UNCOMMON SENSE TEACHING

Practical Insights in Brain Science to Help Students Learn

From the creators of the popular online course Learning How to Learn

Barbara Oakley, PhD; Beth Rogowsky, EdD; Terrence J. Sejnowski, PhD

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A TarcherPerigee Book

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Library of Congress Cataloging-in-Publication Data

Names: Oakley, Barbara A., 1955– author. | Rogowsky, Beth, author. |
Sejnowski, Terrence J. (Terrence Joseph), author.
Title: Uncommon sense teaching: practical insights in brain science to help
students learn / Barbara Oakley, PhD, Beth Rogowsky, EdD, and Terrence Sejnowski, PhD.
Description: New York: TarcherPerigee, an imprint of Penguin Random House LLC, [2021] |
"A TarcherPerigee Book." | Includes bibliographical references and index.
Identifiers: LCCN 2020055805 (print) | LCCN 2020055806 (ebook) |
ISBN 9780593329733 (Paperback) | ISBN 9780593329740 (ebook)
Subjects: LCSH: Teachers—In-service training. | Educational psychology. |
Active learning. | Learning strategies. | Effective teaching.
Classification: LCC LB1731 .O32 2021 (print) |
LCC LB1731 (ebook) | DDC 370.15—dc23
LC record available at https://lccn.loc.gov/2020055805
LC ebook record available at https://lccn.loc.gov/2020055806

Printed in the United States of America
ScoutAutomatedPrintCode

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A Note to Our Teacher-Readers

Uncommon Sense Teaching may sound like a presumptuous title. After all, if you've already been teaching for a while, most insights about teaching seem like simple common sense.

Enter Barb Oakley and Terry Sejnowski. Their massive open online course (MOOC) "Learning How to Learn," with its brain-based approach to teaching and learning, has catapulted into being one of the most popular massive open online courses in the world, taken by millions. This popularity is a tribute to the value people place on fresh, practically useful insights. The course combined Terry's expertise as a computational neuroscientist and neural network pioneer at the Salk Institute and Barb's know-how as a professor of engineering, a linguist, and an adventurous world traveler to explain how brains learn. Much of the information in the course was so new it hadn't made its way into schools of pedagogy. But it is profoundly useful in helping people learn more effectively. And it also overturns some commonsense intuitions about how to approach teaching.[1]

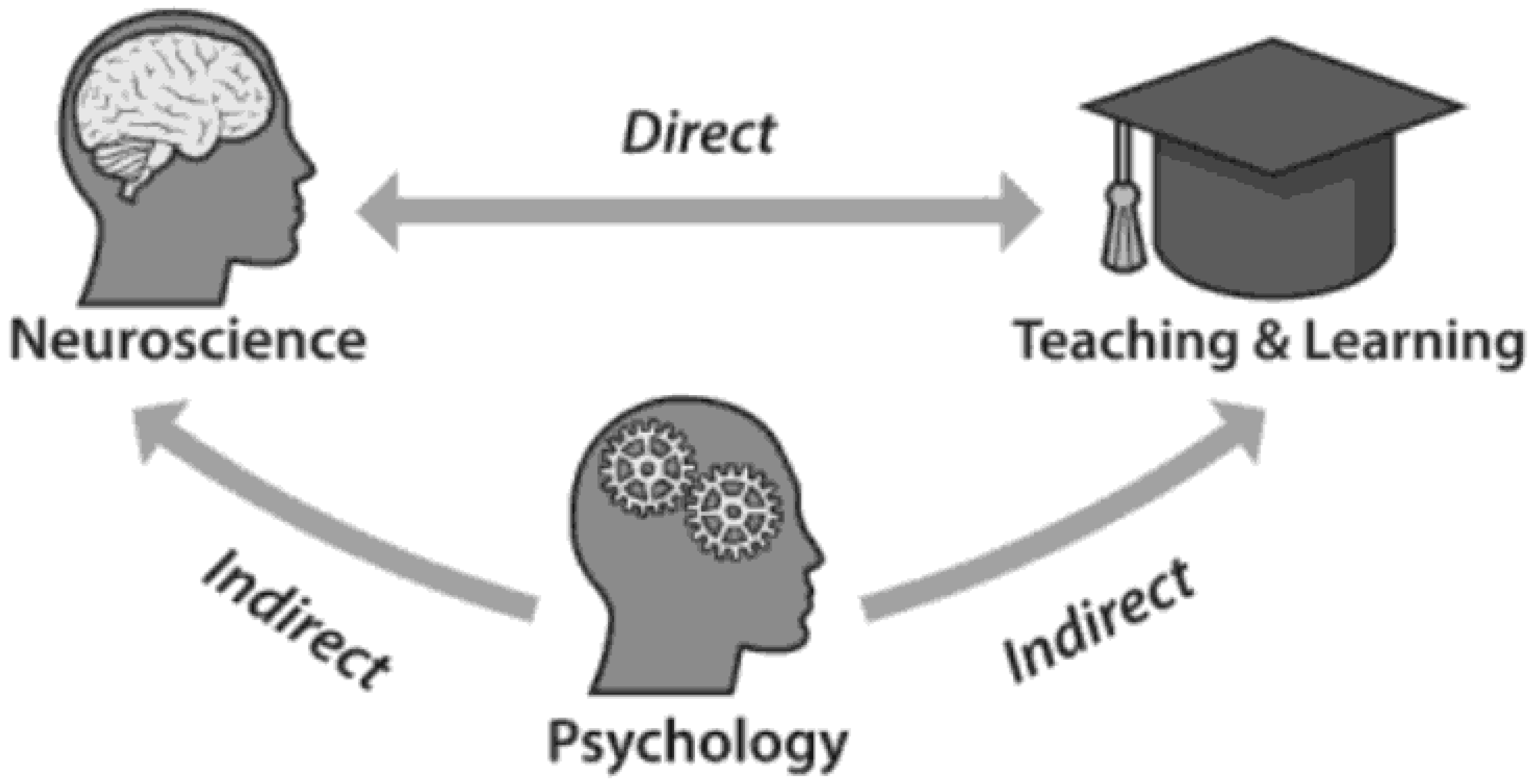
Let's step back a moment. For too long, teaching has been called an art, and yet the art of teaching remains elusive. New teachers enter the profession wanting to create masterpieces, but when they discover classrooms filled with diverse learners and are faced with overwhelming expectations for student success, they quickly move from budding Leonardos to starving artists. Most teachers want to be the best teacher that they can be. But they naturally fall into teaching the way they were taught. Unfortunately, the way they were taught, which was the way *their* teachers were taught, doesn't necessarily work for what students need to learn today.

Enter Beth Rogowsky. In the 1990s, when Beth first began her teaching career, she was eager to change the world, one student at a time. During her fourteen years of experience teaching middle schoolers in both urban and rural classrooms, she became revered as a teacher. But she began to realize that although her students were productive and having fun—a laudable goal—they often weren't learning at the level she wanted.

So she went further. Her doctoral dissertation on computer-based cognitive and language training brought her to the attention of leading neuroscientists. She would ultimately complete a three-year postdoctoral fellowship at the Center for Molecular and Behavioral Neuroscience at Rutgers University, where she worked with a network of prominent neuroscientists. Today, Beth is an education professor at Bloomsburg University of Pennsylvania, where she frequently observes K-12 classrooms as part of her professorial duties. What's striking is how often she sees the same ineffective practices she used in classrooms decades before—even though research has shown us new and better ways.

Beth's experiences have given her an in-depth understanding of two very different worlds—day-to-day teaching and neuroscientific research. She's become convinced, along with her coauthors, Barb and Terry, that teachers can use practical insights from neuroscience to make dramatic improvements in their students' abilities to learn.

Differences in students' working memories, for example, demand differences in teaching techniques. Neuroscience gives us insights about structuring those differences while balancing on the tightrope of teaching live, in front of students. Ultimately, children can give up in their studies, not because they don't have a growth mindset[2] or they haven't been taught in their preferred learning style[3] but because they honestly don't understand how to learn the sometimes difficult topics they're learning. And teachers often don't know foundational research insights, such as those involving retrieval practice and the value of teaching through both declarative and procedural pathways. Breakthroughs in these areas show us how we can help students more rapidly settle ideas into long-term memory so they can think and work more creatively. Neuroscience is vital, because it can give us far more direct insight into the foundations of learning and education than any other discipline.[4]



Neuroscience supports an understanding of teaching and learning (and vice versa) both directly and via its connections to psychology.

This book isn't meant to make a dramatic overhaul of your teaching. Although you'll see new teaching strategies to enhance the approaches you are already using, you will also see tried-and-true techniques. Because you'll be learning *why* these strategies are so effective, you'll also begin to see how to make slight but powerful tweaks that will enhance *all* of your teaching.

We've tried to write this book not just for K-12 teachers but for teachers of all kinds, including university professors as well as parents and caregivers. We keep the jargon to a minimum, and when we use a specialized term, we define it. This is especially useful for those new to the profession. If you're a seasoned teacher, you may even enjoy a refresher on some definitions you've taken for granted for years. We've included a variety of practical exercises and teaching tips for use with students across a wide span of grade levels.

The three of us are writing this book together. We focus here on teaching techniques that are broadly effective based on converging scientific evidence from both cognitive science and brain science, as well as our own classroom experience.

The work you're doing as a teacher is vitally important, not only for students but for society as a whole. Ultimately, teaching is a learning profession—whatever you know, it helps to learn more. Join us, then, as we share our learning together in *Uncommon Sense Teaching*!

