two letter L’s are a different size (L, $\text{L}$), then they would affect different neurons. If you rotate your head sideways so that your ear is nearly touching your shoulder as you read, you can still recognize the letter L. To be certain, I just turned my head sideways as I type, and I find yes, I still recognize the letter L, though it is harder with my head sideways. My recognition for L is not as automatic in this position. I also just tried standing up, with my head turned nearly upside down as I look at my computer screen. Upside down, I find that recognizing that an L is actually an L requires even more effort. What might all this suggest? It suggests that you have multiple neural circuits that recognize L’s. Those multiple neural circuits recognize L’s of different sizes, locations, and shapes, such as $L \L L L L L L L$. You had to learn that each one is an L (or is close enough), and that each one is not some other letter or some other thing.

Figure 11.9 has an example of a neural circuit for L in a font called “American Typewriter.” In Figure 11.9, there are 39 dark spots on the retina. Each of these spots on the retina would release + charges to a neuron for a dark spot—neurons 1a, 1b, through to 1al and finally 1am. I did not number all of the “1” neurons because there wasn’t enough space. Instead, I just drew a line to indicate each neuron 1a to 1am. The lines connect black spots on the retina to target “bar neurons.” The bar neurons are labeled 2, 3, 4, and 5. These are simple bar neurons. (I did not include the neurons connecting the retina to Bar Neuron 4, just to keep my diagram simpler.) Neurons 2, 3, 4, and 5 each pass along + charges when a dark bar of a particular size, orientation, and location is on the retina. Neurons 2, 3, 4 and 5 all have a branch of an axon that reaches to Neuron 6. Neuron 6 passes + charges only when an $L$ is at that location on the retina.
Figure 11.9. In a neural circuit for an L of the font, American Typewriter, the cells from your eye connect to Bar Neurons 2, 3, 4, and 5. I didn’t show the connections to Neuron 4 because the sketch was getting too messy, but you can see how it would work. Neurons 2, 3, 4, and 5 must all combine to cause nerve impulses in Neuron 6. Neuron 6 produces nerve impulses when an L of this shape is at this location.

I hope that by now you could draw a neural circuit for any particular letter or any simple shape—a useful skill. That neural circuit is your memory for that letter or shape. At birth, you did not have the connections to be able to recognize an L. As a new reader, you had to learn to recognize the letter L. As you learned to read, you needed to develop neural circuits for the different kinds of shapes for L, such as Figures 11.8 and 11.9. Each of these neural circuits should connect to a neuron for the letter L in any acceptable shape or form as in Figure 11.10.

Figure 11.10. Neural circuits for each pattern that you recognize as an L should connect to Neuron 6 that will have nerve impulses caused by any pattern of black dots that looks enough like an L. Any one of the Neurons 1-5 in this figure causes nerve impulses in Neuron 6.

Any single neuron that detects an L of some acceptable shape, such as 1, 2, 3, 4, or 5 in Figure 11.10, can pass enough + charges to the “L” Neuron 6 to cause Neuron 6 to send + charges through its axon. I’m oversimplifying as I show you these patterns, and we don’t know all the details about these neural circuits, but this is reasonably close to how they work.

As we think about rows of dominoes again, the “L” Neuron 6 represents a single domino that falls when hit by any single domino 1, 2, 3, 4, or 5. Each of the different shapes of L can fall
against the “L” domino, and any one of them hitting the “L” domino causes it to fall. In other words, any shape that you have learned for an L causes + charges to move to and through the “L” neuron. In Figure 11.11, it is the “Cooper Black” L (Neuron 2) that passes + charges to the “L” neuron. Each time you see an L in any font, one of these circuits has to be activated strongly enough to send + charges out through a neuron for an L to your “L” neuron.

Figure 11.11. In this figure, the “Cooper Black” L causes nerve impulses in Neuron 6. As a row of dominoes, the “L” domino is balanced in a way that causes it to fall when hit by any of the dominoes in front.

Eight new chunks about neural circuits and memories

This is a good place to summarize the new concepts and terms you need from this part of this chapter. Here are the eight new chunks:

1. Seeing a shape you have learned triggers a neural circuit for that shape. Your memory for that shape is the neural circuit.
2. The back of your eye (the retina) is sheet of cells that detect spots of light or dark.
3. Each cell in your retina connects to a neuron for a dark spot and another neuron for a light spot.
4. Rows of black spots make vertical bars, horizontal bars, or diagonal bars ( | _ \ / ).
5. Bar neurons pass along + charge only due to a bar at a specific spot. Bar neurons are called “simple neurons.”
6. Bar neurons send axons and + charge to complex neurons.
7. Complex neurons pass along positive charge only due to a particular shape at a specific spot. (For example, a complex neuron for L requires an L shape at a specific spot on the retina.)
8. Any simple shape can be recognized by a combination of simple and complex neurons. (For example, many shapes for L can be recognized by neural circuits that all connect to a more complex “L” neuron.)

Stop a minute or two now, and think back through each of these new chunks. Reread each of the eight chunks above. Close your eyes, and try to recall a key sketch and explanation for the concept. If you cannot recall it, go back and review. Then look at or think about something else for 30 seconds—just long enough to clear out your working memory. Again, try to recall each key sketch and explanation. This recall practice will help start developing your memories for these chunks.
More questions?

If you’re like me, you might have many new questions. What happens if one of the neurons in a neural circuit dies? Do you lose your ability to detect L in some font, or even lose L entirely? What about curved shapes (0, 6 or S)? Do curved shapes use “bar” cells or “curve” cells? Do we recognize whole words in the same way as letters, with neural circuits for the entire word? Do we have a different neural circuit for every letter in every possible font? Why can we usually recognize ☛ in a font we have never seen before, or recognize a badly drawn L? What about shapes made of more than one color, and what about gray, instead of black or white? What about other aspects of vision, such as recognizing a pattern of movement? Do we have “movement” cells? Do we have neural circuits like this to recognize each person we know? Is there a neural circuit that ends at one neuron for the face of my grandmother, for example a “grandmother” cell, like the “L” cell in Figure 11.10?

We have answers only for some of these questions. For others, neuroscientists do not yet know the answers. If you study more about vision and learning and memory, you’ll find more answers. In this chapter I give you a Fish-version for the neural circuits for learning and recognizing the shapes you see. It’s a pretty good Fish-version, but of course you can learn much more; just as for Fish, you cannot start learning about neural circuits of learning without misconceptions. You have to build on the chunks you already have in fluent recall with understanding. The more you learn, the more of your first misconceptions you will replace with improved chunks and combinations of chunks.

Neural circuits for recognition are different from neural circuits for a concept,

The neural circuits to recognize different shapes of L are necessary but not enough. Each of these must connect to a neural circuit for your concept of letter L (Figure 11.12). What is your concept of the letter L? Your concept of the letter L probably includes the visual shapes of L, the position and sequence of L in the alphabet, the concept of words, and the sounds of the letter L. If you happen to be deaf, then you would have all of these concepts except the sounds of the letter L, but your image for the letter L would probably include a sign-language letter for L. If you are blind, you would have all of these concepts except the visual shape of the letter L, but you probably have a much better set of neural circuits than most people for the touch-shape of the letter L, and probably also the feel of a Braille pattern of raised dots for L. Figure 11.12 shows a part of the neural circuit for your concept of the letter L. One of the neurons that is part of this neural circuit is the “L” image neuron from Figure 11.10.
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Figure 11.12. The concept of the letter “L” is held by neurons that produce impulses in response to an L: the letter “L” neuron in this figure. You need to recognize an L in different ways, including the “el” sound, the image of an L, the alphabet, or words that contain an L. Neurons that produce impulses to those specific ways in which you might encounter an L all should connect to a neuron that produces nerve impulses due to any kind of L.

Why am I saying that your recognition memory for the image an “L” is different from your concept of an “L”? You may not be convinced, but I can show you that the two are not the same. In Figure 11.13, I have placed L’s in different patterns. In each of the four images in Figure 11.13, you will have no trouble finding the shape of L. However, in all of these cases, the L’s appear to be something other than a letter.

Figure 11.13. The L shape is presented in ways that you might not notice as an L.

If you look quickly at any complete pattern in Figure 11.13, you might not recognize the shape as a letter L. However, for every single L in Figure 11.13, if you look directly at one of the L’s while ignoring the entire rest of the image, you see it clearly as the letter L. The image that makes it most challenging is on the left, in the words. Because the L’s overlap each other, it is not easy to see the three L’s as individual letters. In contrast, it is easiest to recognize the individual isolated L’s as L’s (and not corners, eyes, or a nose) in the face on the right.

Learning is making new neural circuits.

You can see any shape, but you do not recognize all shapes, and you will not remember all shapes. Think back to Figure 11.1 WITHOUT LOOKING. (No peeking.) I will remind you that Figure 11.1 showed the first letter of the alphabet and then rearranged the three lines from A to form ten other shapes. (Still no peeking.) How many of the shapes from Figure 11.1 do you remember? My prediction is just the A, maybe one or two more. I actually remember four of them, as I write this, but I drew the figure, so perhaps I remember more. By tomorrow, though, unless I practice, I will already be forgetting the other ten shapes in Figure 11.1. That’s good—I SHOULD forget those other shapes. It would be a waste of neuronal circuits to remember all of those different shapes, because they have no meaning! I used those particular shapes only as
examples of shapes that use the same lines as A but are not A. If your brain remembered those ten shapes, it would be empty memorizing—of no use ever again, even when you reread this chapter. Worse, if you had automatic recall and therefore you thought of one or more of those shapes often when you see the letter A, it would be highly distracting, wasting valuable space in working memory. It is important not just to remember important chunks but to forget useless chunks.

When you learned the alphabet, you had to grow new neural circuits to recognize every letter. Neuroscientists have an incomplete view of how that happens. I can give you a Fish-version. Before you knew any letters of the alphabet, your bar neurons had many weak connections to complex neurons for shapes you had not learned to recognize. At the age at which you began to learn the alphabet, your bar cells also had strong connections for shapes you had seen many times and practiced often (the shape of a table, chair, bed, door, person, tree, but not the words for these). For letters, though, your connections were weak. Figure 11.14 shows how your neural circuit for shapes related to L might have been before learning about the letter L.

Remember one of our earlier chunks: neurons have dendrites that receive + charge, a cell body that receives + charge, and branching axons that can send + charge to other cells. The connections for + charge are at synapses. Figure 11.14 shows the synapses from the two bar cells on part of the L cell. What is different in this image compared to the original in Figure 11.8 is that the synapses in Figure 11.14 are far away from the cell body. Why does that matter? It matters because the + charges spread, leak, and dissipate—charges can drift away and be lost.

The further a synapse is from the axon, the less effect it has on the neuron. When a synapse is far away, very few + charges move into rest of the cell, which means that the neuron labeled L on the right is likely to have few nerve impulses (or maybe none) when you see that shape. Before learning the alphabet and the letter L, your neural circuit for an L might have looked like the circuit above.

The further a synapse is from the axon, the less effect it has on the neuron. When a synapse is far away, very few + charges move into rest of the cell. In addition, synapses on separate branches of a dendrite have less effect than synapses that are near each other on the same branch. Distance is one of the things that makes a weak connection in a neural circuit. With a circuit such as Figure 11.14, when you look at an L there would be a small effect on the L neuron. You would see the shape, but might not recognize the L as something you had seen before. You would not know it had meaning. If you looked at the L repeatedly, perhaps 30 seconds each time, over and over, thinking about the shape and trying to remember it, the connection would strengthen. There is both a temporary strengthening and then a longer-lasting strengthening.
Chapter Eleven: Neural Circuits and Memories

Here is an important point: **as you use a neural circuit, it gets stronger**. I want you to have a good Fish-version of what happens, because that explains why you need to practice new memories many times. Remember that in Chapter 1 I gave you a Fish-version of learning as being like a mud drawing; each time you add a little mud, it gets better, while time washes a little mud away. Here’s an improved way to think about learning: Each time you have focused, interested practice, the neural circuit strengthens. How? You can think of strengthening as more synapses, stronger synapses, and synapses that are closer to the axon. The top part of Figure 11.15 shows a weak neural circuit to recognize L, before practice. It has few, distant, small synapses on separate dendrite branches. The effect on the L neuron is small, and little + charge moves through this circuit.

