Learning Engineering Toolkit

Evidence-Based Practices from the Learning Sciences, Instructional Design, and Beyond

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Chapter 2

Learning Engineering Applies the Learning Sciences

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CHAPTER 2

Learning Engineering Applies the Learning Sciences

by Jim Goodell, Janet Kolodner, and Aaron Kessler

Learning engineering is a process and practice that **applies the learning sciences** using human-centered engineering design methodologies and data-informed decision-making to support learners and their development.

In 1928, Alexander Fleming discovered the miracle drug penicillin. That scientific discovery had limited value to humanity until, more than a decade later, the chemical engineers at Pfizer developed a process to make penicillin available to the masses. The medical breakthrough took both scientific discovery *and* innovations in engineering to produce the drug at scale.

In 1967, the father of learning engineering Herb Simon wrote, “learning is a complex psychological process, and it would be naïve to think that anyone can design an effective learning environment and an effective program of learning experiences for students without a mastery of what is known, scientifically and practically, about that process.”[1]

While the twenty-first century has been called the “golden age for brain research,” many learning science discoveries have yet to be applied at scale. Formalizing the tools and practices of learning engineering as a profession might create the opportunity for us to move from the “golden age for brain research” to the “golden age for human learning.”

This chapter examines some key concepts from the learning sciences. It includes closely related concepts about learning and the human *mind* (a conceptual model

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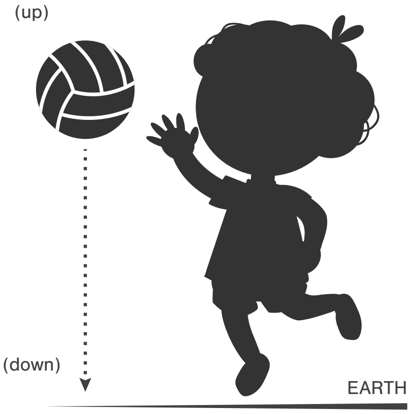

FIGURE 2.1. A simple conception of up and down

of how people think and learn) and concepts related to the *brain* (the physical and chemical aspects of the human nervous system that enable thought and learning). Some concepts apply to both the mind and the brain, even if just one of those words is used. Of course, this chapter only scratches the surface of what's known about how people learn. It's intended as a primer for those with backgrounds in other fields but who are entering the world of learning engineering, perhaps as part of a multidisciplinary team. It might also be a refresher for some with prior knowledge of the learning sciences.

[1]

Let's start with a fictitious story as we unpack how learning works. Mia is four years old, and her brother Kai is three. They're naturally curious and always learning. They learn by observing the world around them. They learn through play. They learn from interactions with their parents and other adults. They've both learned some basic notions of quantity. Mia learned from her mom how to count ten blocks. Kai so far can count to three, and Mia is helping him as they play with blocks. They're also exposed to educational media such as *PBS Kids* and recent iterations of the preschool classic *Sesame Street.*

Mia and Kai have imperfect understandings of the world. They observed how gravity works by dropping food from their highchairs and then by falling down when trying to walk. They assume that the world is flat and that things and people can fall down. Their concept of gravity is something like the idea shown in Figure 2.1.

Both have learned how to recognize a circle, and Mia understands that a circle is round. So, when someone tells Mia that the world is round, she fits

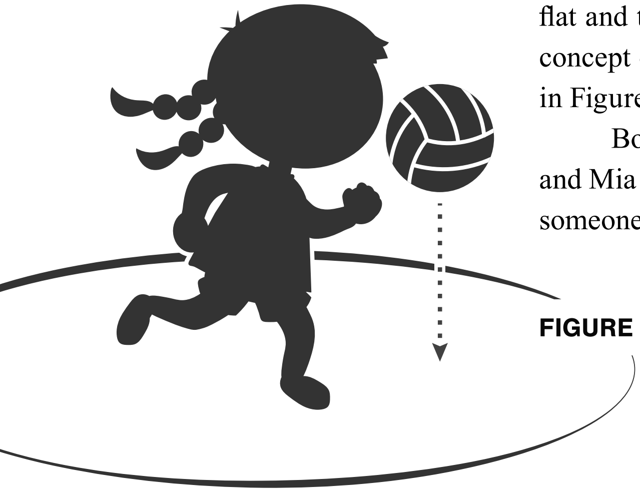

FIGURE 2.2. "Round" earth conception

this new information as best she can into what she already knows. Combining the concepts of *down* and *round* might look like the idea in Figure 2.2.