Barbara Oakley
Beth Rogowsky
Terrence Sejnowski

1

Building Memory:

How Students Fool Themselves into Thinking They're Learning

Katina begins to tear up as she looks at her score. You already know why she's ready to cry—she barely passed the exam. "I just don't know why I lose everything when it comes time to take the test," Katina maintains. "I understand it fine when I'm at home or in class. It's just that when I see the test, I freeze. I think I suffer from test anxiety. Or maybe it's just that I can't do math. My mom says I'm just like her—bad at math."

Katina, by all appearances, is a good student. Testing has ruled out obvious challenges such as reading or math disorders. And Katina does her best to focus on what's being taught. She finishes her homework, even if it's sometimes imperfect. She also creates great craft projects and has many friends. In other words, she's creative and the kind of person other students enjoy being around.

It's not just Katina's stress with math.[1] Ben has the same problem. And Federico struggles with writing, Jared with Spanish, and Alex with understanding the periodic table. In fact, perhaps a third of your class seems to have already boxed themselves in with an "I can't" mentality in one subject or another. You worry that when it comes to state standardized tests, Katina—and others like her in the class, will pull down the school's average. Downward goes the school's average and the school's morale. And downward goes *your* morale.

What's going on? Can you help Katina, Jared, and the others improve their ability to be successful learners in their seemingly weakest areas?

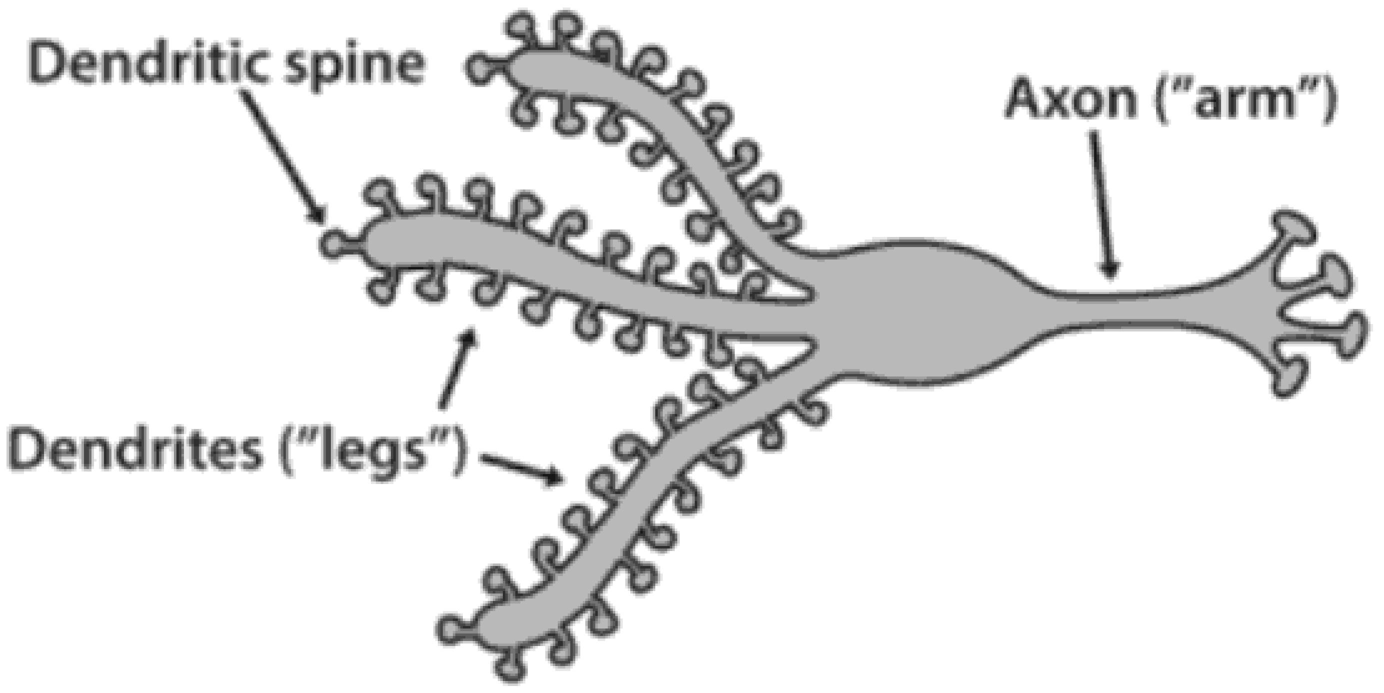
Learning Creates Links in Long-Term Memory

To understand what's going on, it helps to take a step back and look at the fundamental building block of our brains—the biological cell called a *neuron*. Each person has about 86 billion neurons. There are plenty of neurons to go around—even your most challenging students have loads of them! Whenever you or your students learn a new fact, concept, or procedure, you are making new connections between small sets of neurons.

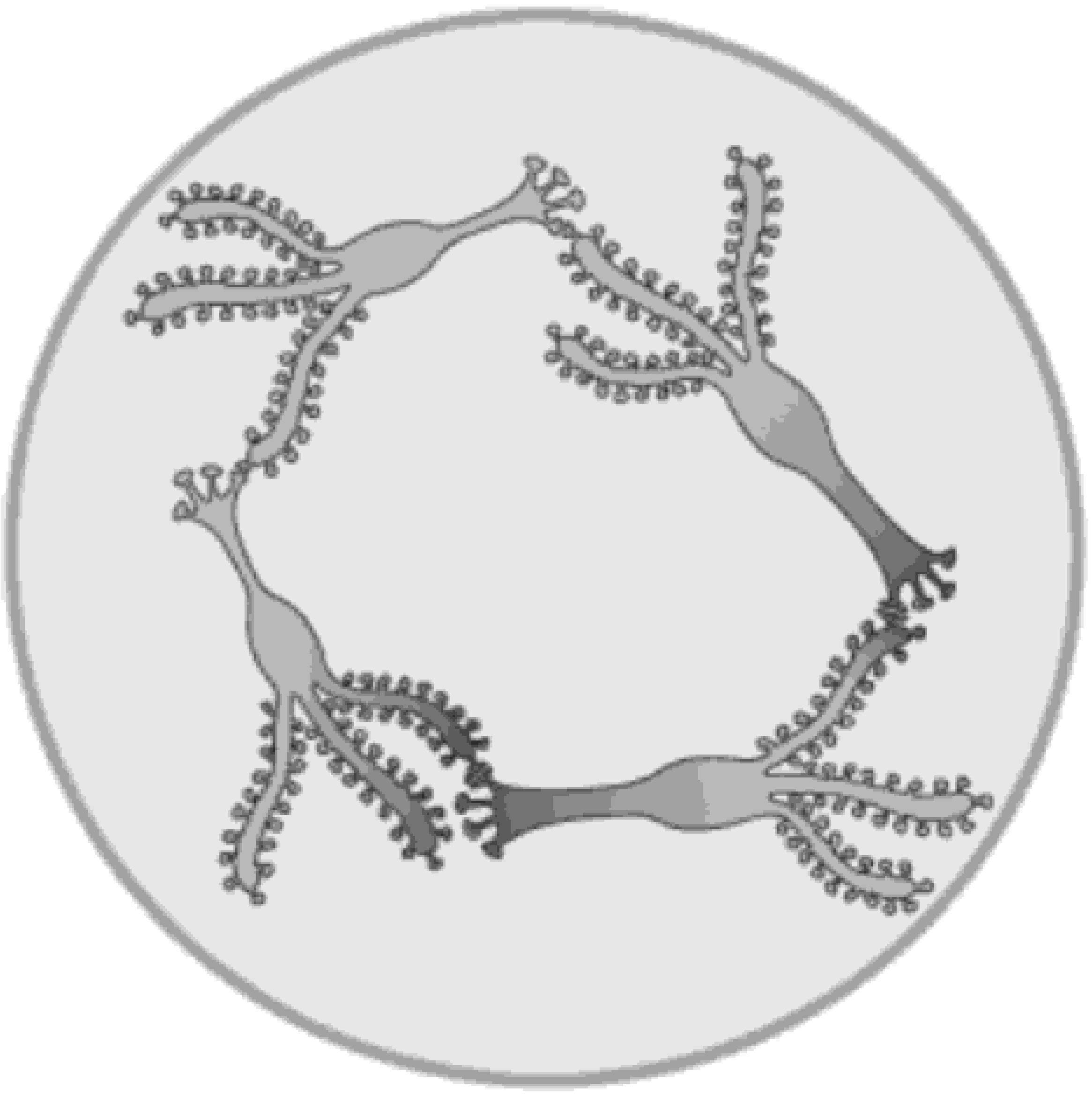
Neurons, if you look only at their main parts, are simple. They have legs, which are called *dendrites*. The legs have lots of *spines* on them, almost like a cactus (technically, these are called *dendritic spines*). And they have an arm, which is called an *axon*.

When students are actively focusing on their learning, they are *beginning* the process of making connections between neurons. These connections start forming whether students are sitting in front of you in class, reading a book at home, trying out their first lay-up in basketball, or deciphering the ins and outs of a new computer game. In other words, they are encouraging their axons (neural arms) to reach out and almost touch dendritic spines.