The bottom part of Figure 11.15 shows how the circuit might look after repeated practice, day after day for months and years. With practice, the circuit grows more and larger synapses closer to the axon. You do not need to remember the details. You do need a chunk for this phrase: **with practice, synapses get stronger**. With practice, neural circuits get stronger. That is what develops fluent, long-lasting recall over long periods of time: reusing a neural circuit, with attention and interest.

![Figure 11.15](image)

Figure 11.15. The top of this figure shows a neural circuit from someone who has not learned the letter L. The bottom shows how the circuit might look after months or years of practice. For the new circuit, you have grown larger synapses and more synapses, and the synapses are now on the cell body. These changes can take months or years.

There are many combinations of lines that you’ve never learned as a symbol. You can see those combinations, as I’ve shown you in Figure 11.1, but they are not memories you’ve practiced. For all those other ways to connect the lines, your neural circuits are still weak, with few, small synapses far from the cell body of other neurons. In Figure 11.16, I’ve shown a neural circuit for a symbol that you’ve never practiced, and that is not strong enough to be considered a memory. If you practice the symbol in Figure 11.16 a few times right now, you would temporarily strengthen these synapses, and you would begin the very slow process of growing the new synapses that could eventually make this neural circuit into a long lasting memory.
Figure 11.16. This symbol is a way to rearrange the two angled lines and one horizontal line of an A. Because you’ve never practiced this symbol, the synapses are small, few, and far from a neuron that could become a memory for this new symbol.

For a pre-reader, writing letters and reading handwritten letters of others is very hard. They are still developing all of the neural circuits they need for each letter. A pre-reader has to learn not just the shape of each letter, but the limits to an acceptable shape for the letter. There are a great many similar shapes that are all the letter L, both when written by hand or in different printed fonts. A reader must learn which shapes are close enough to A to be an A and which are different enough to be N, R, H or L. Thus, A A A A A A A A are all the letter A, but they are not all the same shape. It would take serious effort for a pre-reader to be sure that each of these is an A and that another symbol, such as R is not. You can figure it out easily (probably).

Figure 11.17. When is an A not an A? If the shape is close enough, it activates your neural circuit for an A. If the differences are too large, you do not recognize it as a shape you have learned. You can decide for yourself. For me, the arrow is at the symbol at the boundary. Left of the arrow, they are A’s. The one above the arrow might be an A, but might not. For me, those right of the arrow are not an A. They do not activate my learned neural circuit for an A.

How to make and strengthen new neural circuits and memories

Each time you recall a chunk with interest, you develop more fluent recall of the chunk. You learn new chunks by making new connections between chunks that are already in fluent recall. We develop the neural circuits for those new chunks by making strong neural circuits. For understanding and connections, those neural circuits need to grow connects to neural circuits for other memories. Those strong connections are made by growing and strengthening synapses, which you make happen by practice with interest and focus.
Working memory can be loaded with anything you see or hear or think about, as in Figure 11.16. Unless you pay attention with focus and interest, the contents of working memory are lost within about 30 seconds. The neural circuits will be exactly as they were before. Working memory does not make new connections.

An important conclusion is that you can read and review the same thing over and over and over again and not strengthen or make a new neural circuit. Each time you reread, you load the chunks you already know or the things you see into working memory. If you are not interested and focused, however, none of it gets out of working memory.

Here’s what’s worse. Even if you are interested, you may still not strengthen neural circuits very much as you reread. Why not? What if, each time you read the same thing, you pay attention to a different set of chunks, in a different order, and with different amounts of interest. You will strengthen neural circuits, but they will be different every time. Each neural circuit will be only slightly strengthened, and each will be quickly lost.

This is why I try to persuade all of my students to do more than just reread and reread and reread. As just one example, think about what happens if you do retrieval practice. (Remember that retrieval practice is stopping to think and try to remember all of the important parts of what you just read. Then review briefly and repeat.). In retrieval practice, you practice the neural circuits you have already started to strengthen; if you reread, you may practice a different circuit each time.

Finally, how long does it take to develop a new neural circuit for long-lasting fluent recall? The neural circuits have to be used, and after each use the synapses grow microscopically different. After each use, the differences will be tiny. The synapses have to be used and grow tiny changes and then used again and again and again. It seems to take months to develop truly fluent long-lasting recall. Automatic recall takes even longer. I used to think that important memories might develop faster—maybe right away. Some memories I have seemed to become automatic right away. For example, it felt as if I quickly developed fluent recall of experiences such as a painful punishment, an amazing new insight, a first kiss, a moment of triumph, or a bad betrayal. All seem to go into fluent or automatic recall. However, I now think that this was not as fast as it seemed. Rather, the event or fact or insight was simply so interesting that I thought about it several times a day, or even more often, for the first few days, and then often even after that. I practiced so often that it felt like a fluent or automatic memory very quickly, but in fact, that memory was getting a lot of practice.

The conclusion is this: Building strong new neural circuits of memory takes a lot of practice and time. If you want to learn something as a memory that lasts a long time, you have to practice many times over many months or years.

More new chunks about neural circuits and memories

In the second part of this chapter, I want you to understand THREE more chunks.

(9) Neural circuits that are used to recognize a shape differ from neural circuits used to understand a concept. (A neural circuit to recognize the shape of an L is different from the neural circuit for your concept of the letter “L”.)
(10) Learning is making new neural circuits.
(11) Moving, adding, removing, or strengthening synapses makes new neural circuits.
In previous chapters, we’ve talked about a memory as a neural circuit or a row of dominoes. Recalling a memory is what happens when + charges pass through the neural circuit—when the row of dominoes is knocked over, starting with the first domino. Learning requires making changes in neural circuits. That’s like adding branches or connections to rows of dominoes. In this chapter, I want you to understand why learning something new takes repeated practice, attention, and interest. It also takes the same repeated practice, attention, and interest to unlearn something old. I want you to understand how connections in neural circuits form and the reason they need repeated practice. The connections are the synapses, the place where one domino hits another.

Making and Strengthening Memories

The way you understood learning before reading this book was a Fish-understanding of learning. You knew that if you read and studied something, you might learn it, and you might remember it for a while. If you worked hard, practiced enough, and were interested enough, you might remember the new things very well for a long time. Before I began learning about the brain and learning, my view of learning was the Fish-version in Figure 12.1. Facts or rules for

![Figure 12.1](image)

Figure 12.1. The way I used to think about learning: knowledge was facts I poured into my head. Once in my head, the facts should stick. Later, I could pour facts could back out of my head. solving problems went into my head, and then I could say those facts or do those problems. That’s a shallow view of the brain and learning, but it actually isn’t that bad. It is not wrong to say that information enters the brain and is stored there, and that learned information can be brought back out at the right times. Your own view of learning was probably not much different from mine in Figure 12.1.
In Chapters Ten and Eleven, I gave you some new information. Knowledge is more like chains of dominoes that are arranged in your head like on the left side of Figure 12.2. Knocking over the first domino in a chain recalls a memory as shown in the middle of Figure 12.2.

![Figure 12.2](image)

Figure 12.2. Knowledge and memories represented as rows of dominoes in our head. One chunk that we see or hear, such as “Columbus,” knocks over the branching row of dominoes that recalls the memory.

In that new concept for memory and learning, the memory is a row of dominoes in our heads. Seeing or hearing the word “Columbus” knocks down the first domino, which in turn knocks down all of the other dominoes. Each domino is one part of the memory; knocking them all down recalls the complete memory. Recalling the complete memory allows you to think or say the words, “Columbus sailed in 1492 to Central America” as on the right side of Figure 12.2.

The deeper understanding of memory from Chapters Ten and Eleven allows you to view a memory as a learned neural circuit. With this deeper understanding, you can see how the learned neural circuit for this information uses recognition memory for the written word “Columbus.” You can understand how recognizing the word “Columbus” makes you recall the complete memory, which then allows you to say the words, “Columbus sailed in 1492 to Central America.”

Let’s apply the information on learning letters from Chapter Eleven to this process. Seeing the word “Columbus” causes neurons from single spots in your eye (on the retina) to receive + charge. Those neurons send axons to bar neurons that are activated by receiving − charge only from neurons in a specific location. When you learned the alphabet, those bar neurons gradually developed strong connections (the synapses) to complex neurons for each letter. In order to recognize the word “Columbus” written on a page, you had to learn the combination and sequence of letters for that word. You learned the word “Columbus” by developing strong connections from “letter neurons” to a neuron that can be activated only by the letters C-o-l-u-m-b-u-s, in that order. That neuron (or, more likely that neural circuit) is your “Columbus-Word-Neuron” or neural circuit.

With these newly chunked pieces of information, we can develop an even deeper version of learning and memory to improve the version in Figure 12.2. We’ll use neural circuits, synapses, and working memory. When I write “Columbus-Word-Neuron” or some other kind of neuron, you should always realize that anything this complicated would be a neural circuit, not a single neuron. As it is our new Fish-version, though, thinking about it as a single neuron is fine.
Seeing the word “Columbus” activates our Columbus-Word-Neuron. Your Columbus-Word-Neuron has an axon branch and synapses on your Columbus-Concept-Neuron that is activated by images, sounds, words, or other things that make you think of Columbus. If you think about this, this is similar to your L-Concept-Neuron (Figure 11.12). Many things activate your L-Concept-Neuron, including the image of an “L,” the sound “el,” or thoughts about the alphabet. In the same way, seeing or hearing the word “Columbus” activates your Columbus-Concept-Neuron as shown on the bottom of Figure 12.3. Your Columbus-Concept-Neuron has strong, learned connections (synapses) to neurons for the concepts of 1492, sailing ships, and Central America. As a result, activating your Columbus-Concept-Neuron also activates your neurons for 1492, sailing ships, and Central America. That makes you recall your memory for Columbus sailing in 1492 to Central America. What does it mean to say that you “recall that memory?” It means that those concepts are put into working memory (top right of Figure 12.3).

Figure 12.3. Before you see or hear (or think of) the word “Columbus,” your neural circuit for “Columbus sailed in 1492 to Central America” is in your brain, but inactive. You are not using it. When you see or think of the word “Columbus,” it sends positive charge through all the neurons in that neural circuit. The result is that these chunks are put into working memory. Those chunks become your thoughts at that moment. If you decide to say what you are thinking, then you’ll say “Columbus sailed in 1492 to Central America.”

Before you recall the memory, working memory is empty (or filled with other information). That’s like the situation in the top left side of Figure 12.3, before the memory circuit has been activated. Before you see the word “Columbus,” something else is in your working memory. The connections (the synapses) are in your brain already, because you have learned this fact, but the neurons are not active. The memory exists, but it is not being recalled.

When you see the word “Columbus,” that causes + charges to move through the neural circuit. When you recall the memory, you are placing all four concepts in working memory.
That’s what recall is: you are now thinking about Columbus, 1492, sailing, and Central America because you have recalled those concepts to working memory. Because you have recalled the memory, you can use the information. You can, if you choose, speak the words. If conditions are right for you to give this information to others (for example, in a class), then your brain regions for speech are active. In that case, working memory activates connections to your speech centers from your concepts for Columbus, 1492, sailing, and Central America. Those connections are synapses that you have learned. Choosing to speak activates neurons that go to the muscles of your mouth and voice box—a behavior. Neural circuits from your speech centers cause each of the complex movements for each sound, one after the other, to state words: “Columbus sailed in 1492 to Central America.” You have connected a learned memory to a learned behavior.