It's actually quite complex to come to the understand that *down* depends on where you are on earth, and cognitive scientists and educational psychologists have done much research to learn how to help children who are having difficulty grasping that idea.[2] It won't be until years later that Mia understands the concept of a spherical earth or the force of gravity, even as imperfectly conceptualized in Figure 2.3.

But it's not only children who have to make sense of new ideas and concepts, and it's not only children who have difficulty grasping the complexities and nuances of new concepts. Adults, as well, are continually adjusting our **mental models** (or "schemas" or "internal models") to refine our understandings of concepts and to accommodate new discoveries. For example, learning engineering professionals need to be life-long learners who make it their business to always be up to date on what's known about how people learn—continuously updating their understanding so that they can design the most effective learning experiences and conditions.

Indeed, gaining **expertise** is the process of constantly reworking one's mental models. The more varied experiences someone has had with some idea, the more chance that person has had to add complexity and nuance to their mental models. We recognize someone as an expert when they've organized and filled their mental models so well that they can figure things out faster than others and when they can use their mental models to figure out things others can't. We'll explore expertise in more detail later in this chapter; for now, the important thing to recognize is that becoming an expert requires more than just memorizing more facts. Experts think differently than novices because they've developed better mental models. As learners move from novice to expert, they are continuously reconstructing their understanding, reorganizing knowledge into categories, and connecting new ideas to previously learned concepts.

Throughout this chapter we'll follow Mia and Kai as they develop a deeper understanding

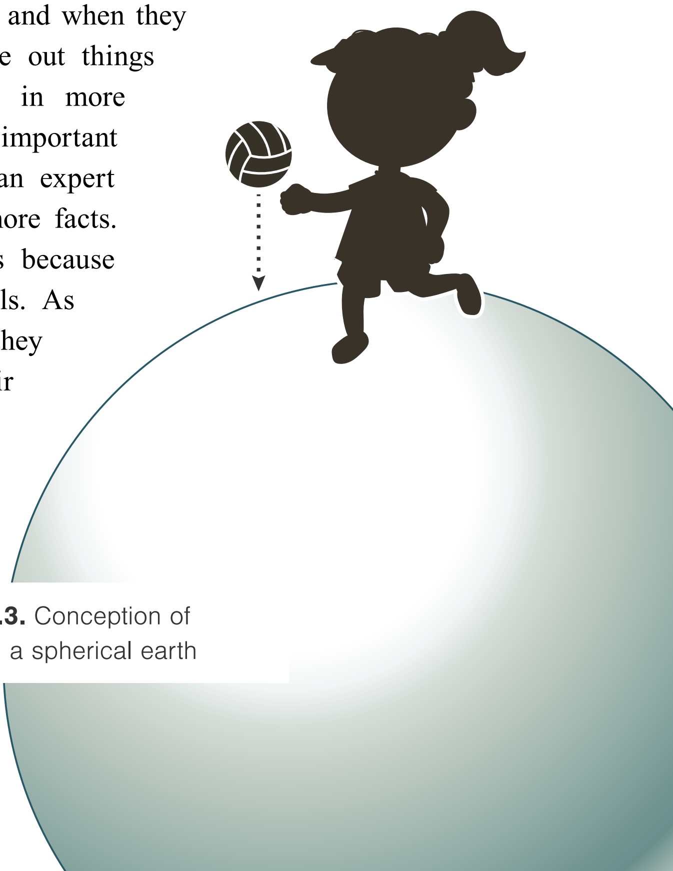

FIGURE 2.3. Conception of gravity and a spherical earth

of the world in which they live by perfecting their mental models through formal and informal learning experiences.