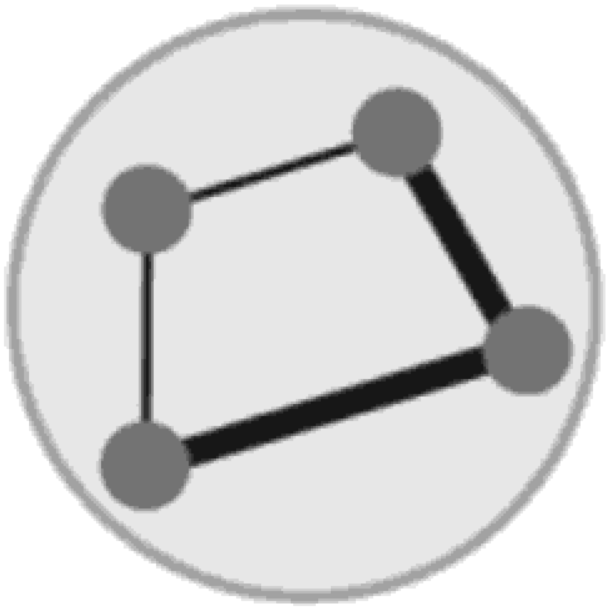
Once a neuron involved in the learning process comes close enough to a neighboring neuron, a signal jumps across the narrow gap (called a *synapse*) between the two neurons. That signal, as it passes from neuron to neuron, is what forms our thoughts—it's the foundation of our learning.



The main parts of neurons are easy to understand—they have spiny legs and an arm. We've dramatically enlarged certain features of the neuron in this drawing so that you can clearly see the axon, dendrites, and dendritic spines.



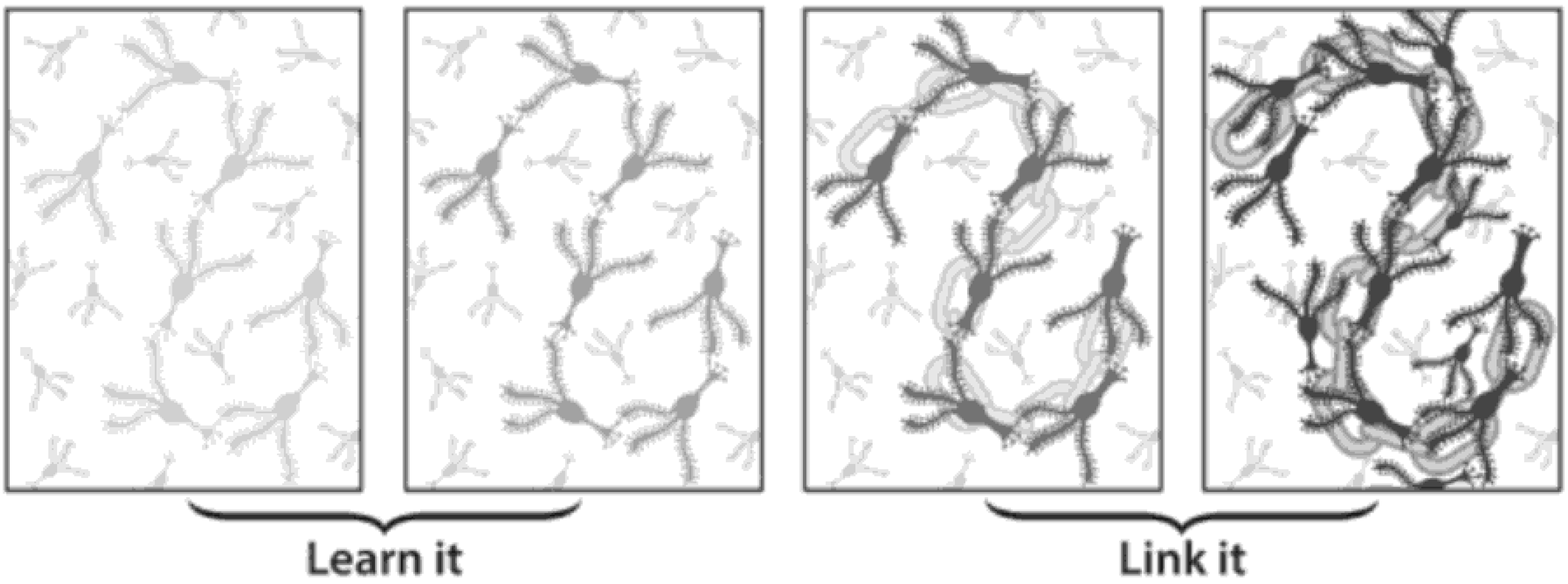
When students learn something, they form links between neurons. The spine of one neuron comes up against the axon of another neuron.



A set of connected neurons can be simplified as a connected set of dots. Stronger connections are shown with thick lines, and weaker connections with thin lines. A shaded circle is drawn around the set of links. This circle, with its "dot neurons" and links, represents a newly learned concept or idea.

Learn It, Link It

As students are learning, neurons are linking and strengthening. We refer to this process as *learn it, link it.* This term has its origins in *Hebbian learning*, a process where neurons that fire together near simultaneously in time wire together.[2] (Donald Hebb, a Canadian psychologist, first described this process.) In other words, when a certain set of neurons begins to work together more often, they become like a well-practiced choir. "Singing together" is in fact how neurons form a sequence of links with one another, as shown in the above illustration.[3]



Learn it, link it: In the first *learn it* image on the left, you can get a sense of neurons beginning to find one another as a student is introduced to a new concept—for example, during a brief period of explanation by a teacher, or while reading a textbook or watching a video. Connections are made as a student follows along and practices the material (the second image). As a student works in active ways with the new idea, concept, or technique, links solidify in long-term memory and form the basis of proficiency (the third image). Still more practice in novel ways can extend the learning to new areas (the fourth image), which allows the neurons to tie in with other neurons that underpin related concepts.

To get a sense of how the neurons link together, look at the "Learn it, link it" panel of images above. When a student first starts to learn something, neurons begin to find one another and make connections, as you can see in the panel's first and second images. We refer to this as the *learn it* phase. (Actual neurons are laid out in a more complex structure in the *neocortex*—the evolutionarily new area of the brain that helps us do our heavy-duty thinking. But we'll keep things simple here with our neural layout.)

As a student solidifies her learning, she creates stronger links, as shown in the third image. Here, she reaches proficiency. As she practices the learning in novel and challenging contexts, she strengthens the foundational links and extends them even further, as shown in the fourth panel. We refer to this strengthening and extending of neurons as the *link it* phase. This broader neural entanglement is symbolized by the larger-sized links, with the richer set of neurons underlying these links.

People sometimes think they have only limited room in their long-term memories. This isn't true. The brain's information storage capacity appears to be around a quadrillion bytes. (A quadrillion is a 1 followed by 15 zeros—you can think of it as the number of dollars owned by a million billionaires.)

This means that far more information can be stored in the brain than there are grains of sand on all the beaches and deserts of the world.

People's real problem with memory isn't how much they can store. It's getting the information into or out of memory. This is a little like having a music streaming subscription with a nearly infinite capacity for songs. In this situation, your real challenge is getting to the song you're looking for. There are around 10^9 seconds in a lifetime and 10^{14} synapses in the brain, so we can afford to dedicate 10^5 synapses per second as we experience the world.

The kinds of neural connections we are talking about form in long-term memory. Getting these connections started can be hard work. Think about this. A student has to get a dendritic spine to pop out on one neuron, and the axon of another neuron somehow has to make a good connection with that spine.[4] And it's not like neurons have to connect in just one place. Altogether, clumps of neurons need to make dozens, hundreds of thousands, sometimes even millions of these kinds of connections, even when a student is learning something relatively simple—like how to say a word in a foreign language or how to solve an easy multiplication problem like 5 × 5.

But here's the challenge. Katina and Jared are *not* forming links in long-term memory when they study. Instead, they're placing the information in a different place altogether—a temporary storage shelf called *working memory*. You can think of working memory as a slightly slanted shelf that doesn't hold things very well. When you place balls (pieces of information) on it, they roll off as soon as you let go.

But before we dive deeper into memory, let's take a quick survey—a preassessment* of the material we're about to explore.

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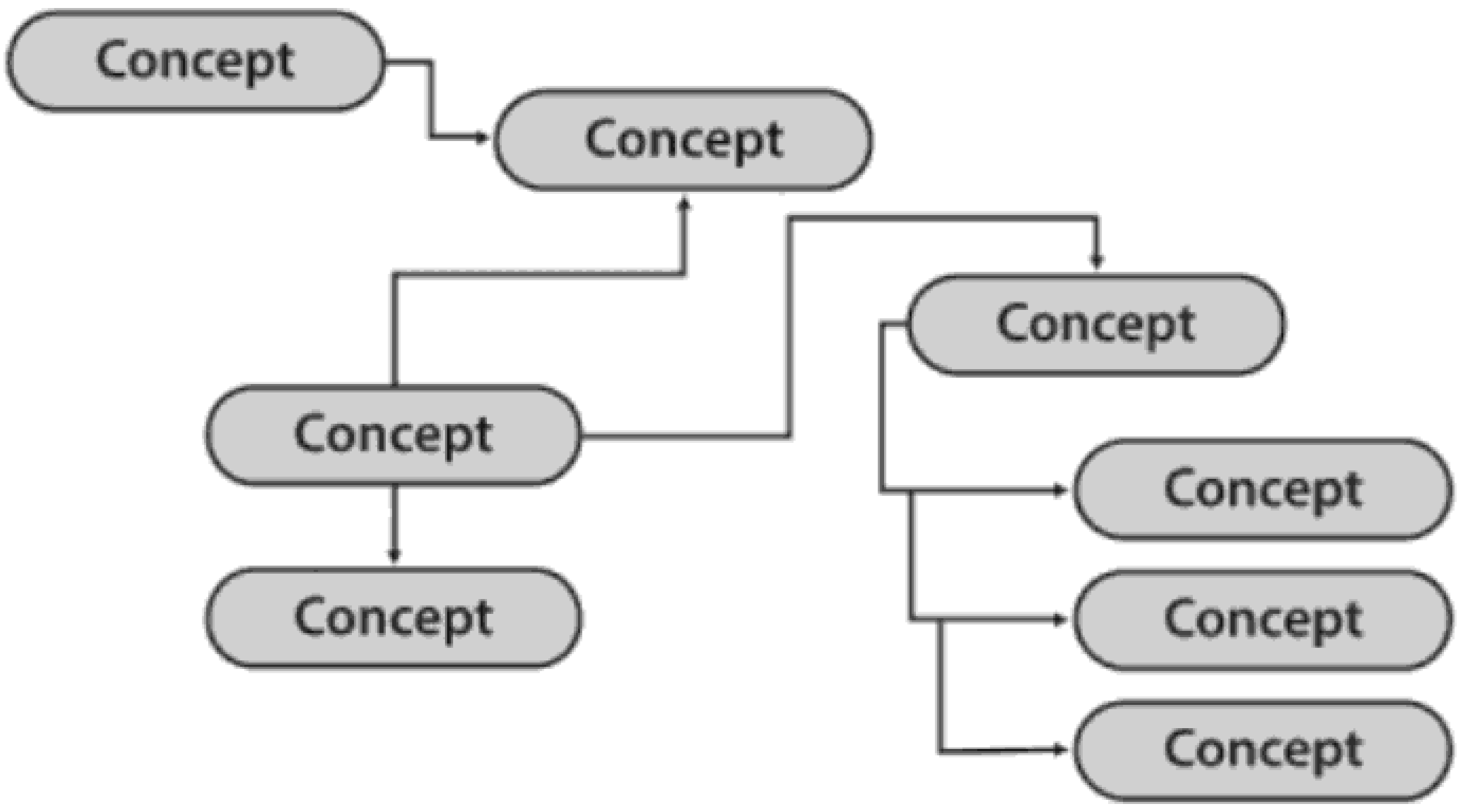
* Preassessments include those methods teachers use prior to instruction to gather information about students' knowledge, attitudes, and interests. The results are often used as a starting point for designing instruction—allowing teachers to identify strengths and weaknesses, avoid redundancy, and make instruction relevant. They are also used to establish a baseline and determine growth.