Memories and the behavior need to be learned. You have to learn each part of the circuit in Figure 12.3. It is possible to learn one part without the other parts. For example, you might have learned to recognize “Columbus,” 1492, sailing ships, and Central America but with no connections between them. In that case, seeing the word “Columbus” might make you speak the word “Columbus” but not 1492, sail, or Central America (left side of Figure 12.4). Perhaps you learned this fact in written English but never learned to speak the words aloud (if, for example, you use sign language or are a Chinese speaker who can read English but have
never practiced speaking English). In that case (right side of Figure 12.4), activating your Columbus-Word-Neuron could make you think of Columbus sailing in 1492 to Central America but would not connect to speech centers to allow you to speak the words aloud.

Here’s the important conclusion: if you have not formed a working neural circuit with strong synapses, then you cannot recall that memory.

**Making stronger memories**

I keep saying that learning happens because we practice a neural circuit enough to make strong connections (strong synapses). Strong connections make strong memories, and strong memories are easy to recall when we want them. Too often, we do not practice enough to make strong memories. Strong memories develop easily only if something feels important and is interesting to us. One of the best ways to make something we want to recall feel important and interesting is to make it feel as real to you as you possibly can—as if the object is floating in space in front of you or as if the event is happening right now, right in front of you.7 (If you DON’T want to remember something, don’t ever allow it to feel real! Make it stay as words on a page, or symbols the meanings of which you don’t recall.)

If something is interesting enough, we make it feel real to ourselves, and we think about it often—we can’t help it. If we think about it often and it feels real, then each time we recall the memory, we are practicing that neural circuit. Each time we practice, the connections become a little stronger. If things don’t feel real, it is much harder to make strong memories. A problem for learning is that many things that are important to learn are not interesting enough to feel real or to make us think about them frequently.

It can be hard to persuade ourselves to practice enough, while making things feel real, to make a strong memory or a strong learned behavior. We don’t want to bother with the effort. We want to quit far too early. We are usually ready to quit when we recognize a concept and understand it, but before we can recall it easily and correctly for weeks, months, and years. Synapses do not strengthen to make long-lasting memories without many repetitions. For a really long-lasting memory, we need to spread the repetitions out over weeks, months, and years.

**Making stronger synapses**

Synapses and all other parts of a cell are made of molecules. In this chapter, we’re going to use the bacterial ruler to shrink ourselves smaller than the size of a cell. At that small size, we can see the membranes of cells as if they were the size of the wall of a building, and see proteins the size of ping-pong balls. At this size, an axon or dendrite looks like a long, long hallway. A synapse is the size of a large classroom. At that size, we can watch as we put memory traces in place and strengthen them through learning. (A memory trace is a neural circuit that holds a memory.)

It is not enough, though, just to shrink yourself to this small size. I also want you to go back in time, to when you were a child learning about history. I want you to see how you made the neural circuits to recognize and recall something as simple as a letter of the alphabet or as

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7 To test this out for yourself, try Metacognition Experiment 9.1 in Chapter Nine.
complex as a fact in history. The process will help you chunk what learning actually is. Learning results from new or strengthened connections that make new neural circuits in your brain.

How can using a neural circuit change the synapses? With a simple rule: synapses that are used together (as a branching row of dominoes) get stronger. Neuroscientists say, “Neurons that fire together, wire together.” Synapses that are used together are usually useful. Synapses that are not used get weaker. Eventually they may be lost. To understand how this rule of synapse growth strengthens memories, you need to understand a little more about synapses.

First, you need a deeper concept of a synapse. Remember that in Chapter Ten I gave you the idea that neurons are like tubes that can pass along + charges. In fact, neurons actually are tubes—but tubes with branches, as in Figure 12.5. The cell body of the neuron is where the cell makes all of the proteins and other molecules that keep the cell alive and functioning. For now, you can just picture the cell body as a bulge in the tube somewhere.

![Figure 12.5](image12.5)

Figure 12.5. We can think of neurons as tubes for positive charges. Positive charges enter at one end and repel nearby positive charges. Because each positive charge repels its neighbor, one-by-one down the length of the tube, then each positive charge entering will push one positive charge out the other end.

Synapses are the connections. Synapses are the places where + charges from one neuron can make + charges enter the next neuron in the chain. Synapses are a little wider than the rest of the tube, and so they bulge out as in Fig. 12.6. The synapses bulge because synapses have to hold all of the proteins and cell machinery to be able to grow and change. The rest of the tube just needs to pass along charge and the materials for growth, so it can be thinner. Figure 12.6 shows two neurons. If you look at the top left corner, near the cell body of Neuron 1, you can see tiny synapses from three more neurons coming out of the image on the left side. My sketch of Neuron 1 includes a cell body, an axon, and some branches of that axon. I have not shown dendrites on Neuron 1. (Recall that the dendrites are where + charges enter the neuron. See Figure 10.21.) I left out the dendrites and most of the branches of the axon for Neuron 1 just to keep my sketch simple and clear, but Neuron 2 shows one long dendrite and a branched axons. The dotted lines near the cell body (near the 1) are a reminder that I am not showing all of the axon branches nor dendrite branching (near the 2).

A typical neuron in your brain has about 1000 branches off of its axon. Each branch makes a connection with another neuron at the end of the branch. The connections are called synapses. My sketch of Neuron 2 in Figure 12.6 shows just one of the many branches and
dendrites. I have shown only five of the synapses on the dendrite of Neuron 2. There would be one synapse wherever an axon comes from another neuron. My sketches of the neurons in Figure 12.6 show far too few synapses, and the cell body should be much bigger on this scale. This is a Fish-version of numbers of synapses and sizes of parts of the neuron. However, Figure 12.6 gives you a good chunk for the multiple synapses going into neurons on dendrites and out of neurons from axons.

Figure 12.6. The positive charge arriving at the synapse from Neuron 1 (noted by the arrow) causes positive charge to enter the dendrite of Neuron 2. Three axons synapse on the cell body of Neuron 1 in the upper left.

Figure 12.7 shows the direction in which charges pass through these neurons. In this case, there are enough + charges coming in to Neuron 1 to cause the neuron to pass + charges (to knock it down in the sense of a domino). The + charges reach the end of every branch of the axon. If enough + charges enter Neuron 2, then Neuron 2 passes + charges to the end of every one of its axons.

Figure 12.7. The direction of flow of charge through Neurons 1 and 2. Positive charge begins at one synapse at a dendrite but then passes on to the end of every branch of the axon.
What is a + charge?

Synapses come in two types. In both types, + charge enters the dendrite. In both types, this + charge is mostly sodium ions. Table salt is sodium chloride. Sodium ions are half a molecule of table salt. This is one important reason why all humans need table salt in their diet! Recall that sodium and chloride are both elements on the periodic table. Each molecule of table salt is one sodium attached to one chloride by charge—an “ionic bond.” Out of water, sodium and chloride stick tightly. In water, sodium chloride dissolves into separate sodium and chloride ions. Each sodium ion has a + charge, and each chloride has a - charge. Any charged particle is called an ion, so both sodium+ and chloride- are ions. The plus charges we have been talking about all along are mostly sodium ions. These are usually referred to in sketches as Na⁺, the periodic table symbol for the element sodium along with a + sign. To understand the rest of this book, you don’t actually need to remember what the + charges are, and you do not need to remember ions or chloride. I’ll keep using + charge in the written text and in my sketches. If you wish, you can assume that usually the + charge is Na⁺. However, these concepts about sodium, chloride, sodium ions, and Na⁺ are concepts that you need only as recognition memory, NOT in fluent recall.

Electrical Synapses

One important type of synapse is an electrical synapse. Electrical synapses pass electrical charge directly through the synapse from one neuron to the next, exactly like the sketches I drew earlier. These electrical synapses pass + charges through tiny protein tubes that poke from the end of an axon through and into the dendrite. These protein tubes are just large enough for + charged ions to pass through. Therefore, if enough + charges enters one neuron, then + charges pass to the next neuron in a chain (Figure 12.8).

Electrical synapses don’t seem to change much once they first appear. Electrical synapses are only rarely part of learning circuits. For this book, electrical synapses are a useful chunk to know as you begin understand chemical synapses in the next section.

synapses are very important for learning.

Figure 12.8. In electrical synapses, protein tubes connect one cell to the other, and positively charged ions move directly through them. In these synapses, the positive charge that enters one neuron pushes positive charge into the next neuron.
Chemical Synapses

(These WILL be important to us.)

The second type of synapse is a chemical synapse. Chemical synapses each use a chemical to open channels for + charge. They are called chemical synapses because a small chemical opens the channel. In Figure 12.9, I show how this works as a Fish-version. If you have had enough biology, you already have a deeper understanding.

Chemical synapses pass charge in a four-step set of events, if you count the first step as “nothing happening.” In the first step in Figure 12.9, a chemical is inside little vesicles (little spheres) in the axon, and no + charge arrives. Step 1 shows the chemical as little triangles. In step 2, + charge arrives and attaches to the little sphere holding the chemical. In step 3, the + charge causes the sphere to touch the end of the axon and pop, like a bubble opening. That allows the chemicals out of the axon. In step 4, the chemicals attach to a protein channel. These channels are normally closed, with an opening too small for + charges to pass through. However, the axon’s chemical can fit like a triangle into a matching notch on the channel. If that happens, the attachment changes the shape of the opening. For as long as the triangles are bound, which is only a tiny fraction of a second, + charges can pass through and into the dendrite. This event is the equivalent of one domino falling against another. The channels opening for + charges is like being hit by a falling domino within a chain.

Figure 12.9. At a chemical synapse, (1) small spheres hold chemicals that can be released from the end of the axon. (2) The arrival of positive charge causes some of the vesicles to pop open. (3) The chemicals inside the triangles can stick to receptors on the dendrite. (4) When these molecules stick, channels open for positive charge, which enters the next cell.

Synapses that get used often get bigger or make new synapses nearby. Bigger synapses or more synapses between the same neurons make the connections stronger. That’s great, because making stronger connections at chemical synapses is how learning happens.

How do the connections get stronger? If a neuron gets just a few + charges through a synapse on a dendrite or on the cell body, often nothing happens. When you are tuning out whatever is happening, then you don’t move enough positive charge for anything to happen. If you pay attention for long enough, then enough + charges reach the axon, move down the axon...
to the end of every branch, and affect the next neuron (next domino) in a chain. In that case, learning might happen.

When a neuron sends charge down the axon, the neuron makes molecules that it can add to synapses. However, only some synapses get to use those new molecules; only some synapses actually change. Which ones? Only the synapses that were just active. The synapses that just passed along + charges will be able to use the new molecules to become stronger or to make new, nearby synapses connect to the same neurons. In Figure 12.10, + charges entered Neuron 1 from the upper left. Enough + charges entered to send + charges through the axon to every synapse on the axon. Enough + charges entered Neuron 2 to reach the axon. That caused + charges to move through the axonal branches of Neuron 2. Because they were active, the neurons made new materials. In Neuron 2, the new materials were pulled only into the synapse that had been active at the gray arrow in Figure 12.10. Only that synapse can grow.

![Figure 12.10](image.png)

Figure 12.10. When positive charge from one neuron causes positive charge to flow through the next, then new materials in Neuron 2 are moved back and used in the synapse that was just active.