[2]

EXPERTS DON'T JUST KNOW MORE.

THEY KNOW DIFFERENTLY.

Novice learners, in any new domain, start with an incomplete and imperfect understanding. Learning and practice build new connections and replace others, gradually improving their understanding and ways of organizing the concepts.

As Mia enters elementary school, she has a foundational understanding about how addition works based on her background knowledge about quantity derived from, for example, her time spent playing with blocks. She understands the concepts of *more* and *less*. Counting sets of blocks may have also helped her build an understanding of the concept of multiplication, and that puts her at an advantage over children who try to learn multiplication as simply a set of facts. Mia has a deeper understanding of the concept of multiplication, which builds a foundation for more advanced mathematics learning. In contrast, a child who only memorizes a script of multiplication tables probably won't have the necessary conceptual understanding needed to move on to more advanced topics.

Despite Mia's early experiences with basic arithmetic, her mental model is imperfect, and it'll be challenged later in elementary school when learning new concepts such as negative numbers. For example, she understands that taking away two blocks from three blocks leaves one block.

But she's confused by a subtraction problem that would result in a negative number:

She thinks, *you can't take away three—because there's only two!* Negative numbers don't make sense when your mental model is based entirely on counting blocks. Mia will experience **cognitive dissonance** when a new concept contradicts her existing understanding of the world. “Cognitive dissonance refers to a situation involving conflicting attitudes, beliefs, or behaviors. This produces a feeling of mental discomfort leading to an alteration in one of the attitudes, beliefs, or behaviors to reduce the discomfort and restore balance.”[3]

Mia’s fourth- or fifth-grade teacher will need to help her transform and refine her existing concept of *quantity* into a more sophisticated form that includes negative numbers. Cognitive scientists would say this is refining an imperfect mental model of how the universe works so that it’s more accurate and consistent with new experiences.[4] As this description implies, the idea of mental models recognizes that people construct small-scale internal models of the world and of their places in it.[5] Old ideas can combine with new ones to improve upon a naïve or imperfect understanding or ability.[6] No one can know all things, so we do our best to create those internal representations and then fill in the gaps to make sense of what we already know or eventually learn. Children learning the concept of negative values must, in a sense, build in their mind an improved internal model so they can better understand how quantity works in the real world. As they adjust their mental models, new connections are formed in the structures of the brain. In the case of learning to add and subtract, the new mental model must eventually work for both positive and negative quantities.

How can we help learners develop better mental models? One way is by helping them recognize a connection to something else they’ve already learned or experienced. For instance, Mia had a mental model of fractional quantities from when she baked snickerdoodle cookies with her grandma and measured a half cup of flour. That experience helped her when it was time to learn fractions. Before learning about negative numbers Mia had played “store” and acted out not allowing her brother Kai to buy a plastic food item because he didn’t have enough money. She told him he needed to “go to work” and earn two more dollars, and then he would have enough. She understood that money is used to buy things and that a person can only buy something if they have enough money. She modeled in play with her brother what she had observed from the adults in her life, who had to go to work to earn more money.

If the teacher picks up on this tangible example rooted in Mia’s prior conception of the world, then it’s a short way from there to making the connection to negative numbers (as useful for expressing how much more of something, like money, that someone needs). Another student in her class may also have played store but in a less sophisticated way that didn’t get into figuring out the difference between how much more someone needs to buy something. For that student, the prior knowledge