Check one of the following to indicate which technique has been shown by research to enable you to learn most efficiently.

- ☐ Reread
- ☐ Highlight or underline
- ☐ Recall (retrieval practice)
- ☐ Create a concept map such as the one shown here.



(Check the footnote for the answer.*)

Long-Term Memory Versus Working Memory

The "rolling away of balls" we alluded to in the last section leads us to do a deeper exploration of the difference between long-term memory and working memory.†

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* Recall (retrieval practice) is better than the alternative approaches (Karpicke and Blunt, 2011).

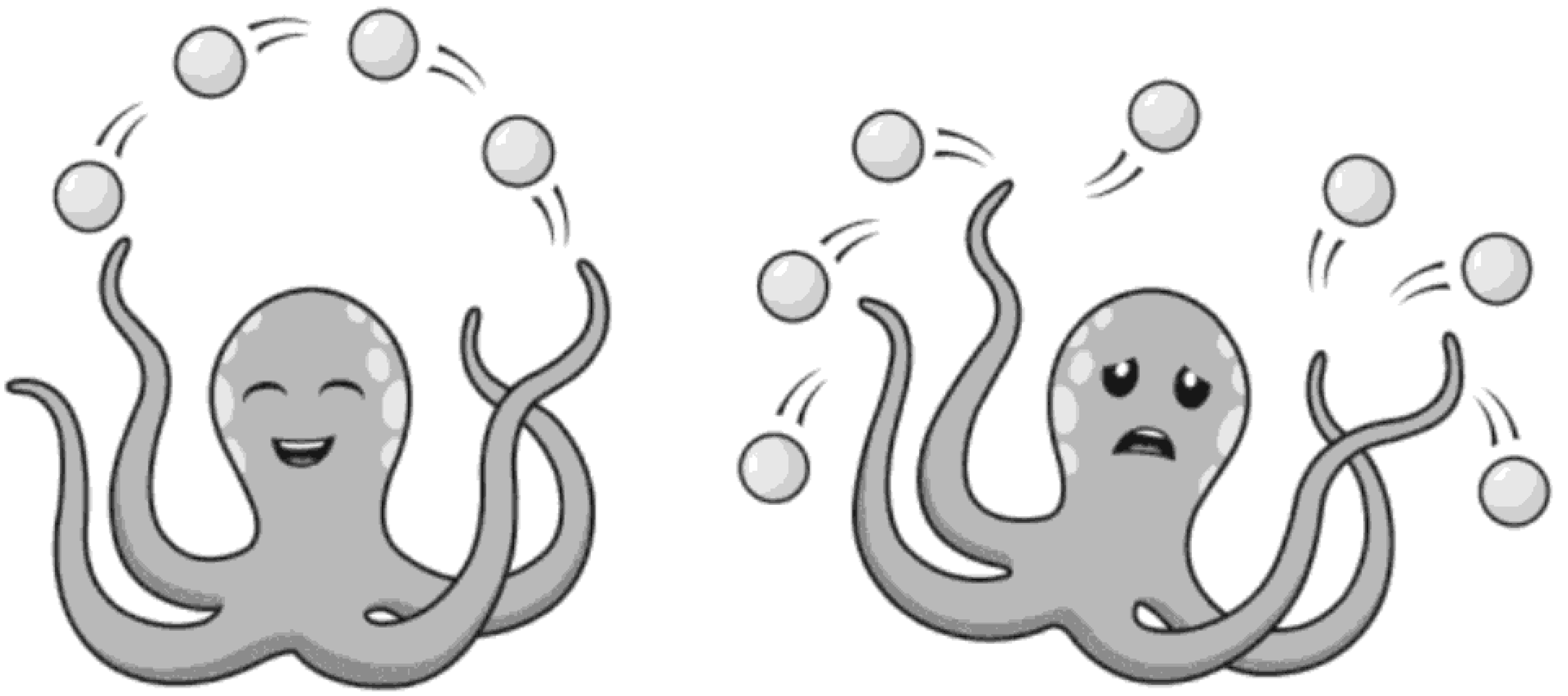
† You might wonder why it's called *working memory* instead of *short-term memory*. Short-term memory basically includes only what you are temporarily holding in mind—as when you look at a short sentence and can see it in your mind's eye or hear it in your "mind's ear." Working memory includes short-term memory as well as your ability to hold and manipulate the information in. So, for example, if you were to say the sentence backward, you'd keep holding it in short-term memory as you were manipulating it in working memory to say it backward.

Long-term memory is what it sounds like—it holds the information we're able to store and bring back to mind from weeks, months, or even years before.[5] As we've seen, you can think of long-term memory as sets of neural links that students have developed when they've learned the material well. As we also mentioned previously, these neural links congregate in the neocortex—the thin sheet of neural tissue that rides over the ridges and deep grooves of the brain's surface.[6] If we reinforce the links of long-term learning through varied practice, our learning is generally in good shape.[7] (By *varied* practice, we mean not just practicing with the same material. For example, you don't want to just sit around testing yourself on lists of new foreign language vocabulary words. You also want to use those new words in a variety of different sentences and contexts.)

But *working memory*—that temporary holding pattern for thoughts—is different from long-term memory. Rather than sets of links that reside happily in the neocortex, working memory is more like an octopus tossing a set of balls. These balls represent thoughts that bounce over and over again from the front to the back of your brain, as long as you are holding the ideas in working memory.[8] An average working memory can hold up to four "balls" before ideas begin slipping from the mind, as you can see in the "quadropus" on page 8. (Incidentally, students can't grow more arms on their octopuses. But the more students practice with the material, the bigger the balls of information can become. More on this soon.)

For now, you should know a quirky thing about working memory. Whenever the octopus gets distracted from throwing and catching balls, the balls can vanish. This leads to one of the fascinating aspects of working memory—its cunning ability to fool students into thinking *surely* they've put something in long-term memory. A student can, for example, stare at a list of ten new vocabulary words and think, *I've got them!* The student *does* have the words in mind—that is, as long as she is staring at the list.

Similar problems arise when a student glances at the solution to a complex math problem. *No need to waste time working this out on my own,* she might think. *I've got it in mind already.* And she *does* have it at least partly in mind—but only temporarily. Students discover the vanishing act when they take a