How does that happen? Using a synapse causes a temporary change in some molecules in the synapse. The + charge at a synapse temporarily changes the shape of specific proteins. These particular proteins can pull new materials into the area of the synapse. Figure 12.11 shows these molecules as a physical guide that directs new materials into the synapse.
In step 1, the synapse has been inactive, and certain proteins in the dendrite are folded and inactive. These proteins are the diagonal lines in step 1 of Figure 12.11. When they are arranged in folds, these proteins cannot attract the various molecules to build a larger synapse or new synapses. However, + charge changes their shape for a few hours or overnight (steps 2 and 3). Unfolded into this new shape, the proteins cause new materials to move into the synapse (step 4). The new materials are used to make a larger or a new synapse. Over the next few hours or the day, for as long as proteins stay in this unfolded position, when new materials move along the dendrite, that synapse can use those materials to add more channels, become larger, or make a new synapse. However, only this synapse can grow stronger. You only strengthen the synapses you use, and so you only strengthen the memories you practice.

Practice using a memory on a particular day strengthens that memory. You can get a temporary improvement on that day and also a longer-lasting improvement on the next day. After a certain amount of practice on one day, more practice on that same day doesn’t help. Why might that be? Because a synapse can only grow so much in one day. Once you practice enough to get the full amount of synapse growth, you are physically unable to do more that day. More practice might feel good, but it won’t help you learn better. For the same reason, practicing something 1 or 2 times on each of 7 different days will give you much stronger memories over time than practicing 10 or 14 times on a single day.

I want to give you some more details on how synapses change as you learn. The change might be a larger synapse or a synapse with more channels for + charges. Either of these makes the connection stronger. However, the change may also be the growth of a new synapse. Figure 12.12 shows a new synapse growing from the active dendrite on Neuron 2.
Figure 12.12. In Neuron 2, materials from the cell body are sent back into the dendrite only to the location of the synapse that was used. In that area, the materials are used to increase the size of the synapse or to begin making new synapses.

At this point, you may have noticed a problem with my story. My model or hypothesis for how learning happens appears to work to grow larger or stronger synapses on the dendrite. What about the part of the synapse that is at the end of the axon? Notice that on the dendrite for Neuron 2, only one synapse received chemicals and had + charges enter. That synapse on Neuron 2 is the only one that has the proteins extended to collect new materials, and so that synapse on Neuron 2 is the only one that will grow. On the axon of Neuron 1, EVERY synapse from that axon passed along + charges (Figure 12.10). So, when Neuron 1 makes new materials that go down to the ends of its axon, why doesn’t every synapse on every branch of Neuron 1 get stronger? In order to get stronger, synapses on the axons need a chemical signal from the dendrite. If the + charges to the dendrite were strong enough to fully activate Neuron 2, then Neuron 2 sends a chemical signal back to that end of the branch of the axon. The chemical signal tags proteins in that single branch of the axon. That tagged protein uses materials to make a stronger synapse or a new, nearby branch of the axon. Figure 12.13 shows this message being passed back and the final result.
Figure 12.13. An active synapse on a dendrite in a cell that just passed positive charge sends a message back to the axon that sent the signal. That causes new materials to be sent to that synapse, causing the synapses form the axon to change.

Figure 12.13 shows how stronger or new synapses can grow. Importantly, they only grow if a synapse has been used and if that synapse had enough effect to make + charges move through the target neuron, which is Neuron 2 above. That fits our rule: when a synapse is used, it gets stronger. In other words, practice using a neural circuit strengthens that neural circuit. Practice using memories makes them stronger and longer lasting.

Making stronger or new synapses is one half of the story of learning. The other half of the story is shrinking or removing synapses. This is just as important. You do not want to be distracted by old information. (Where you left your bag today is important, but not where you left it every day for the past 10 years). You do not want to see a letter N and think M or see a letter b and think d. (Trust me, this DID happen to you when you were learning to read.) You do not want to be distracted by old Fish-versions of concepts when you have new, more complete and better ones. Synapses we don’t use lose their materials. In your declarative memories—the memories you can describe in words—if the memories are not used, synapses are likely to have material taken away. Eventually, even quite strong connections can shrink until they are no longer capable of activating neurons to pass + charges—no longer able to knock down that domino.

In your declarative memory, you lose synapses fairly quickly. That can happen for most of what you are learning in a class, for example, unless you use the synapses a lot. Anybody can know something for one exam and forget most of it just a couple of weeks later. In some other kinds of memory pathways, however, synapses can grow more slowly and also be lost.
more slowly. As one important example, your skill memory, based in the neostriatal cortex of your brain, seems to hold on to the skills you learn for a very long time. Those synapses, once made, seem to last a long time. After you learn a skill, such as riding a bicycle, you can still do it many years later, even without practice for all of those years. That’s one reason why developing skill memory for chunks, such as by sketching them, is a useful study method, IF you want to remember those chunks for months or years.

I need to add one more point about learning and synapse growth. The strongest effects on synapse growth happen when more than one synapse on a dendrite receives neurotransmitter chemicals at the same time. In other words, if two synapses are activated at the same time, both will get stronger than if just one synapse was activated. If four synapses are activated at the same time, all four will get stronger than when just two are activated. In the next section, we will use these rules, facts, and this model or hypothesis of memory and learning. You are probably tired of hearing that this will be another Fish-version. However, take heart that this Fish-version will be an improvement on your old understanding of memory and learning.

Applying information about synapses to how neurons learn

I want to use these rules and this model of learning to show you the neural circuits you use to recognize shapes as letters. I also want you to see why you recognize only those shapes and not other ones. Simple bar neurons from your retina in your eye can make many, many connections with branches of their axons. Each bar cell might have about a thousand branches from the axon to a complex neuron. Any of those neurons can connect to working memory. When you were a child and before you learned the alphabet, each complex neuron received on its dendrites around a thousand synapses, each at the end of an axon branch from different bar cells. Those connections allowed you to see any shape (Figures 12.14, 12.15, and 12.16).

Figure 12.14. Just a few of the connections from simple bar neurons to a complex neuron are shown here. This particular complex neuron would allow you to see a pattern of bars, but you wouldn’t have developed them as a memory. None of these synapses have been strengthened, and so you wouldn’t recall this pattern as something useful. After practice and learning, this complex neuron might respond strongly only to one pattern of bars.
However, you had not yet learned to recognize specific shapes, such as an A (Figure 12.15). What is different between just seeing a shape versus recognizing a shape? To see a shape, you just have to have the shape on the retina in your eye, which activates simple bar neurons, which send axons to your working memory. Seeing a shape does not require learning to recognize any specific shape.

![Figure 12.15](image-url)

Figure 12.15. A complex neuron that has learned to respond with positive charge only to bars that form the letter A. Other synapses, on the bottom of this dendrite, have shrunk or disappeared.

For shapes like A that you learned to recognize, you had to strengthen the connections to a complex neuron to develop a learned neural circuit. Before you learned to recognize the letter A, the complex neurons had equally strong connections from the axons of many different simple bar neurons. Figure 12.14 shows just five of the connections to a complex neuron. This neuron has not yet learned any shape. It has about 1000 synapses on its dendrites, and each synapse is from a different bar neuron. Because this neuron has not yet learned any shape, I put some bars at different angles in the cell body—just a few of the angles and combinations of bars that this cell could learn to recognize. To understand how this neuron learns to recognize an A, we need to look at the neuron over time. Imagine yourself as a pre-reader, practicing the alphabet.

Synapses on the dendrite of this neuron are strengthened especially strongly when groups of synapses are stimulated repeatedly, all at exactly the same time. Imagine what happens if you look at an A over and over and over. Each time, you activate bar cells that respond to the bars / - \ on your retina. However, you do not activate just any of these bar cells but only the ones for which the / - \ are in the right place to make an "A." That combination occurs at exactly the same time—the dendrites receive + charge from each of those synapses simultaneously. Each time you look hard at an A, with interest and attention, you send charge through those synapses. Practicing day after day (but not for very long on any one day), you strengthen the synapses with the / - \ simple bar neurons in the locations to make an A. You also weaken other connections with combinations of simple bar cells for things you never see. Over time, your “A” complex cells learn by strengthening only those synapses and weakening or
losing others. Figure 12.15 shows how the connections might change after repeated use to learn to recognize an “A.”

You also had the potential to make a neural circuit to recognize other shapes, such as _\Lambda (Figure 12.16). Back then as well as today, you could see both an A and _\Lambda. (Let’s call the second shape a “bar upside-down-V”). As a child, you did not have a neural circuit to recognize either a letter A or a “bar upside-down-V,” but you could have learned either one or both.

Figure 12.16. Here is a neural circuit that you have never developed. You could learn this circuit to recognize the shape _\Lambda, but you never have. You’ve never practiced recalling and recognizing this shape, so this is not a chunk that has a neural circuit in your brain.

You still lack a neural circuit to recognize _\Lambda. You do not have the cell I have sketched in Figure 12.16 because you have never practiced learning _\Lambda. However, you do have a neural circuit that recognizes A in many shapes and fonts. You developed the A neuron by repeated use of synapses that were strengthened over time, while others stayed weak or were lost. You never developed the bar-upside-down-V neuron. Why not? Because you never tried, and you never practiced.

How long does it take a neural circuit to learn something well?

First, as we have discussed previously the more interested we are in learning the subject, the faster we learn. There seems to be an effect of interest by the learner. Real interest while practicing seems to make memories form faster. It might be simply because when you are interested, you want to recall that memory more. And if you recall the memory frequently, you are practicing the neural circuit every time. High interest might also cause materials to be made and sent to synapses faster to make them grow faster. Either way, if you can make yourself more interested in something, then you will learn it faster.

Second, our genetic background may make a difference. There are specific mutations to genes that, at least in fruit flies and mice (and some other animals), make learning happen faster. In these experiments, the normal animals take multiple periods of practice to learn a
behavior. However, the mutant animals can learn the same simple task after just a few practices. With these mutations, it can take fewer than half as many practice sessions to make a strong memory. The memories do not just form faster; they last longer. This suggests that there might be genetic variation for the speed at which synapses grow and how much practice they need.

It is probably true that we all differ genetically, at least a little, in how fast we learn. However, I’m not sure that this is very important or useful to think about. Consider the fact that reading is a very, very complex skill that takes a long time to develop, and yet nearly everyone who puts in the effort and time with the right coaching and steadily increasing challenges becomes an expert. That suggests that how we train our memories and our learning is much more important than our genes.

Why don’t we have better memories?

If simple genetic changes in animals can give them better memories, why don’t we all have better memories? The normal genes in fruit flies, mice, and (it appears) in humans are not for the fastest learning and longest-lasting memory. Why not? My first, unthinking guess would have been that fast learning and slow forgetting would be the best thing to have. However, fast learning is only good if you learn the right things. Slow forgetting is only useful when whatever you learn remains important and true. What happens if sometimes you learn in the wrong way or you learn the wrong thing? What if someone lies to you, and you believe them? What if a person thinks they are giving you a true new chunk, but it is wrong? What if what you learn is true but is only important for tomorrow, next week, or until the end of the year? In that case, the things you could not forget might become extremely distracting.

Many of our memories become useless with time. Do you really want to remember fluently (with FRUCO) every unhappy moment from when you were age five, ten, or fifteen? In my own life, it turns out that how embarrassed I was as “the woodsman” in my school play in first grade is not a useful memory. It happens to be a memory I cannot get rid of. Imagine that every time you see your relatives and oldest friends, you remember each and every time they made you feel bad. Imagine that every one of those unhappy memories feels as strong as memories from yesterday. (There actually are people who seem to have this curse.) This would not be a good thing! Most of those events don’t matter. You don’t want working memory cluttered with useless and outdated chunks. Forgetting things that are no longer important or useful is just as important as remembering the things that are important. Brains that only learn after repeated practice with interest are probably better to have than brains that learn fast and then cannot forget. Brains that can forget allow us to get rid of chunks and connections that are useless, wrong or distracting.