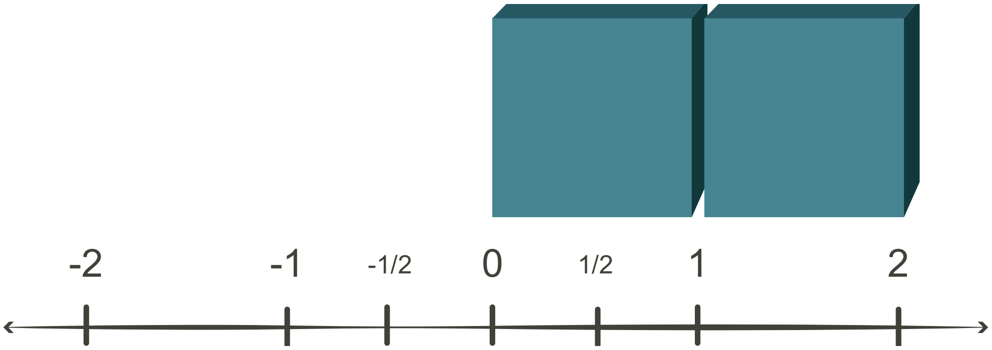

FIGURE 2.4. The child exposed to a number line is given a new mental model allowing negative numbers and fractional quantities to make sense alongside prior knowledge of whole number quantities

gained from play may not be a sufficient anchor for the new concept. As we'll explore later in this chapter, developmental factors also affect this. A learner may not be developmentally ready to grasp a new concept.

Teachers may also help Mia and her classmates expand their mental models by using a number line as shown in Figure 2.4 (above). First the positive side of a number line is used to help children understand whole numbers and fractional quantities. Later the negative side is used to introduce the concept of negative numbers. The number line introduces fractional quantities and then negative numbers in a way that makes sense alongside well-established concepts of positive whole number quantities from playing with and counting blocks. With the number line model, addition and subtraction of positive integers still works, but children can begin to grasp more advanced concepts like negative numbers and fractions.

[3]

Cognitive science defines categories of learning processes. Each can lead to different kinds of knowledge changes and, ultimately, to robust learning outcomes. Cognitive learning categories include:[7]

- Understanding and sense making
- Induction and refinement
- Memory and fluency building

Across all of the categories, an important component for learning is **constructive feedback**. Feedback gives learners information about the quality of their ideas and performance that they can use to make adjustments, and effective feedback is specific, understandable, timely, non-threatening, and actionable.

In the 1940s, Dutch chess master and psychologist Adriaan de Groot wanted to find out why world-class chess masters outperformed their challengers. He showed world-class masters and less experienced—but still extremely good—players examples of chess games and asked them to think aloud as they chose the moves they would make. "DeGroot's hypothesis was that the chess masters would be more likely than the non-masters to (a) think through all the possibilities before making a move and (b) think through all the possible countermoves of the opponent for every move considered."[8] He was wrong.

His research found that the world-class experts were able to recognize patterns of information that the extremely good players couldn't see. More recent research has discovered that information is organized differently in an expert's brain and chunked together in ways that allow them to solve problems. "DeGroot concluded that the knowledge acquired over tens of thousands of hours of chess playing enabled chess masters to out-play their opponents. Specifically, masters were more likely to recognize meaningful chess configurations and realize the strategic implications of these situations; this recognition allowed them to consider sets of possible moves that were superior to others."

In his best-selling book *Outliers: The Story of Success,* Malcolm Gladwell popularized the idea that those who are the best in the world—at everything from music to computer programming—have probably spent ten-thousand hours practicing and developing their abilities.[9] He makes a case that the 1960s rock band, The Beatles, had ten-thousand hours of deliberate practice before becoming worldwide superstars. There's nothing scientific about the number "ten thousand," but there is science behind the idea that to become highly skilled in any profession requires deliberate practice with feedback. Of course, there are those who have practiced music, a sport, or chess for more than ten-thousand hours and haven't become superstar musicians, Olympic athletes, or world champion chess players. Some of the differences may be influenced by innate abilities or disabilities relevant to the given domain. For example, it's harder for someone under six feet tall to become an NBA basketball player when competing against others over seven feet tall. (Although players like Isaiah Thomas, at five feet and nine inches, show that sometimes shorter people *can* train their body and mind to become among the best in the world!)