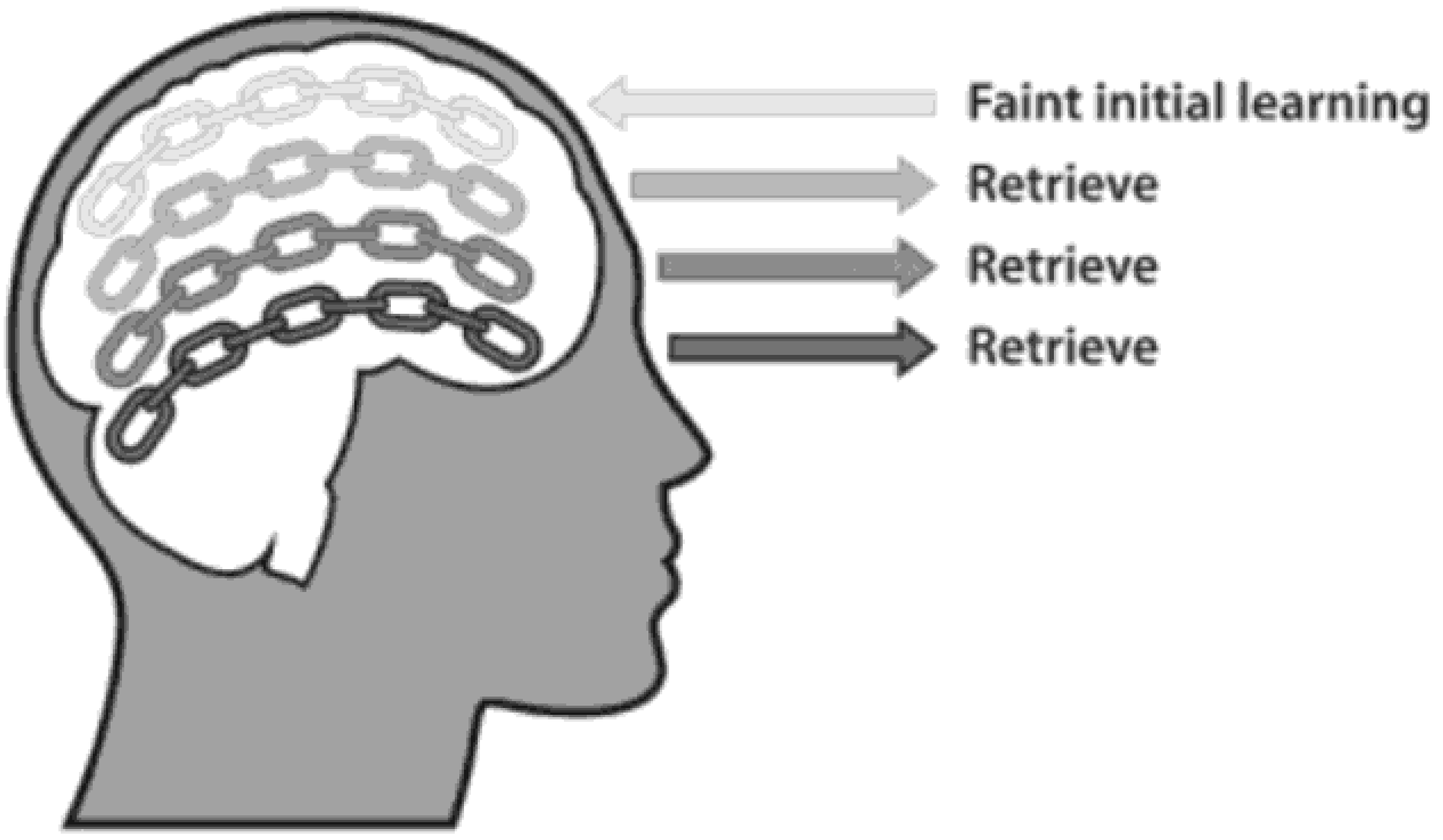
Most people can hold a maximum of about four pieces of information in working memory at once. But if they get distracted or they try to keep too many balls in mind at once, the thoughts can all fall out!

test. ("I suffer from test anxiety" is in fact sometimes code for "I feel panic when I reach into long-term memory and nothing's there.")

This "false friend" nature of working memory is why students naturally tend toward rereading and underlining. What could be more comfortable and more helpful than running your eyes past the information one more time, highlighting to add emphasis?[9]

But getting the information into long-term memory can be difficult. We'll be exploring this vital topic in more detail in chapter 3. The key idea, however, is that *retrieval practice* is one of the best techniques for strengthening new information in long-term memory.[10] Retrieval practice means drawing ideas you're starting to learn from your own mind rather than simply looking at the answer. Good examples of retrieval practice include using flash cards or merely looking away from a page to see if you can retrieve the key idea or ideas on the page.

As we'll see, retrieval practice is far from some simple mindless memorization technique—it also builds conceptual understanding. But students often need to be taught to use retrieval practice. It's hard for them to figure out on their own that this seemingly tough technique is beneficial.[11]



Retrieval practice is one of the best ways to strengthen neural links in long-term memory.

Working Memory: Master Trickster

All of this leads to our single crucial point: Despite the very different processes involved, students often can't tell whether they have something in working memory or in long-term memory. Katina can look at an explanation in a book open right in front of her, and think, *I've got it!* But she's got it only in working memory—not long-term memory.

Why are Katina, and others like her, not able to do well on tests? You may have guessed the answer already. Katina's been using her working memory to help her learn the material. (This is a great way to *start* learning.) But come test-taking time, there's very little information in Katina's long-term memory for her to draw on. She panics.

But how could that be, especially if Katina is putting both time and effort into her studies?

Let's look at how Katina studies her math and how Jared studies his Spanish. Each is trying to do well. But both struggle when it comes to test-taking.

When Katina is looking at you in class as you teach concepts of, say, algebra, she is absorbing the information and following your logic with her *working memory.*

Later, when Katina sits down at home to study her algebra, she first quickly looks through the chapter. The example problems seem clear. So she skips right to the homework, looking for problems that are similar to what she's just read and what you've done in class. She does those problems right away, her finger following the example while she writes the solution to the homework problem. If a homework problem doesn't look like an example, she takes her best guess at trying to put it into the form of one of the example problems.

Notice that the example problems are *not* the issue here. Work done by educational psychologist John Sweller and his colleagues has shown that being exposed to and working with sample problems can be invaluable in allowing students to *begin* to form mental templates that allow them to understand and solve a wide variety of problems.[12]

The problem is this: Nowhere in her study process is Katina actively and independently working problems by herself, without looking at the solution. *She is only using her working memory to solve the problems*. Although she rereads the notes she took in class multiple times the night before the test, when it comes to test-taking time, no surprise, Katina does badly.

When Jared is working on his Spanish, he looks at the list of vocabulary in front of him and thinks he knows it. Why shouldn't he know it—*it's right there in front of him!* When it comes to completing the exercises in his homework, he fills in the blanks by looking back at the examples. Done? Great! Time to knock off!

Keep in mind—in all probability, no one has ever taught Katina or Jared anything about effective studying. These two students are doing as well as they can, given what little they know about how their brains work.

In the next chapters, we'll pull these ideas about creating links and different types of memory together to see how to best help Katina, Jared, and the many other students who find themselves lost come test-taking time. We'll also look at students who get things quickly. As you'll see, just because a student is fast *doesn't* necessarily mean that the student is successful.[13]

NOW YOU TRY!

INTRODUCING RECALL

Students generally have no idea about the differences between working memory and long-term memory. This is part of why they can be so easily fooled about whether they've truly learned the material. The perfect way to address this is to do an active exercise with your students that teaches them the valuable learning technique of *recall*. (This is a form of what psychologists call *retrieval practice*.[14])

1. First, explain to your students the difference between working memory and long-term memory. (You can use the illustrations from this book, found in the DOWNLOADS tab at barbaraoakley.com.) Tell them that working memory is like an octopus that has to constantly juggle the information to keep it in mind. An octopus can usually keep at most four pieces of information in mind—and that information can easily fall out. Long-term memory, on the other hand, is like a set of links in their brain that they can easily draw on—easily, that is, if they've made sure those links are solid and well connected. (If you can associate pictures, like the octopus and the sets of links, with the ideas of working memory and long-term memory, respectively, these concepts will stick better in students' minds.[15])
2. Next, ask the students to pair up and explain to each other what you have just taught them about the difference between working memory and long-term memory.
3. After students finish, explain that they have just used the *recall technique*. That is, they've just checked whether they have understood and can remember the key idea. In this case, they've performed the check by trying to explain the concept to their partner.
4. Explain to students that they can use the recall technique even when they are alone. To use this technique when they are by themselves, all they do is look away from what they've just

learned and see if they can *recall* the key idea. Or they can test themselves to see whether they can remember a word or work a problem from scratch. In their excellent book *Powerful Teaching,*[16] Pooja Agarwal and Patrice Bain refer to this kind of recall as "no-stakes" testing—it's an easy way to see whether the material is lodging in long-term memory, where it should be.

Perhaps surprisingly, the recall technique has been shown to build an understanding of the material far better than any other approach tested, including rereading, underlining or highlighting, and concept mapping.[17] (We'll show you why in chapter 2.)

BUILDING EVEN FURTHER: PRACTICING JOT RECALL

Recall can be easily added into your teaching routine by using the *Jot Recall* technique. Use an upbeat tone to remind students about checking to see whether they've moved the material from working into long-term memory.

- ***Jot Notes:*** As you are covering essential sections in your lesson, pause and ask your students to take a fresh piece of paper or sticky note and briefly, without looking at their notes, jot down the most important ideas you have covered. Move around in the class while you are doing this. Your quick sweep provides a check for you about whether the students are following along and getting the key ideas you are trying to convey. If time permits, when most students are finished, ask students to get together in groups of three or four to compare and discuss what they found to be the key ideas.

- ***Jot Sketches:*** Along with their notes, have students create drawings that represent their understanding of the material being taught. Allowing students to get creative can increase their interest as it deepens their understanding. Drawing pictures in place of words is also effective with emergent learners who are developing their writing skills.

- ***Jot Reading Materials:*** If you are having the students do quiet reading of materials in class, ask them to pause as they finish each page. As they pause, they should look away and see if they can recall the key idea of that page without looking back at the material. Have them jot that key idea down. (Remind students that this is also an exercise they can do at home.) Again, if time permits, when most students are finished, ask them to pair up and compare and discuss what they found to be the key ideas.
- ***Jot Previous Materials:*** Ask students to jot recall materials they learned the day before, or in the previous week or month. (This is an example of *spaced repetition*—when there is a time interval between the content being taught and the student being asked to recall the information.)

Key Ideas of This Chapter

- Learning involves connecting, strengthening, and extending sets of neural links in long-term memory in the neocortex. We refer to this process as *learn it, link it.*
- The strengthening of connections between links as a student practices is known as *Hebbian learning.*
- There are many types of memory with different purposes. Two of the most important types of memory for classroom learning are *working memory* and *long-term memory.* Information in working memory can fade away within seconds. Information in long-term memory is more persistent, sometimes lasting (with subtle and occasionally not-so-subtle shifts) for a lifetime.
- An average working memory can hold up to four "balls" of information before ideas begin slipping from the mind.
- Students will often place information in working memory and mistakenly believe it has made its way into long-term memory. Later, they can perform poorly on tests because they have no information to draw from long-term memory.
- *Retrieval practice* encourages and strengthens the connections between neurons in long-term memory and prevents students' working memory from tricking them.