In presentations with an audience, I sometimes offer them the following:

“Imagine that on a chair at the back of the room, I have a pill that will help you make perfect, lasting memories very quickly. If you take it, you will quickly learn perfect memories the very first time you experience something. The pill will make those memories strong and real for your whole lifetime. You may take the pill, but make sure you think about it first! If you take the pill, you will have this ability to make fast, perfect, long-lasting memories forever, for the rest of your life. You cannot undo it. Raise your hand if, on your way out of the room, you would like to take that pill.”
In audiences that include people who are mostly 50 or older, usually no one raises their hand. In contrast, in audiences of college students, many raise their hand. Why this difference? By our 50’s and older, most of us have many memories we would rather not have. There are things we may wish desperately to forget but cannot. We know how the wrong memory, always in mind, can poison a friendship or can bring frequent pain and sadness. By that age, people see the costs of forming memories too fast and holding them too long.

But, college students have different goals. College students want to learn fast; often they are desperate to learn fast. College students have the pain of being unable to remember things they are expected to know, and college students often want a quick fix. When I ask college students to think more carefully, though, most see the trap. You could call this the Midas-Touch memory curse. Would you really want to remember every one of the embarrassing, confusing, and painful events of your middle school and high school years in sharp, vivid detail for the rest of your life? By the time I was in college, I had plenty of memories I would have been happy to lose or at least to have fade into the background. Even though I was struggling to learn as much as I could and as fast as I could, the cost of that perfect memory would have been too high. If I could make my memory permanently faster, better, and longer lasting, either by changing my genes or taking a memory drug, I would not.

**Fast-growing, long lasting synapses would slow down the process of becoming smarter.**

To become smarter, we don’t just learn more. We don’t just add new chunks and connections. Instead, we replace earlier, simple, incomplete chunks and connections with more organized and more efficient connections. Remember that the rules of synapse formation strengthen the synapses that are used most and shrink the synapses that are used less often.

As we get smarter, we need to forget the Fish-versions. That is possible because whenever we learn and practice a better and more efficient or better-organized chunk, we weaken the synapses for an earlier “Fishier” version. Becoming smarter or an expert is partly about getting rid of chunks and connections that are poorly organized, inefficient, or useless. It is possible to have a fantastic memory with 10,000’s of chunks, none of it very useful.

Experts do not necessarily learn things any faster or better than an average person who has a strong interest in something. What is at least as important (and probably much more important) is that experts learn things in their area of expertise in very organized ways. Experts make many logical, useful connections. Experts practice these memories and well-organized connections, over and over again. Experts become good at not being distracted by unimportant connections and chunks. Because they practice, experts often are quick to notice connections that beginners never see. In addition, experts often practice specific things on purpose, even chunks or procedural rules they already know well. They review as soon as they sense that they are starting to forget connections and details they need, and they review quickly and efficiently. It is important to realize that this efficient, organized learning seems to happen only in an expert’s area of expertise. While an expert might be smart in more than one subject or skill, sometimes many more than one, that’s only true if they practice the same learning skills in other subjects or skills.

Learning everything fast makes for a good memory, but it does not make for great organization and usefulness. Think of a house in which every possible thing is packed, like a mind with every memory retained. Each room is so full that stuff tumbles out of doors and
windows, with nothing ever thrown away. You couldn’t move, and you couldn’t use anything in
the house without tripping over something else. That’s a good Fish-version for an unorganized
mind filled with facts. Those thousands of unorganized facts are not useful, all jumbled and
confused. Organization of what you know and the ability NOT to be distracted by useless or
irrelevant things seem to be much more important than how quickly you memorize.

To make us experts, what we really need would be a drug to make us organize things
efficiently and well. That seems unlikely to be possible, because too much of becoming smarter
is based on how we practice, not how quickly new synapses can grow. For now, the best way to
develop your mind is to learn how to learn and how to develop expertise.

New chunks about molecules, synapses, and memories

To summarize the new concepts and terms you need from this chapter, here are the chunks:

(1) Something you notice can recall a memory, which acts like knocking over the first
domino. This causes the memory to be put into working memory.
(2) That memory is in working memory when you are thinking about it.
(3) In the right conditions, something in working memory might trigger a behavior related to
that memory, such as saying, “Columbus sailed in 1492 to Central America.”
(4) You learn a memory by making connections between neurons, like adding connections
among rows of dominoes. Missing connections or weak connections prevent you from
being able to recall that part of the memory.
(5) The connections between neurons are synapses. Chemical synapses are used in
learning.
(6) Synapses that are used get stronger. Synapses that are used at exactly the same time
get especially strong.
(7) Synapses that are not used become weaker or lost.
(8) Synapses that are used have proteins that change shape for the hours or a day or so
after being used.
(9) Those proteins move new materials into the synapse to make the dendrite and axon
branch stronger or to make new synapses nearby.
(10) “Seeing” a shape (such as a \_/\) does not require learning. “Seeing” a shape does
require that simple bar neurons have axons that reach to working memory.
(11) “Recognizing” a shape (such as an A) requires learning. “Recognizing” a shape
requires strengthening of some synapses and leaving other synapses weak (or losing
them completely).
(12) Specific genetic mutations or possibly, eventually, specific drugs might allow people to
grow the new synapses for memory much faster.
(13) Having those mutations or using the drugs would also make us remember bad things
longer and better.
(14) Those genetic changes or drugs probably would not help that much at developing
expertise. Experts are not just dictionaries of facts. They have organized knowledge in
complex and efficient ways that allow them to solve complex problems, usually quickly.
Optional: A Fish-version of chemical synapses.

I’ll warn you of something here. First, while my explanations of learning will deepen your understanding, it will still be a Fish-version. As neuroscientists discover more about learning, they keep getting better Fish-versions of understanding of learning. However, we do not yet understand many, many aspects of learning. We know a lot, just as Fish picturing a bird as a fish with wings knew a lot more than he did before he met Frog. But we don’t understand memory and learning fully. It is as if we keep modifying our flying Fish-version of a bird. We keep correcting errors, and our concept of a flying fish becomes more and more like a bird. However, it is hard to get rid of all of the fish-features. Think about being told that a bird does not have gills but breathes with lungs. What is a lung? Well, it is a bag with air, sort of like a stomach, but filled with air. We would imagine a bird with no gills and breathing with a bag like a stomach instead. This is more accurate than a bird with gills, but it still isn’t a very good description of a bird lung—though it turns out to be pretty close for Frog’s lung.

Second, my Fish-version for learning about chemical synapses is based on some of the best-accepted hypotheses and theories for some kinds of learning and memory. Unfortunately for my explanations, neuroscientists are still gathering data and changing their ideas on many aspects of memory and learning. Even if I knew all of this stuff perfectly, I still wouldn’t be able to give you the “correct” version. As I write this, I expect that experts on learning and memory reading this book might not like the Fish-versions I have decided to use! Others may wish that I had not left out some important aspects of learning and memory. (Try a web search that has as key words “LTP,” “learning,” and “memory,” and you’ll find one of the things I left out completely.) I have left some aspects out because I don’t think they help a beginner start to understand learning and memory. I think that the explanation I give you is a useful start. If, later, you develop into enough of an expert to understand all of the terms and concepts, you will prune and grow the synapses to match. My hope is that this is a good way to think about memory and learning. I can’t yet think of better Fish-versions for memory and learning.
Chapter Thirteen: The Hippocampus: Sequence and Place as a Part of Learning

In this chapter, I want you to understand how your working memory, which holds information for only about 30 seconds, combines with another brain area, your hippocampus, to give you longer lasting memories. Your hippocampus does almost nothing to extend working memory, unless you are interested and focused. When you are interested and focused, your hippocampus gives you temporary recall of what was in working memory for minutes or hours. If you keep recalling those memories, eventually you grow the new synapses for long lasting memory in other brain areas. Those memories can last for weeks, months, or years.

Your hippocampus helps form your declarative memory. Declarative memory includes the things you can describe and explain, which is most of what we think about as memory. Non-declarative memories are the other major category of memories. Non-declarative memories, such as how to ride a bike or make a basket in a basketball, cannot be explained. Bicycle riding and playing basketball are skill memories (also called muscle memory or kinesthetic memory). Skill memory uses a different brain area to make memories: the neostriatal cortex. We’ll come back to skill memory at the end of the chapter.

Where in the brain is working memory?

Working memory is not one single part of the brain but seems to use many areas. Neural circuits for chunks such as “house” may include neural circuits in multiple brain areas. Your concept of house includes an area of visual cortex that has memories for letters and words. For example, it contains a neural circuit that passes + charge when you see the printed word “house.” Your chunk for house also includes a different part of the visual cortex that has memories of what a house looks like, such as a simple figure of a house. Other neural circuits are in your auditory cortex for the sound of the word “house.” Because these neural circuits have strong connections (synapses) to each other, you might activate all of them as your chunk for house. In other words, your chunk for house is like a long complex branching chain of dominoes. When you see or hear the word “house,” all of these circuits might be active, just as an entire long chain of dominoes might fall over. When that happens, when those neural circuits are active in your association cortex, you are recalling your memory for house. During the time when you recall your chunk for house, those circuits are part of working memory. That’s what working memory means: a recalled memory of a chunk that you are thinking about at that moment.

Any area of the brain that is activated as part of that chunk and for which you have conscious awareness is part of your working memory. Working memory is not one place in the brain. Working memory can be many places, depending upon the chunks you are recalling. If you think “a dog in my house,” then your working memory includes neural circuits for “dog,” “my” and “house,” which are not the same as the neural circuits you activate if I ask you to think of “a pig in the store down the street.”
Working memory cannot make memories.

Working memory cannot make memories. Working memory can only recall chunks you already have. You can see, hear, or think of chunks that you have already learned—that already have the strong synapses to make a memory.

In our Fish-version, imagine working memory as hundreds, thousands, and millions of branching rows of dominoes, all set up and ready to be knocked over. Each chunk you have learned is one of these branching rows of dominoes. Whatever you see, hear, or think about can knock over a domino. As a full row of dominoes falls, that makes you recall that memory as a chunk in working memory.

Working memory doesn’t make new connections. Working memory can only activate chunks in the association cortex that are already there. Working memory can only knock over old chunks waiting to be recalled.

Working memory can hold new things.

Something very important about working memory is that it can hold old chunks in new combinations. I’ll give you an example using approximately seven chunks. You already know all of the chunks, but I am certain that you’ve never combined them in this way. “Seven trees came to my door and asked for dinner.” Close your eyes and imagine: seven trees at my door asking for dinner. (Please close your eyes and imagine those seven trees, clumping to the door, spilling dirt, and requesting dinner.) While I am certain that you know every chunk in this sentence, I am just as certain you’ve never before thought of them quite like this.

If my statement is true, this would be a new concept for you: trees that walk to a door and ask people for human food. If you practiced recalling this sentence, you could combine those chunks in your memory to form a single new chunk for this new concept. (But, don’t bother).

Here is the important point. Working memory will hold this phrase as a new combination of these chunks. This is a new thought for you, and this new thought could, with review and practice, develop into a new chunk. However, working memory by itself cannot turn this combination of old chunks into a new memory for a new chunk.

How can I be so certain? I can be certain because of what we have learned from people who have suffered brain damage to another part of the brain, the hippocampal cortex. Those people are unable to form new declarative memories. Without the hippocampal cortex, a person cannot make new memories for new chunks. Their working memory still works just fine, doing all the old things. Even without the hippocampus, the association cortex still holds the old chunks. Without a hippocampal cortex, a person can still hold any seven chunks they already know in working memory. What changes if the hippocampus dies is that no memory for new combinations of chunks lasts. That person cannot remember a new combination or sequence of chunks for longer than a minute or so.
Hippocampal cortex forms memory for new chunks.