Very often it's not inherited ability or disability that keeps the novice musician, basketball player, or mathematician from becoming an expert. Moving toward expertise can be held back by a lack of foundational knowledge, lack of interest, faulty mindsets about what's possible, lack of a sufficient level of focus or intensity of deliberate practice, or lack of the right formative feedback.

A person must learn the basics before attempting to learn the advanced concepts in most knowledge domains, and they also must develop connections with:

1. the *contexts and practices* in the world in which the knowledge is intended to apply,
2. *core concepts* that serve to organize and make sense of the knowledge, and
3. the *representations and ways of communicating used by experts* in the domain.[10]

Early introduction of these connections can build bridges to higher levels of learning and ultimately to transfer of learning. **Transfer** is one of the characteristics of expertise; it's the ability to extend knowledge, reapplying it to new contexts or new kinds of problems. Transfer involves a variety of steps, including recognizing the potential fit, figuring out the correspondences, making the mapping, and adapting the *old* into the *new.* This is easier or harder depending on **reflection** done in earlier situations, the specifics of existing mental models, and the connections among those mental models.

[4]

Fredrick Reif was a physics teacher at the University of California who shifted his interest from research in physics to research on thinking and learning in complex domains. He joined Carnegie Mellon University in 1969. His 2008 book, *Applying Cognitive Science to Education,* was dedicated to the memory of his friend and colleague, the father of learning engineering, Herb Simon. In the book, Reif advocated for "a truly scientific approach to education" that strives to better understand "the underlying human thought processes and knowledge required for good performance" in particular domains. "Such an approach would then deliberately exploit an understanding of these underlying mechanisms to help students learn."

Technological advances in the way we study and explore the brain have discovered that "the brain is a dynamic organ, shaped to a great extent by experience—by what a living being does and has done."[11]

We now know that neural pathways in the brain are continuously being formed based on life experiences. Learning organizes and reorganizes your brain, changing its physical structure. This and other breakthrough findings direct us to think differently about teaching and learning, about the structures and culture of current systems, and about the practices and processes of education and training.

How Your Brain is Wired

The "wiring" of your brain is shaped by experiences that determine both the behavior of individual brain cells (neurons) and the network of connections among them. Figure 2.5 shows the structure of a neuron.[12]

You can think of a neuron as the basic wiring of the brain, with inputs controlling outputs. Like how an electrical circuit for a light may have a switch (input) that controls whether the light is on or off, each neuron may have inputs in the form of chemical stimuli from the nervous system that result in output conditions. If you turn on a light switch (the input) something happens at the output, the light bulb illuminates as shown in Figure 2.6.

A slightly more complex circuit has two double-pole switches controlling one light, like when there's one light switch at the top of a set of stairs and one at the bottom. If the light is off, switching the position of either of the switches will turn it on.

An electrical circuit with multiple switches is a helpful mental model for beginning to understand the underlying principles of the neuroscience of learning. Each neuron is wired to react to a combination of inputs. A certain set of inputs, in the form of chemical or electrical messages, will trigger the neuron to "turn on" outputs. Through experiences and effort, learners' brains change. Learning builds new connections and changes how individual neurons respond to stimuli. This "rewiring" improves the memory recall and capability of the brain.