2

Teaching Inclusively:

The Importance of Working Memory Capacity

Barb used to teach undergraduate and graduate level electromagnetics. This difficult material uses advanced calculus to quantify the interwoven dance of magnetic and electric fields. Semester after semester, she watched as students struggled.

But almost invariably, each semester, there would be one or two "star" students for whom electromagnetics was straightforward—even easy. A complex question would barely be out of Barb's mouth when one such student—say, Farid—would whip his hand in the air with the answer. Quickly wrapping his mind around the idea and giving the answer, Farid would then go on to pose a deeper question.* The other students in the class would exchange furtive, embarrassed glances. Few of them could think fast enough to answer questions like that.

It was clear that Farid or Désirée or Mark—whoever the fast thinkers were that semester—had something like race-car brains. They could get to

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* You might think that Farid would have had top grades overall in his engineering studies, but he didn't—he was basically a B to B+ student in most of his engineering classes. Getting top grades just wasn't that big a deal to him.

the finish line—the answer—very quickly. Other students in the class had more like hiker brains. They could get to the finish line, but more slowly.

Most learners are race cars on some topics and hikers on others. Or midway between fast and slow in their learning. Whether you are teaching college undergraduates or kindergartners, different types of learners are present in every classroom and make twenty-first-century teaching a challenge. To teach inclusively, today's teachers have to figure out how best to differentiate instruction to assist *all* the learners in their class.

The challenge is, some students do indeed have something akin to race-car brains: they can think very quickly, and in class, they are often the first ones with their hands up. But as we'll see, *speed is* not *necessarily an advantage.* Think about it this way. The race-car driver gets to the finish line quickly—but everything goes by in a blur. The hiker, on the other hand, is much slower. But the hiker can reach out and touch the leaves on the trees, smell the pine in the air, see the little rabbit trails, and hear the birds. It's an entirely different experience from that of the race-car driver—and in some ways, much richer and deeper. Nobel Prize–winning economist Friedrich Hayek, for example, observed that unlike his swift-learning colleagues, his innovative breakthroughs came from his slow, muddling struggle to grasp the material. Being forced to find his own way of expressing accepted ideas allowed him to see gaps and unjustified assumptions that others missed.[1] We will see in the upcoming chapters that two different neural pathways to learning—*declarative* and *procedural*—may relate to the race-car and hiker approaches to learning.

To get a better sense of the advantages of slower learning, we'll take a look at a Spaniard named Santiago Ramón y Cajal. Cajal was a prototypical hiker student—learning came hard and slow.[2] He had a poor working memory, which made it difficult for him to put new information into long-term memory. He also had behavior problems—his antics resulted in his being kicked out of several schools. Cajal wanted to be an artist, but his father wanted him to be a doctor. (This was back in the 1860s. Some things never change.) Ultimately, his father washed his hands of him.

But surprisingly, Cajal would eventually go on to get his doctorate in medicine. As if that weren't enough, he became so esteemed for his breakthrough research findings in neuroanatomy that he eventually won the Nobel Prize. And as if *that* weren't enough, Santiago Ramón y Cajal is now considered the father of modern neuroscience.

What are perhaps equally astonishing are Cajal's thoughts about how and why he was able to achieve so much.[3] His conclusion? That his success arose in part from the fact that he *wasn't* a genius. His scientific breakthroughs came precisely *because of* his slower, more flexible, way of thinking. When Cajal was wrong, he could change his mind. The geniuses he worked with, on the other hand, were used to being right and had little practice in acknowledging and correcting errors. So these race-car brains tended to jump to conclusions with speedy answers, and when they were wrong, they were unable to correct their mistakes. Instead, they'd use their intelligence to find ways to rationalize why they must have been right after all.

Having a powerful working memory clearly isn't the only way to be a successful learner. Let's take a more in-depth look at this fascinating area.

Where Is Working Memory in the Brain?

In the last chapter, we said that working memory was akin to a system of balls (thoughts) that your mind kept alive by juggling—the balls reach across several regions of the brain. We can get a more definite sense of this process by imagining the working memory octopus (the *central executive*) as being at the front of your brain. It keeps a ball (the information) in mind by throwing that ball toward the back of your brain. The ball bangs against a reflecting surface (the *focus of attention*), bounces against the hearing and seeing networks, and then winds up back up at the front again.[4]

This focus of attention involves the parietal lobe,* possibly as a central hub of a *focus-of-attention network*. All this juggling is done through sets of neural links. As long as the information is lobbing back and forth between the front and back of the brain, it stays alive in working memory. This volleying is why you might keep silently repeating the names of the

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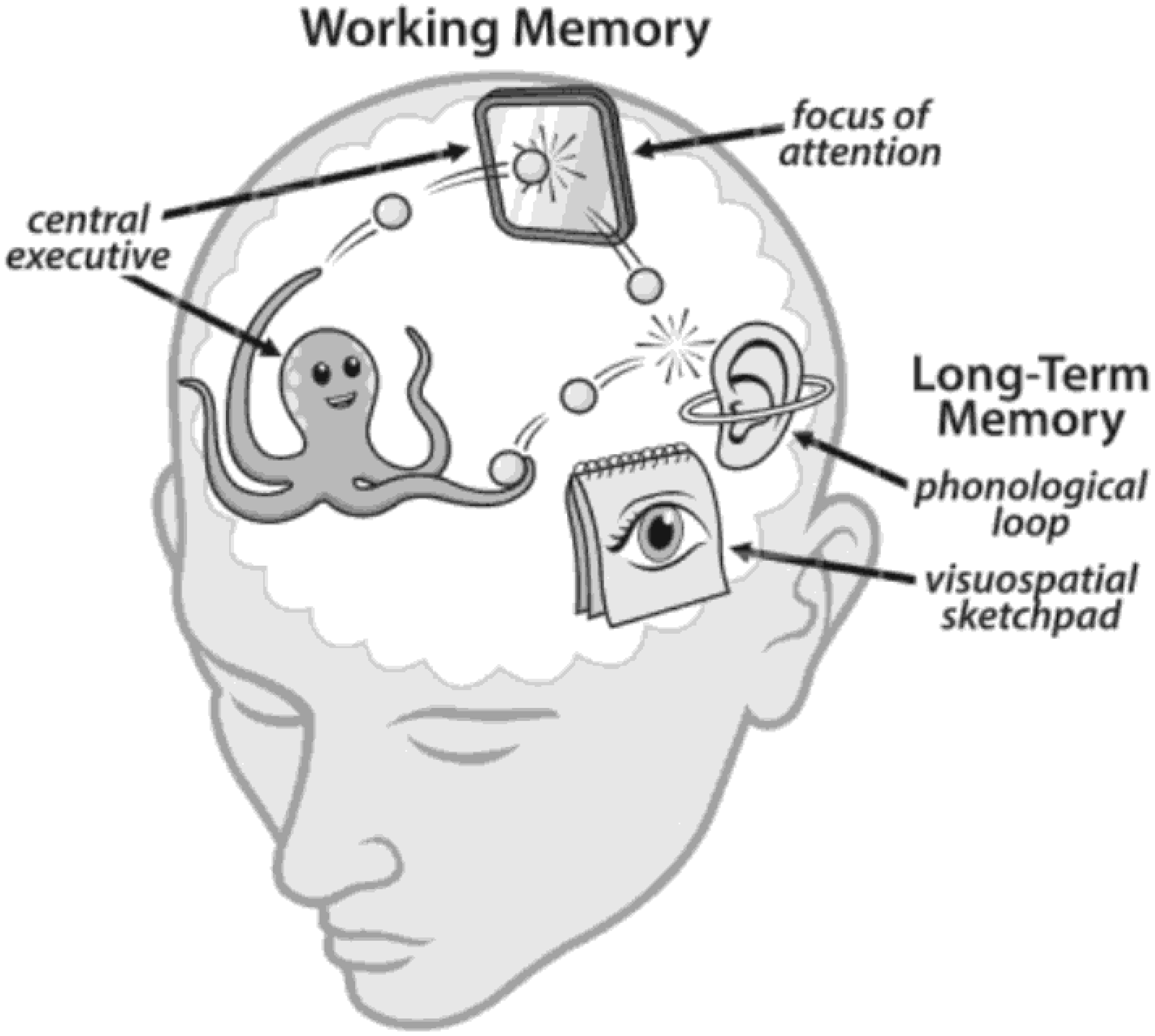
* Specifically, the *intraparietal sulcus*. But if you happen to be reading this as a textbook for class and a teacher ever tests you on this phrase, they are missing the forest for the trees!



Working memory is like an octopus (or quadropus!) in the front of your brain that keeps tossing the thoughts toward the back of the brain. Those thoughts reverberate back around again to the front of the brain as you focus your attention on them. That's what keeps the thoughts alive in working memory.*

two new teachers you've just met, or the numerical code you're trying to transfer from your cell phone to a computer website.

But don't worry about the specifics. The key idea here is that the balls of information are kept alive in working memory by bouncing around the brain. The roundabout movement of the information as it's being tossed back and forth in working memory is why students can hold only so much information in their minds at once. It's a lot like a juggler who has a shorter and shorter amount of time to grab and toss each ball, the more balls she is trying to throw. Too many balls at once and, poof, everything falls away!