The hippocampal cortex is about the size of a slightly curved index finger. You have two hippocampi. If you hold your first finger up next to your ear and point to the back of your head, your finger would be about the size and shape of the hippocampal cortex on each side of your brain. Your two hippocampi are about 3 to 6 centimeters inward from your ear canal. Hold your fingers up next to your ears right now, close your eyes, and imagine you can see or touch your hippocampi. Remember them. Your hippocampi remember you.

Figure 13.1 shows the locations of your hippocampi and some other areas of the brain that are important. On the right side of Figure 13.1 is my sketch of the brain seen from the left side, with your left eye in approximately the correct place. From the eye, the optic nerve (visual nerve) goes back into the brain. The axons of visual neurons make chains, like domino chains, leading to the back of your brain to your visual cortex. The spinal cord is on the bottom, sticking out and chopped off. I added the cerebellum, a brain area that helps you move smoothly in texting, sports, or dance, in the lower right. The hippocampal cortex, or hippocampus for short, is the finger-like gray thing. As I said before, there are two of them, one on each side of your brain. The left side of Figure 13.1 shows a simpler version of the location of the hippocampus, which we'll use later. From now on, I'll usually just say "hippocampus," even when I mean both hippocampi. That's what most neuroscientists do. Back when I was learning this new chunk in neuroscience, I remember being surprised when I first realized that there were two hippocampi, and not just my Fish-version of one hippocampus.

Without a hippocampus, you could read and study about trees at the door asking for dinner over and over again, hour after hour, day after day, and you would never remember it for more than a couple of minutes. It would be equally new and strange every time, as long as you wait at least a few minutes each time you study again. Your hippocampus is what keeps track of what you were thinking about over the last few minutes. Your hippocampus is what makes your temporary declarative memories. If you were studying something new about Columbus’s voyage three minutes ago, your hippocampus formed temporary memories of the new combination of chunks you studied. Without the hippocampus, you would have already lost those new combinations. If, while studying about Columbus, you saw a friend who said that on Tuesday
you will be going by car to his house at number 1203 on 5th street in Dallas, Texas, then Columbus’s voyage is gone from working memory, gone as if you had never thought of it before (Figure 13.2).

How the hippocampus works is complicated. We don’t understand it completely. In the sections below, I’ll give you a Fish-version of what we know.

A Fish-version of hippocampus memory formation

The hippocampus is like a spider in the center of a spider web, sending threads out to the association cortex. Threads go back and forth between the working memory and the hippocampus. A tiny thread from the hippocampus touches each of the neural circuits for each chunk in your association cortex. Each neural circuit in your association cortex is your memory for that chunk. When a neural circuit for one chunk (“tree,” for example) in your association cortex is active, you are holding “tree” as a chunk in working memory at that time. The chunk for tree hasn’t moved—it is still in your association cortex, but your chunk for “tree” has activated a thread of axons to the hippocampus. The neuron from your association cortex passes + charge to the hippocampus, and the hippocampus sends charge back through a neuron that goes the other way. Each chunk that is currently in working memory activates a connection to your hippocampus, and your hippocampus connects back out to each chunk. A Fish-version is the thread from the chunk for “tree” tugs on the hippocampus like a bug twisting and turning in threads in a spider web, and the hippocampus tugs back.

Imagine a game, in which you are a hippocampus. You have ten threads going out to ten other people. Each person represents one neural circuit in the association cortex—one chunk that you know. Each person is a chunk for one word. The words are house, dinner, store, tree, dog, door, my, seven, ask for, came, and sing. Imagine that you get seven tugs, in order, from the people holding these specific words: seven – tree – came - my - door – ask for - dinner. So
far, you—the hippocampus—don’t know what their words are; you only know which strings were
tugged and in what order. Even though you don’t know the words, you keep track of the threads
and the order of tugs. Later, I ask you, “What was that thought in working memory a bit ago?”
You don’t know—you’re just a hippocampus. But you can tug on the strings in the same order.
You pull hard on those strings in the correct order, and the people each yell their words when
they feel the tug: “seven,” “tree,” “came,” “my,” “door,” “ask for” “dinner.” (Figure 13.3). You—the
hippocampus—are not the full memory. The chunks themselves are still in your association
cortex. The hippocampus only kept track of the order of pulls on threads leading to chunks for
the memory.

![Hippocampus diagram](Figure 13.3)

Figure 13.3. The hippocampus keeps track of which chunks you have in working memory and
their order. To remember something after they are gone from working memory, your
hippocampus pulls on those neural circuits, in the right order, to bring them back into working
memory.

I want to emphasize the role of the hippocampus. As the hippocampus, you don’t need
to hold the chunks. Your hippocampus doesn’t need to understand the chunks. Your
hippocampus doesn’t need to know anything at all, except the order in which the threads were
tugged and the order in which to tug back if you need to recall the memory.

![Hippocampus diagram](Figure 13.4)
Figure 13.4. The hippocampus recalling that you a few minutes ago you were thinking about Columbus’ voyage.

In this Fish-version, the threads to your hippocampus are axons of neurons in the association cortex that reach down to your hippocampus as on the left side of Figure 13.4. The tugs going out back to your association cortex are axons from your hippocampus that reach back out to the neurons for old chunks you know as on the right side of Figure 13.4. Your hippocampus keeps track of which neuron sent charges and in what order using what I will call sequence neurons. Sequence neurons activate each other in order, in the very same sequence every time.

Imagine that later you decide you want to remember what you were thinking a few minutes ago. Your hippocampus sends + charges from the sequence neurons, in the same order, back out to activate those specific neural circuits for those specific chunks. When those neural circuits are activated, you recall those same concepts in working memory. (Stop and do this now, to test your own hippocampus. Close your eyes, and try to recall my new chunk above about “seven trees came ….” If you can recall the phrase, your hippocampus faithfully pulled on the strings out to those seven chunks and pulled the strings in the correct order. If you couldn’t recall it, then you are either too sleepy or too distracted. (Perhaps you might want to stop reading and take a break.) Your hippocampus does not hold any chunks of its own, and it knows nothing about what it does. Combined with your association cortex, however, your hippocampus can hold your memories of the past minutes and hours. In Figure 13.4, you could add the order in which the strings should be tugged going in and out.

**Temporary memory in hippocampus is made by extra channels for + charges.**

How do you form and hold these temporary memories? We need a new concept. When + charges pass through synapses in hippocampal neurons, their synapses open extra channels for + charge. With these additional and extra channels, the same neurons and synapses are more easily activated again.

Let’s go back to our Fish-version of neural circuits as dominoes. In this Fish-version, the synapses are places where one domino falls against another. In our hippocampus it is as if a very small domino was suddenly made very large, just by being knocked over once. Before the chunks for *seven trees came my door ask for dinner* were in working memory, the synapses from the hippocampus to those chunks were far too weak to be activated. However, once the chunks *seven trees came my door ask for dinner* are in working memory, their synapses were temporarily given extra channels for + charges. With these extra channels, the synapses are able to pass much more + charge, much more easily. The ability to pass more + charges strengthens this row of dominoes, and each domino can now easily knock over the next one in the chain.

The increase in the number of channels for + charges occurs quickly. The channels were already there in the synapses, even though they had been closed. When synapses in your hippocampus are used, the extra channels open, and those synapses become temporarily stronger. You have made a temporary memory, which lasts only as long as those extra channels are kept open. While the extra channels are open, you can recall the specific chunks that were in working memory, and you can recall them in the correct order. Each time you recall that memory to working memory, you reopen or keep open the temporary channels for + charge. If you don’t think of that combination of chunks again, those channels begin to close. As
those extra channels begin to close, you start to lose your temporary memory for that chunk. Once the extra channels are all closed, you have lost that memory as if it never existed, unless something else has happened. You only start developing a lasting memory if you begin to grow and change the connecting synapses out in the association cortex. It is very easy to learn some new chunk that you think you will never forget and then forget it anyway because you did not practice it.

How long do temporary hippocampal memories last? That depends upon the way you think about you new combination of chunks in that memory.

**Your state of mind affects how long hippocampal memories last**

You can test out how long your hippocampal memories last. Imagine that I ask you to stop reading now or to stop what you are doing at any time of the day. Write down all of the things that you have been thinking about for the last ten minutes or for the last hour. This turns out to be quite hard. I’ve tried this many times. Alone, I usually cannot do it. (I suggest that you do this now. It might be more fun to find a friend or relative nearby, interrupt them, and ask THEM to describe to you everything that they have thought of during the past 10 minutes or hour.) I’ve done this just to try it out. In a conversation with friends, I suddenly ask, “What exactly have we said for the past hour or ten minutes?” Three or four of us can sometimes recover much of our last ten minutes or hour of conversation, but it’s not easy, and usually there are arguments (“... and then you said this, and I said that....” “NO, that was earlier!” “No it wasn’t.”)

To learn a lasting new chunk, it matters how long that hippocampal memory lasts. So what makes hippocampal memories last? Two things especially: (1) focus, and (2) practice (regular recall of the chunk, especially in multiple contexts). In other words, trying to understand and learn, not allowing other thoughts or boredom to distracted you and going back over the chunks much more than once is what matters. If you are bored or not trying hard to learn, your focus wanders. When you’re not focused, other thoughts enter working memory easily. (“I’m hungry.” “Was that a text message?” “I wonder who it was.” “Is that clock even working?” “I think I need a dog.”) Things you would normally ignore are free to enter working memory. Each unfocused thought squeezes out something else in working memory, and each one tugs on the hippocampus and inserts itself into the sequence of tugs on your hippocampus. Loss of focus with low attention weakens your hippocampal memory and inserts chunks that don’t belong. The more times you practice recall of chunks with focus and attention, the stronger the memories are, and the longer they last.

Imagine our game with the ten threads again. Now, while you are getting the seven correct threads tugged, have other people give a distracting tug on their thread now and then. If asked to recall what was in working memory, you might tug on seven – dog – came – my - door - ask for - dinner. That would be pretty close to the correct words and the correct sequence, but now you have a very different memory. The distraction made your memory wrong. You would now be learning a false chunk.

Distractions can easily mess up your hippocampus. You’ve probably had an experience in which you thought of something you want to do at home, and you started to do it. At the same time, you were thinking intensely of something else that was important to you. You got to another place or room and became puzzled. You thought to yourself, “Why did I come here?” and could not remember. That was a failure of your hippocampus. Without a working
hippocampus, that would be your life. You would never know what you’re doing or why you’re where you are. “What’s going on? How did I get here? Why? What am I doing? Who is this person? Why does this TV program seem so confusing? Who are those characters? What is this conversation about?” It is miserable to lose your hippocampus.

**If you don’t care, the memories don’t last.**

Besides focus and practice, a third thing matters in the formation of memories: (3) **interest with caring.** The more you care and the more interested you are, the longer your hippocampal memory lasts. Unfortunately, you cannot fool yourself. If you truly don’t care and are not interested, you won’t remember. While fear can help a little (“If I don’t learn this, I’ll do really badly on the test!”), what you learn is connected to the fear. After the exam, memories made from low interest quickly fade. I’m sure you’ve had the experience of learning something important for an exam, remembering it correctly at the time of the exam, and a week or two later, finding it is completely gone from your memory. That was, sadly, too much of my high school career. When I truly didn’t care and wasn’t interested, I didn’t remember. I started using better methods of learning only when I was in college.