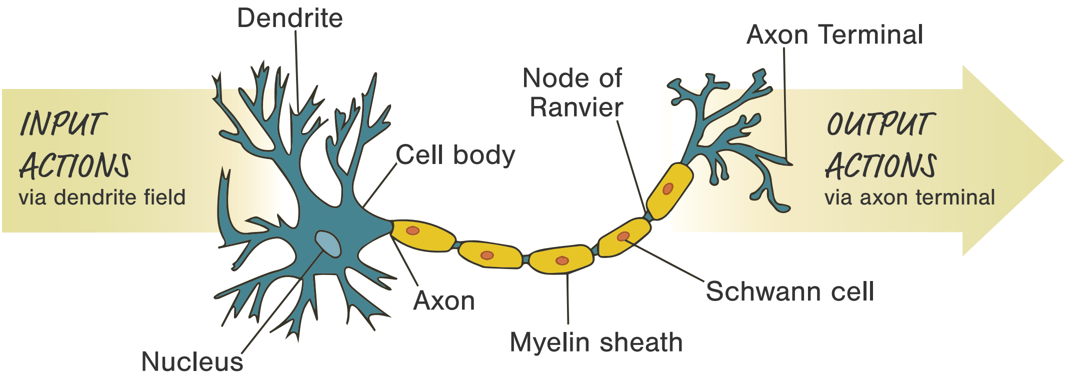

FIGURE 2.5. Function of a neuron

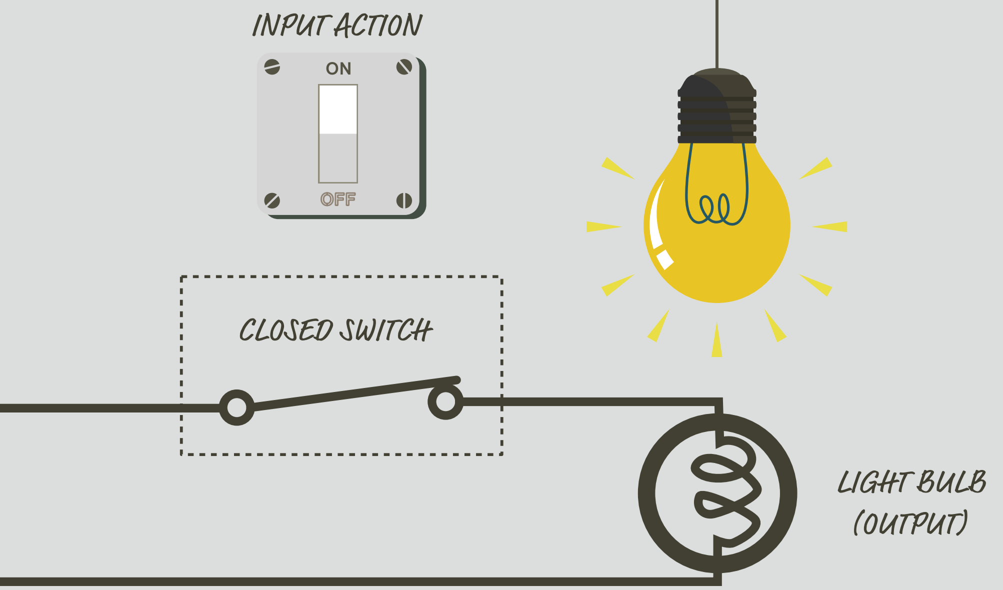

FIGURE 2.6. A simple single switch circuit: Closing the switch turns on the light