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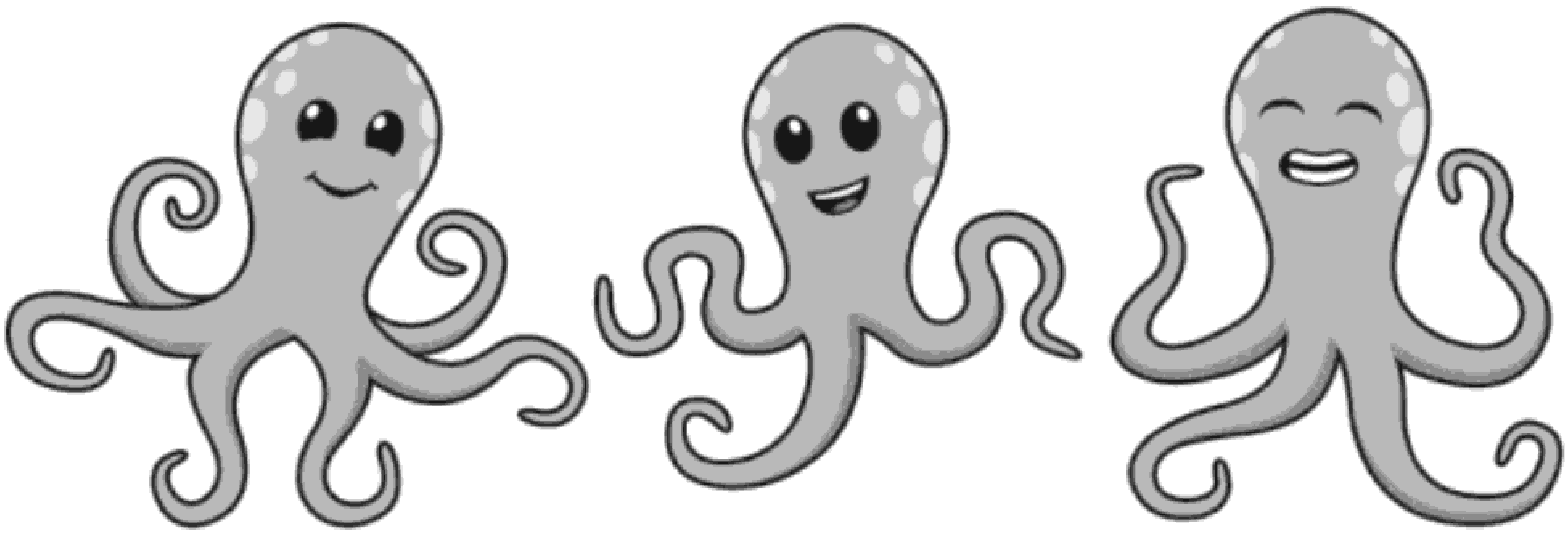
* If you're hungry for more neural geography lessons, research reveals that the hearing network (i.e., the *phonological loop*) centers on the left temporoparietal region, while the seeing network (the *visuospatial sketchpad*) is cradled in the right temporoparietal region. The *central executive* is toward the front of the brain; it works in tandem with the *focus of attention* that helps direct thinking.



Students can vary substantially in their working memory capacity. Although the average is four "arms" on their attentional octopuses (that is, four pieces of information they can hold in mind), some students may have only three arms, while still others can have six or more arms.

these students can learn well—they just need different approaches to enable them to be successful. (We'll be giving you a supply of these different approaches!)

Sooner or later, you will probably teach students with a working memory capacity that is far less than average. In these cases, it's not as if a student is actively fidgeting in a way that might raise a red flag, as with attention deficit hyperactivity disorder. Instead, a busy, sometimes overwhelmed teacher can conclude that a student is just something of a bumbler, especially when the other students seem to be able to follow instructions just fine. Students with working memory deficits often struggle as tasks get more demanding. They also lose track when it comes to more complex activities. For instance, when writing a sentence, a student with working memory deficits may leave words out or repeat the same word.

At younger ages, students with a working memory capacity that is less than average can also quite honestly forget even a simple assignment or request. A set of directions such as "Put your sheets on the green table, put your arrow cards in the packet, put your pencil away, and come and sit on the carpet" can be overwhelming.[8] Testing the working memory of students who have difficulty holding a number of ideas in mind can go a long way toward capturing a potential learning challenge early on.[9]

STRATEGIES TO HELP STUDENTS WITH LESSER-CAPACITY WORKING MEMORY

By accommodating students in your class with lesser-capacity working memory, you can often assist all students. Here are some ways to help your students.[10]

- **Be brief and as linguistically simple as possible with your directions.** Lengthy instructions will likely be forgotten.
- **Make sure your students are looking at you when you are giving directions.** “Please turn so you can see me” can be surprisingly helpful.*
- **Give instructions one at a time, including “step checks” to make sure everyone is with you.** (A typical step check might be to ask students to turn to their desk partners and gently tap their paper with their pencil, saying, “Well done!” if the step is completed. If the partner isn’t quite done, the teacher offers assistance.)
- **Provide instructions on the board or as a checklist on students’ desks** for them to refer to while completing the assignment.
- **Use mnemonics** (memory tricks) to enable students to more easily recall larger pieces of information.
- **Supply spellings of unfamiliar and challenging words** to students as they respond to a writing prompt. (Having to stop and think about spellings of new and challenging vocabulary slows students down and can make writing both tricky and clunky.)

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* Students on the autism spectrum may feel uncomfortable or unable to do this, so don’t make looking at you a hard-and-fast rule (Hadjikhani et al., 2017).

Strengthen Working Memory by Building Long-Term Memory

The terms *working memory* and *intelligence* describe related underlying processes.[11] And sure enough, those with lesser-capacity working memory can struggle more with their learning. But remember, long-term memory can ultimately become a part of working memory, especially with retrieval practice. This is good news. It means that *if the person with a lesser-capacity working memory creates and strengthens neural links in long-term memory, those links can extend their working memory on that topic.*[12] Another way of saying this is that the more assistance working memory gets from the prior knowledge stored in long-term memory, the easier it is for students, especially students with less capacity in their working memory, to learn new material.

Background practice is critical in ways that can at first be difficult to grasp. For example, let's take the sentence "The green penguin is eating an apple." It would be easy for you to write each letter of the sentence down a minute later. Now let's take another sentence: "Зеленый пингвин ест яблоко." Unless you're a Russian speaker, it's going to be pretty difficult for you to hold all the letters in mind and write them down a minute later, even though the Russian green penguin is similarly eating an apple. Our working memory capacity appears to be much greater, depending on whether our long-term memories have had English or Russian implanted. Your background training matters—*a lot.* It increases the size of the "balls" of information (sometimes referred to by neuroscientists as *chunks*) that your working memory can hold. So even though the number of arms on your attentional octopus can't increase, more background training on that topic means you can hold more information in working memory. The balls of information your octopus can hold are bigger.*

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* You may wonder what the size of the balls of information (chunks) could be, and what the range is between minimum and maximum—a word, a sentence, a concept, or more? These are issues that researchers are currently grappling with. For now, it's best to just think of the ball as a generic chunk of information that could get bigger—sometimes much bigger—with practice.

As researcher John Sweller, perhaps best known for his theories related to cognitive load, has pointed out, the intricate relationship between working memory and long-term memory is easily the most critical factor in human cognition. It goes a long way toward understanding how our mind works.[13] But long-term memory is like a wedding crasher—it sneaks into any attempt to measure working memory. This is because the contents of long-term memory massively transform the capacity of working memory.

Sadly, there's no good evidence from research that general working memory capacity can be increased through training—although something that looks like working memory increase occurs within specific areas of practice.[14] (This relates to the idea that the attentional octopus can juggle larger balls of information with the same number of arms—if, that is, the information has been well-practiced to strongly secure it in long-term memory.) In other words, practice with geometry can increase a student's apparent working memory capacity with geometry. Practice with a language—say, French—can increase apparent working memory capacity with French. Practice with the piano can increase apparent working memory capacity with piano, and so forth.

Of course, no one wants to create and strengthen links via poorly designed "drill and kill" approaches. But as we shall see in chapter 6, drill is not all bad—in fact, when drill is done properly, the expression might better be put as "drill and skill." Given additional time and well-designed practice, people with lesser-capacity working memories can become as good as those with larger-capacity working memories in their areas of expertise—or even better.[15]

The transformative effect of education is *not* that it changes students' working memory capacity.* Education instead changes the amount of knowledge held in long-term memory. The more knowledge held in long-term memory, the easier it is to add more. (This is the *expertise reversal effect*, where the more knowledgeable students are about a topic, the less guidance they need. Too much guidance in these situations can impede learning.[16]) With the right

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* Although it does seem there is a single factor that may generally increase learning memory capacity: simply becoming literate as opposed to remaining illiterate (Kosmidis, 2016).

kind of information implanted in long-term memory, people can effortlessly process enormous amounts of information—even if their working memories aren't that capacious. This is why building students' prior knowledge in a given subject area is critical. (More on this when we get to schemas in chapter 6.)

Keep in mind, though, that there are several ways to get information into long-term memory. One way—the declarative pathway—uses working memory. We'll describe this in more detail in the next chapter. But there's an even more astonishing way—the procedural pathway—that we'll explore in chapter 6.

TEACHING TIP:
Gauging a Student's Working Memory Capacity

It can sometimes be difficult to deduce a student's working memory capacity. (Remember, the average is four balls of information.) Here are some rules of thumb that can help, at least for students who are old enough to transcribe and synthesize notes:[17]

- If students can understand your more complex classroom explanations and simultaneously take notes, they probably have excellent working memory capacity.
- Students who can take notes during your explanations but sometimes lose track of what your explanations mean, especially when you are covering more challenging material, probably have average working memory capacity.
- Students who struggle to both take notes and simultaneously understand what you are saying, even with relatively simple material, probably have lesser-capacity working memory.