We don’t know how this works. We don’t know how **caring** and **interest** make a memory last longer. Some research studies suggest that only wanting to remember something is not enough. If researchers offer people money to remember a boring list of things (enough money to care, but not enough to obsess over it) people don’t do better than if they are just asked to remember that same boring list with no reward. I would have guessed that result. Every semester I have students who care desperately about learning in my courses because they need good grades for medical school or a job. It doesn’t help. If they don’t care about those chunks and don’t practice, it doesn’t help. What helps is if they find reasons to be interested in the class. It seems that you cannot learn something just because you decide you want to know it. So why do caring and interest matter? It might be because they make us focus more; we make it feel real to ourselves; and we practice. As I said in Chapter Nine, making something feel real tends to make us care more about something, which helps strengthen memory. Caring and interest might just make us recall more often and more intensively. That would mean more + charge through the neurons. Caring and interest seem to open extra channels at the synapses, making temporary hippocampal memories last longer.

**Too sleepy? Your hippocampus fails.**

In addition to focus, practice, and caring, a fourth thing helps form hippocampal memories: **sleep.** If you don’t get enough sleep, your hippocampus works badly. Imagine a sleepy spider, struggling to pay enough attention to the threads being pulled and sleepily pulling back. Trying to think and learn when you’re sleepy is a just a little like losing your hippocampus. When we are very, very sleepy, our hippocampus may completely fail to keep track of what goes through working memory.

Think about times like this: you are sleepy, but you are trying to study or read anyway. You get to the end of a page, and you think, “I have no idea what I just read.” Blame your hippocampus. Your hippocampus stopped keeping track of what was in working memory. Whacking yourself on the side of the head won’t help (I know this is true, because I’ve tried it). Just wanting to remember won’t help, which I also know very well. When I was on a long three-day interview visit for my current job as a college professor, I drank so much coffee because
people kept offering it to me that I couldn’t sleep during the nights. I was nervous, so I hadn’t slept much on the days before the interview. By the third day of my interview, I sometimes couldn’t remember the beginnings of my sentences long enough to finish. I was trying hard to remember what I was talking about. I hoped that my soon-to-be boss didn’t notice. My last day was a blur, but I still remember how horrified I was that I might be making no sense at all. (Fortunately, they didn’t seem to notice.)

Lack of sleep causes the hippocampus to make mistakes. That alone is a problem. Sleep is critical because during sleep synapses are strengthened or weakened and because it is necessary to gradually turn brief hippocampal memories into longer-lasting connections in the association cortex. If people are allowed to sleep after practicing many kinds of learning tasks, their memories improve. If they are not allowed to sleep, the memory of what they practiced fade. Sleep seems to be a period in which the temporary changes in charge in neurons are changed to the growth of synapses.

When you cram the night before an exam, you are forming temporary hippocampal memories that won’t last. The memories might last through the exam, but they won’t last much longer. After the exam, it is unlikely that you will keep practicing the temporary memories. After all, if you had been interested enough to learn this and had the time, you would have been thinking and practicing and reviewing the ideas long before you started cramming. It isn’t likely that you’ll be interested in practicing the new chunks after the exam is over. While cramming, you have not grown or changed new synapses very much. While cramming may get you through an exam, cramming seems not to make you smarter. To get smarter, you need enough practice and sleep to allow your synapses to grow and change.

**What makes a temporary memory last longer than a few minutes?**

Most of your hippocampal temporary memories quickly fade away with no lasting memory. You might think that’s a bad thing, but it’s actually good. You don’t need to remember every thought or chunk you ever have. In fact, most of what passes through our working memory isn’t worth remembering. Most of it is not that important, except to allow you to keep track of where you are and what you are doing. You probably remember fewer than 1 out of 1000 groups of chunks that were in your working memory today. In fact, you can go through some days in which nothing is worth remembering. (I hope not!)

The more often you recall a set of chunks from working memory, and the more you care about that combination of chunks, the stronger the hippocampal memory. Something you really care about will temporarily have a very strong set of synapses. The connections are so strong that the slightest reminder with the remotest connection on the same day will make you recall that memory. People can develop strong and lasting memories for their first real kiss this way. Equally, they can develop strong memories for a truly horrible event in this way. I remember events that were so powerful that I thought about them over and over on the day it happened, perhaps hundreds of times. For days after, the slightest hint, a name or an image, would make me recall the memory. Each recall is another round of practice. Each round of practice makes the memory stronger (Figure 13.5). If you are obsessed enough, you can get hundreds of cycles of deeply interested, focused, practice into a few days, and you can stay so interested that the easy triggering of that memory becomes automatic. For people a little older than I am, the assassination of President John F. Kennedy in 1963 became a memory like that. For many people in the USA today, the events of 9/11 are equally powerful, and for the same reasons.
When you care about and value a new set of chunks, you review them over and over again, with focus and attention. This is a big reason it is much, much easier to remember some things than others. When you care, you also tend to think of your new combination of chunks in connection with other chunks. Those new connections start the process of transfer, and they also help you retain the memory longer. It is much, much easier to learn things you care about, not necessarily because you care, but because you spend so much more time reviewing them with vivid attention and focus.

Figure 13.5. Recalling a memory increases the channels that allow positive charge into the next neuron, but the increase is temporary at first. Step (1) above shows molecules waiting to be released at a synapse. When positive charge arrives (2), that causes the vesicle (sphere) holding the chemical message (the triangles) to open up. The chemicals cross to the next neuron and open channels (3), which allow positive charge into the next neuron (4). Using the synapse by recalling the memory causes a temporary increase in the chemical in the axon and in the number of channels in the dendrite (5). Therefore, when positive charge arrives, more channels open (6), making the memory easier to recall. However, if the memory is not practiced the extra chemical and channels are removed (7), making the memory weak again (8).

This is an important point. I remember tutoring a friend, call him Jim, in high school chemistry. Jim needed to memorize the formula for a sugar for an exam. The formula was for glucose: $C_6H_{12}O_6$. As you can see, this formula has only three letters and three numbers. Over and over and over again, we would review the formula. Within ten minutes, he would be getting it wrong again. I got really frustrated. I remember thinking, "Wow what a dumb guy. I have this
really stupid friend.” I was wrong about this, and I don’t like this memory of myself. (The memory won’t go away. This is a memory I would rather not have.)

Here’s how I know I was wrong about Jim. Two weeks later, I was working at my night job, and Jim came to find me. He had just watched a movie that he liked so much he wanted to talk about it. He started to tell me its plot and act out some of the parts. He spoke the lines of one character, then another, on and on through whole scenes. He continued for almost an hour so vividly that at times it felt like I was watching the movie, step-by-step through the events and dialogue, all the way through. I remember sitting with my mouth hanging open, thinking, “How can my dumb friend remember all of this stuff! This guy can’t remember three letters and three numbers together. He’s only seen this movie one time!” The next night, I watched the movie and felt as if I had already seen it. My not-dumb friend had recalled and described the movie perfectly.

Today, the reason for this puzzle is obvious to me. My friend had no interest in chemistry. No matter how much he wanted to pass the test, the formula for a sugar was just completely uninteresting. He wasn’t focused or paying much attention. His hippocampal connections of the words “sugar” and “glucose” with \( \text{C}_6\text{H}_{12}\text{O}_6 \) were always weak, and he was always distracted and thinking of other things. He hated the thought of the test coming up, and so he didn’t want to recall anything that reminded him of the test. His temporary hippocampal neural circuits never lasted very long. He didn’t care whether it was C or N or Au, or whether the numbers were 5 or 6 or 7 or 11. (With better study methods for focus and practice, he could have learned it in much less time, but we didn’t know those methods.) What about me? I was fascinated by the idea that this sweet stuff I loved, sugar, was a molecule with a structure. I was captivated by the thought that it was made of these elements that were also in air, water, and paper, and that each molecule had exactly these elements in one particular shape. My energy to make my body move came from this formula! To me, it felt cool to remember this, just to know it. I thought about the formula for glucose many times, with much more focus than Jim. The formula for glucose was hard for me to forget.

I have my own areas on which my memory is awful. I have the same only three letters and three numbers problem but for different things. For example, I have trouble remembering my wife’s birthday. Her birthday has just three numbers, but I keep forgetting. I sometimes imagine her thinking to herself, “What am I doing with this dumb guy I have as a husband.” Of course, it isn’t that I cannot remember three letters or three numbers. If her birthday matched the formula for glucose, I would have no trouble. The problem is that while I care a lot that my wife was born, I don’t care about the specific date on which she was born. Fortunately for me, my wife is also a scientist, and she understands. She’s never asked, “How can you care more about the structure of glucose than you care about my birthday?”

As I discussed in Chapter Nine, if you don’t care about something, it is hard to learn it, because it makes it hard to practice. You can still learn something when you don’t care about it, if you use the right methods—in other words, things that give you focus and substitute for interest. However, if you do care about something, it is more likely to feel real and interesting, and it is more likely that you will think about it over and over, very intensely. In that case, even something you don’t want to remember may become easy to learn.
Changing from hippocampal memory to fluent or automatic memory

How do we convert hippocampus-dependent memory to long-lasting memory that does not need the hippocampus? In a Fish-version, I can explain your gradually stronger memories this way. At first, your memory for a new chunk is temporarily strengthened connections with your hippocampus. There are two parts: (1) temporarily stronger connections from each chunk to your hippocampus, and (2) temporarily stronger connections from your hippocampus back out to each chunk. Each time you recall that memory, you have the chance to strengthen synapses that happen to connect those chunks in your association cortex.

Over time, that’s what happens. Your association cortex is always doing three things: (1) making synapses larger; (2) making new trial synapses; and (3) shrinking unused synapses. Imagine that a synapse grows or is strengthened between two neurons in your association cortex. That new synapse is a new connection between two chunks (between two neural circuits). Imagine that these two neurons also have a temporarily strong connection through your hippocampus—these two neurons are part of a new chunk that you recall often. Never before did those two chunks have a direct connection in your association cortex, but now they do. It used to be that the only way to recall those two chunks together as part of a new chunk has been through your hippocampus. Now, however, the new synapse will be active each time your hippocampus triggers those two chunks at the same time. Each time you recall the new chunk using your hippocampus, the new synapse in your hippocampus is used, and so it is strengthened. That new synapse grows stronger and stronger and now forms a strong direct connection.

This is the beginning of an important change. As that synapse grows and strengthens, you are developing a faster, fluent or automatic connection between those two chunks. Previously, the only way to connect those chunks was for your hippocampus to recall them both together. With the new connection, you don’t need your hippocampus (Figure 13.6). Activating the first chunk activates the next through that new synapse in your association cortex. You are building a complex chunk that will still be there even if your hippocampus is lost.

Figure 13.6. With enough practice recalling a memory, you no longer need the hippocampus. After 100’s or 1000’s of times recalling a memory—no one knows how many are needed—you gradually grow new connections and strong synapses in your association cortex. Now, even if
your hippocampus were destroyed as on the right side, you would still have that chunk and be able to recall that memory.

As more synapses strengthen and grow, what at first were two chunks with no direct connection can become a single, more complicated chunk that has automatic, direct connections among all the parts. These direct connections no longer need the hippocampus. This new chunk is faster to recall and is now available to be combined with other chunks to form even more new and complex chunks in your working memory. This slow, steady growth of these fast, automatic connections seems to be an important part of what makes us smarter and smarter as we learn new chunks and practice them. We don’t know for sure, but as memories stop needing the hippocampus, they become easier to recall and to use. This is a part of what makes an expert different from a novice. This is also why it takes years and years of steady practice to become an expert in something.