Keep in mind that students' circumstances—for example, a keen interest in a topic (say, computers), or, on the other hand, a stressful home environment—can increase or decrease their apparent working memory capacity.[18]

ceive to be "stupid questions" individually or within the small group. Your one-on-one or one-on-a-few discussion will allow them the opportunity to talk through their understanding of the concept or the task they are supposed to complete.

- **Allowing more time** for a student to complete a task or practice solidifying the skill.
- **Breaking down the steps** of a problem by providing examples for each step along the way toward completion.
- **Using criteria that match *and then* extend individual students' skill levels.** For example, being prepared with a variety of questions at different levels of difficulty.

At the same time, how can you best scaffold instruction for race-car learners?

- **Go beyond simple factual questions** with answers that are "right there" by asking more in-depth questions and exploring how concepts connect.
- **Allow race-car learners the opportunity to work with one another**—to bounce ideas off of and challenge one another with multiple perspectives.
- **Don't just give race-car learners more of the *same* types of problems to do.** They may take it as a punishment. Instead, create more complex, multilayered problems and assignments—or ask them to devise their own problems.
- **Allow students to choose among meaningful "sponge activities" to soak up extra class time.** These sponge activities could be reading authentic* texts on the current topic. Or such an activity could be an extension project the student develops and the teacher monitors.

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* Texts designed for students at a specific grade or reading level are typically written differently from "authentic" texts designed for the general public. Take, for instance, a textbook that starts with an overview, has review questions at the end of sections, and highlights new vocabulary in bold. That isn't how students would find authentic, real-world texts, such as newspaper articles, excerpts from

- **Accelerate learning** by allowing race cars to use video-game-like computer software that individualizes instruction based on their responses.

Differentiating instruction to meet the diverse working memory capacities of your students may seem daunting. Often there is only one of you and upward of thirty students who represent a continuum of race-car- and hiker-type learners. But differentiation can be as simple as lending an encouraging word to a student who needs attention or explaining the meaning of a word to an English language learner. (If you know writing might be difficult for certain learners, you may want to offer a paragraph frame* to get them started.)[25]

Keep in mind that students enter a topic with different amounts of prior knowledge and working memory capacities, and these differences mean that students work at varying speeds. Instructional strategies that support differentiation can include learning stations (different spots in the classroom where students work individually or in small groups on various tasks simultaneously), agendas (a personalized list of tasks that a student must complete in a specified time), and orbital studies (independent investigations that "orbit" around an aspect of the curriculum). The goal is to make it to the finish line, not to make it to the finish line quickly. We are fans of Carol Ann Tomlinson's "teaching up" approach—aiming high and then building the scaffolding for all students to reach the top level.[26]

To be successful in their studies, students can make up for lesser-capacity working memories by creating strong and varied sets of links in their long-term memories. These links extend and reinforce the capabilities of their working memories. Having students downsize their notes from class onto flash cards strengthens the links. Frequently quizzing themselves and one

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a book, journal articles, blog posts, or speeches. Even podcasts, videos, and pictures that can be interpreted are often considered authentic texts.

* Paragraph frames look like a skeleton of a paragraph. Here's an example:
(Title of short story) is about ____________________. The main characters in the story are_______________, _______________, and _______________. One word to describe (name of character) is _____________. _____________ is a great word to describe this character because (cite evidence from the text) . . .

another at the start of class then solidifies the learning. Retrieval practice in all its myriad possibilities is invaluable.

Although it takes work to get information safely planted in long-term memory, this well-seated information provides a special advantage for those with lesser-capacity working memory. Why? The long-term links they form simplify and crystallize concepts.[27] Ultimately, this means that an industrious lesser-capacity type of student can make elegant simplifications that those with larger capacities have difficulty seeing. (In a related vein, being tired, which lessens working memory capacity, seems to heighten people's ability to solve problems that need creative insight.[28])

Working Memory: Implications for Students

Students often question how to study. Take listening to music, for example, which students are often told to avoid. The problem is that some successful students happily listen to music while studying. Why should Sven avoid music when he knows darn well that Jolina listens to it and still gets great grades?

The latest research findings solve the puzzle. Music's effect on studies varies with—you guessed it—working memory capacity.[29] Those with a lesser capacity seem to be better off avoiding music altogether in their studies. Those with larger capacity, on the other hand, can do fine studying to music—their larger capacities allow them to focus more easily. The caveat is that most students should avoid listening to music while studying math. Perhaps this relates to the fact that math and music use overlapping portions of the brain.* Additionally, students with ADHD seem to benefit from white noise and music that other students might find distracting.[30]

What about note-taking? Again, working memory seems to play a role.[31] Those with larger capacity can blithely jot notes while also taking in compli-

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*It seems that when it comes to learning, there's an exception for nearly every rule. Brilliant mathematician John von Neumann, for example, played marching music so loudly while doing his work at Princeton that he annoyed his neighbor down the hall—Albert Einstein (Macrae, 1992, p. 48).

cated explanations. But those with lesser capacity have trouble simultaneously taking notes and making sense of the instructor's explanation. They can end up spending a lot more time outside of class trying to reconstruct the instructor's meaning. Researchers observe that college-level students with lesser-capacity working memory can do well by focusing only on the instructor during the presentation of new material and using others' notes for review.[32] But our own experience is that unmotivated students can use lack of note-taking as an opportunity to tune out. Instead, we recommend the following techniques to allow students to engage with the material more actively.

NOW YOU TRY!

TIPS TO IMPROVE NOTE-TAKING FOR THOSE WITH LESSER-CAPACITY WORKING MEMORY

- Consider providing a skeleton outline or a handout of your notes with missing gaps for students to complete as you present.[33]
- Mind your pace—don't speak or write too quickly.
- **Give structure cues:** "We'll look at five items, the first . . ." Cues make it easier for students to structure their notes.
- **Take mini-breaks** throughout your presentation of new material to give students time to reread their notes and ask a partner or the teacher for any fixes they might need.
- **Pause after an appropriate interval** of the lesson and ask an open-ended question on the material. Have the students get in pairs and give them thirty seconds (for example) to come up with one or more answers. Brief pauses help students practice retrieving the new information.
- Use an approach described in *Powerful Teaching* called "retrieve-taking." Students don't take notes while you are talking. Instead, they jot down the key points after you pause. You can then clarify the ideas or facilitate a discussion and continue.

Working Memory: Implications for Teachers

It's probably no surprise to learn that teaching techniques that work well for students with larger-capacity working memories don't meet the needs of students with lesser-capacity working memories.

Let's take, for example, mathematics instruction. Students with very large working memory capacity can do well no matter what the instruction type—student-directed or teacher-directed—and may even flourish when it comes to directing their own learning. But students who struggle with math—which is common in those with lesser-capacity working memory[34]—appear to do *worse* in student-directed learning, and *better* with teacher-directed approaches.[35] You'll learn more about these two types of instruction in chapter 5.

Research reveals that *practice* seems to have the most significant positive effect on these struggling students.[36] We'll see later that practice builds information in long-term memory through the procedural learning pathway, which is quicker and more automatic to use. An emphasis on automaticity strengthens lesser-capacity students' grasp of a subject by allowing their long-term memory to enhance their working memory. (Automaticity is involved in the ability to correctly punctuate a sentence, for example, or to add two simple numbers without even having to think about it.) As students gain familiarity with the basic concepts, they can begin to work more independently through student-directed approaches.

Similarly, reading instruction can have different effects based on students' working memory capacity.[37] While all students benefit from a teacher-directed phonics approach, it is even more essential for those entering school with lesser reading ability. At the same time, those with better initial performance can speed through phonics training and go on to flourish under whole-language instruction.[38] Again, as students gain mastery, the instruction can shift to more independent, student-directed approaches.

The challenge, of course, is that a typical classroom contains students with a hodgepodge of working memory capacities. The typical mixed teachconscious to volunteer—are left out. The remaining, less motivated students simply seize the opportunity to tune out.

What to Do

Have students individually work through the faulty sentences on their own. Students need private think time to give it an initial try. Afterward, have students compare their responses with a partner. This collaboration increases student accountability and provides a motivating social aspect to the often bland editing exercises.

Bonus Ideas

Provide students with plenty of practice and immediate corrective feedback. As you walk around the classroom, pay attention to students having difficulties as well as to those who have mastered the rules. You can differentiate future sentences to match your students' varying abilities. For example, students who have mastered using commas in a series may be ready to detect comma use (and abuse) before and after appositive phrases.

As your students struggle on their own to identify the errors in the faulty sentences, you may wish to point out that when they were watching you, *they were putting the errors and rules in working memory*—not long-term memory.* That is why working an example themselves can be such a struggle when they first try. (This relates to an important topic in learning called *desirable difficulty*, which we'll explore in depth in chapter 6.) Students will know they have mastered the rules of writing when they don't even have to think about those rules (they've gained *automaticity*).

As students become more and more comfortable with the rules your exercises reinforce, it is time for even more independent practice outside your direct eye. Remember to mix up the types of mistakes students have encountered throughout the year, not just throughout the unit. This provides both *interleaving* and *spaced repetition*—we'll discuss both in chapter 6.

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* And maybe, as we'll see in the next chapter, into the index-links of the hippocampus and faintly into the neocortex.

Generalizing the Principles

Error analysis can be applied to all sorts of subjects.[42] The teacher fixes a faulty example for students while verbalizing her thought processes. She then provides students with error-ridden examples to fix themselves and supervised time for shared practice with corrective feedback. Differentiate examples to challenge the race-car and hiker learners' levels of ability. All these activities help the material to stick in students' long-term memory.

During the lesson, stay vigilant and work with students who need extra support. Before assigning practice homework problems, make sure students achieve proficiency under your watchful eye. When students do not have a solid foundation, homework becomes frustrating for students and parents alike.