Pause here for a moment for some retrieval practice. As you retrieve the information in this chapter, do some transfer. Consider what has happened in your brain as you read this chapter. You have read the word “hippocampus” so often in this chapter (90 times) that you have, I hope, a strong hippocampal memory for the word “hippocampus” right now. Tomorrow or the next day, you’ll probably have trouble recalling the word hippocampus, unless you’re REALLY interested in this stuff. If you’re really interested, then you’ll review it in your head often because you can’t help yourself. You might also review it many times because someone makes you practice the memory. If, for any reason, you do retrieval practice, you’ll recall the word much better. Remember this important point: just reading words and phrases doesn’t help build fluent recall. Reading and rereading merely puts them temporarily in working memory (and it helps develop recognition memory). For fluent recall, we have to do interested, focused practice recalling the words and phrases in connection with what they represent. Reading the word hippocampus 92 times (now) isn’t going to help you recall the word next week.

If you retrieve the memories linked to the word “hippocampus” repeatedly over the next few weeks, months, and years, then any connecting synapses have a chance to grow. A first new synapse might connect two old words you have chunked before: “hippo” and “campus,” in that order. (In reverse order, they would not be useful: “campus hippo,” a very different image.) By itself, the new synapse is just empty memorization: you have a new word, with no connected chunks. Over time, another new synapse might connect the new word “hippocampus” to a neural circuit for “brain,” another to an image of a brain shape, another to an image of a hippo eating a banana (which was one of my first ways to recall the shape of the hippocampus whenever I thought of the word), another synapse to “learning,” and yet another to “temporary declarative memory.” Of course, in order to make these new connections, you also have to be practicing and strengthening the neural circuits for each of THOSE new chunks.

This is the beginning of fluent or automatic recall with understanding of concepts associated with the word hippocampus. It shouldn’t surprise you that it takes longer to develop recall with understanding than it does to develop empty memorization. Empty memorization is faster and easier because you need very few new connections. However, because you grow so few new connections during empty memorization, empty memorization is not very useful. You cannot use the memories for anything EXCEPT recall. Recall alone is not very useful for a person who wants to get smarter. Think back to my example of empty memorization of the word tubig for water—not very useful unless I know when and where to use it. I could wander through Africa for a lifetime and never get anything when I ask for tubig.
The hippocampus has place neurons as well as sequence neurons.

I told you above that the hippocampus keeps track of the sequence of chunks in your working memory, using sequence neurons to keep track of the order of events. In a Fish-version, imagine that a sequence neuron connects to the newest chunk in working memory. Sequence neurons also connect to each sequence neuron before it and after it in a chain. Now imagine these neurons as a chain of dominoes. Knock over the first sequence neuron, and that recalls the first chunk, as a tug on the first thread out to the association cortex. That sequence neuron also knocks over the next domino in our chain. The second sequence neuron tugs on and recalls the next chunk from the tug on the second thread out to the association cortex. The second sequence neuron also connects to the third sequence neuron and knocks it over. One by one, you recall each chunk, in order, always leading to the next one in sequence as your sequence neurons fall, one at a time in order. This seems to be the way we remember events in a complex new story. With practice, your sequence neurons can help you remember sequences of much more than seven things. Even though you can only hold seven things in working memory at one time, you have enough sequence neurons to build chains of more than seven chunks.

You also have place neurons. Place neurons hold the location of events and chunks. Your hippocampus keeps track of where you are (or where your mind was) when a particular sequence neuron and chunk in association cortex were active. The combination of place and sequence can be a powerful way to recall many more than seven chunks (but never more than about seven at a time). You use sequence and place neurons naturally when you retrace your steps coming back from a new place, or when you go to the same new place a second time. Place and sequence together seem to last longer and be more easily recalled as memories than as either one alone. With practice, people can develop skills at remembering many words or digits using this combination. One common technique is to look at a list of words, and as you read each word, imagine it (or what it represents) in a location in an imaginary house as you walk through in your imagination. With practice (and I mean a lot of practice), you can take an imaginary walk through the house, picturing and remembering each word in the proper order. This method is often referred to as using a memory palace, a technique also described in Chapter Nine. People with very ordinary memories can practice this method enough to hold sequences of anything. People use this method to memorize entire books, word-for-word. People can hold 100’s, 1000’s, or even 10,000’s of chunks in order in long-lasting memory. For example, using memory palace techniques someone memorized the first 50,000 digits of pi, all in the correct order.

In my scientific research, I use a version of the memory palace method often in one very specific way. Especially when it has been a while since I have done a complex laboratory procedure with many different steps that have to be done correctly and in order, I close my eyes and “walk and move” through the procedure in my mind. Even when I might not be able to describe the research procedure from memory, and even when I have forgotten some of what I need to do, as I walk my way through, imagining myself moving and doing each step, it all comes back correctly for both place and sequence. I only need to walk it all in my mind—step by step. (Isn’t this a way of making it “real?”)

When I am teaching or learning a complex series of steps in biology, I do the same thing. I can walk through a neuron, from dendrite to cell body to axon to synapse to next dendrite. I can walk alongside the proteins and + charges and other molecules, step by step. I’m not sure if anyone taught this to me, or if I just happened to stumble into it. Most likely teachers
taught me enough so that I could learn and practice this powerful method. For example, I remember my college professors telling me, “Just walk through the steps.” I suspect that “walking through the steps” was, literally, what my teachers were doing in their heads. I do not use a memory palace. Instead, I take walks through an imaginary biological cell, a neuron, a human heart, or a brain.

You can do the same thing, with practice. You can learn to use sequence and place neurons to remember more rapidly and accurately. You can take walks on paper—through a sketch—and eventually, with enough practice, in your imagination. If you want to try this, your goal as you walk is to imagine the place and walk feel as richly vivid, intense, and real to yourself as you possibly can.

**Skill memory has sequence, place, and movement control neurons.**

Skill memory is a non-declarative memory pathway. Skill memory does not use the hippocampus but instead depends upon the neostriatal cortex. However, skill memory seems to have some similarities to the way the hippocampus works, though skill memory is not as well understood.

As a Fish-version of skill memory, you can think of your neostriatal cortex in the same way as declarative memory, with just one difference. Your neostriatal cortex has threads coming from and going to chunks for behaviors (for specific movements) in your motor cortex. In your motor cortex, neural circuits are for movements, not for memories. Neural circuits in your motor cortex are for sequences of muscle contractions that you have learned. Each neural circuit triggers one sequence. One neural circuit might trigger the series of keyboard hits to type the word “car” on a computer. Another might be a dance step, and another a basketball move. Each of these sequences can be thought of as one chunk. Just as with chunks in your association cortex, once you learn simpler chunks (simple movements) that you can connect into more complex chunks (more complex movements).

Your neostriatal cortex learns slowly and requires a lot of practice. However, neostriatal cortex seems to hold memories for a long time and accessing them is relatively easy. Once you learn to ride a bike, for example, you’ll still be able to ride a bike 20 years later, even if you’ve never been on a bicycle for that entire 20 years. You’ll be wobbly, but you’ll ride. If you don’t use declarative memories based on the hippocampus, those declarative memories are very likely to fade and disappear. The French language I learned in two painful years in high school was nearly entirely gone four years later—none of my French ever became free of the hippocampus. What about skill memory? I’ve been surprised by those. For example, in high school and college, I was pretty good at ping-pong—I played for hours each week for about eight years. Then I didn’t play a single game for 21 years between 1988 and 2009. When I played with friends in 2009, I was astonished at how quickly and easily my ping-pong playing came back.

**Skill memory interacts with hippocampal memory**

I’ve been talking about declarative memory (hippocampus with association cortex) as if it is completely separate from skill memory (neostriatal cortex with motor cortex). In one way, they are truly completely separate. You can have damage to either one that prevents learning in that way but still be able to learn using the other. However, there seem to be many connections
between these two categories of memories. Your movements bring back hippocampal declarative memories that you would not recall while sitting still. Hippocampal declarative memory for an event can bring back dance routines or moves from that event. Drawing a sketch can bring back terms and descriptions. The hippocampus and neostriatal cortex have connections that help each other.

You can use those connections. Drawing a sketch on paper, in the air, or in your mind can recall declarative memories for structures, events, and concepts. With practice, a specific word or phrase can recall your movements for a sketch (or hand movements to act out events), and the movements can bring back an explanation. In addition, many facts, events, or concepts have a physical reality. Within science, for example, all of biology has a basis in molecules, structures, and sequences of events. If you use neostriatal skill memories combined with hippocampal declarative memories for location, place, structure, and sequence, the combination can be stronger and easier to learn and recall than either pathway alone.

I don’t know whether it is necessary to use multiple sensory pathways (sight, sound, movement) and these two different categories of memory (skill and declarative) in order to be the best learner. I do know that almost every skilled scientist I’ve asked seems to use both skill memory and declarative memory together. I suspect this is probably true for nearly all experts in anything. Probably there are exceptions, but I don’t think that there are very many. Scientists, doctors, and many other kinds of experts all seem to do this.

Final chunks to learn about the hippocampus and learning

My goal in this chapter has been to give you a Fish-version of understanding of hippocampus dependent declarative memory and neostriatal cortex dependent skill memory. I hope that as you develop your first understanding of these parts of your memory, you begin to understand how to use them to learn better, faster, and more deeply.

My suggestions to you are:

(1) Practice with focus and an interest in making it feel real.
(2) Get enough sleep, so that your new memories can be strengthened as you sleep.
(3) Retrieve the correct memories, and know which are incorrect. If you study poorly, you can develop fluent recall with misunderstanding of things that are false or wrong. If you don’t know that you are studying the right thing, you’re probably in trouble.
(4) Combine skill memory with hippocampal memory. Specifically, learn ways to let your skill memories strengthen your hippocampal memories.
(5) Practice new memories and try to transfer new memories to additional chunks for the weeks and months of regular recall (NOT by rereading!) it takes to develop long-lasting memories.

One more thought for you: learning styles

Most of you have heard of the concept of learning styles. You may feel that you are a visual learner (learning by looking at images and drawing), an auditory learner (learning by listening and speaking), or a kinesthetic learner (learning by moving). One of the conclusions from the hypothesis of learning styles is that each person has a best way to learn, and that other ways will not be as good. If so, then teachers should match the way they teach to the way each
student learns. Experts still argue, however, about whether there really is such a thing as a learning style. In fact, the studies suggest to me and to many others that there are true learning preferences, but that people are not limited to learning well in only some ways. Some people prefer to learn in particular ways, quite likely because it feels easier or we’ve practiced with that method more. Of course, whatever we practice, we tend to get better at doing, so it isn’t surprising that we have preferences. The fact that there are differences in what we prefer is very different from saying that some people can only learn well in particular ways. That’s also very different from saying that they should try to learn only in particular ways. If so, then we might be looking at a preference (“I’m a visual learner!”) and suggesting it’s a handicap (“I cannot learn by listening or reading.”). I don’t think that true, but right now, I don’t know what’s correct.

I’m waiting for researchers to develop a clearer answer. Here’s what I think is useful to take from this topic right now. First, memories we make and chunks we build usually combine all these different ways of learning. Your chunk for “house” includes visual memory (an image of a house and the image of the letters that spell house), auditory memory (the spoken word for house), motor memory (a neostriatal cortex memory—also called kinesthetic memory, such as making a sketch of a house, feeling parts of a house, or actions such as going into a house or opening doors). Obviously, learning about houses in only one way would be incomplete. For most of what we know, we need and use most forms of memory. Good teachers probably should encourage all forms of learning and should mix them up in ways that help us learn each new chunk. Good students should do the same thing.

Until I see more complete research, here’s my advice. Whatever form of learning you’re good at: great! Use it, and use it well. Whatever form of learning you’re not as good at, find ways to practice. Solid research tells us that when students practice well with good methods in any of these ways, they get better. In our modern world, new knowledge comes at us in many ways: visual, auditory, and movement. So practice them all. Make connections between them. You’ll be better off if you can learn efficiently and well by seeing, hearing, speaking, touching, and moving.
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