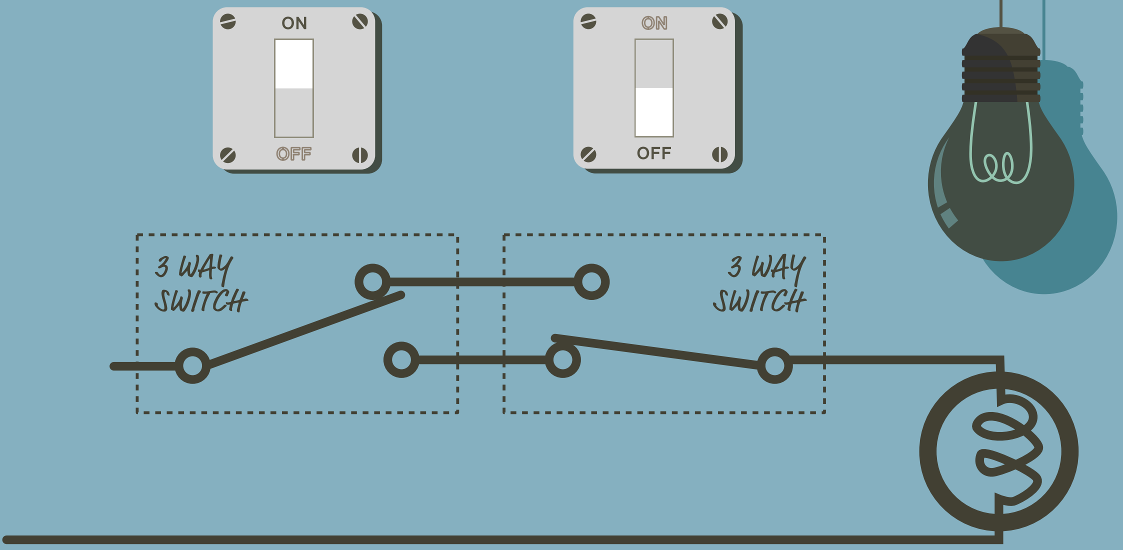

FIGURE 2.7. Three-way switch: Changing the position of either changes the light's state

You don't need to be a neuroscientist to do learning engineering, but it's essential to have some basic notions about how people learn. For example, with the knowledge that learning experiences make structural changes to the brain, learning engineering teams can approach their problem solving unconstrained by old notions that human brains are fixed in structure and capacity. As Channa Cook-Harvey, senior researcher at the Learning Policy Institute, explains:

> The brain and the development of intelligences and capacities are plastic and malleable. The brain develops over the entire lifespan as a function of experiences that activate neural pathways which permit new kinds of thinking and performance. The kinds of experience matter greatly. Relationships also matter greatly for learning.[13]

There is no learning from scratch. Learning is an active process in which a learner constructs meaning by mapping new information onto prior knowledge. As we experience life, our minds try to fit new information into what we already know about the world. Learning works best when we have the background knowledge that helps us make sense of the new information. Learning doesn't work well if the prerequisite knowledge on which to anchor the new knowledge is missing.

FIXED BRAIN NOTION	PLASTIC BRAIN NOTION
Some people are intelligent, some are not	A person can learn (almost) anything with the right conditions, experiences, and will
Fixed curriculum (variable outcomes)	Adaptive learning experiences (fixed objectives)
Fixed pace (some will get it others never will anyway)	Get prerequisite "structure" in place before moving on
Instructor led	Student centered
Uses primarily established pedagogy and andragogy	Considers all approaches, conditions and experiences that might lead to the desired learning objectives

FIGURE 2.8. Comparison of fixed brain vs. plastic brain notions

We used the example of a light switch to introduce the concept of how a neuron works because we assumed some readers wouldn't have prior knowledge of neurons or brain chemistry but that all readers would have experience with light switches. (Ideally, we would have assessed your prior knowledge, left out concepts that you didn't need to learn, and left in just enough for you to anchor new knowledge to existing knowledge. But the book format is limiting. It doesn't adapt and personalize the learning experience to optimize your learning outcomes.)

The wiring of a light switch is only an imperfect model of how a neuron works. A neuroscientist reading this might object to the analogy and point out the ways in which such a simple and concrete model is wrong. Similarly, a cognitive scientist may feel that the cognitive science concepts presented later in this chapter are oversimplified. Novice learners, in any new domain, start with incomplete and imperfect understanding.

[5]

In our fictitious story about Mia and Kai we examined an example of how shallow conceptual understanding of quantity, from counting blocks and playing store, can be enriched by helping learners expand and refine their mental models. We've looked at a shallow conceptual model for how the brain works, building new connections based on existing structures. This notion of "building on what exists" is foundational, and it's a concept shared by neuroscience and cognitive science.

In the early twentieth century, Soviet psychologist Lev Vygotsky theorized that people learn best within the **zone of proximal development**—that sweet spot just beyond what a person can do on their own but not beyond what they can do with help.[14] That is, learning tends to work best when learners are challenged beyond their current levels of development by just the right amount. As a person learns, the zone moves, and they can engage in more advanced learning.

In other words, productive learning requires that learning activities are

FIGURE 2.9. Zone of proximal development

continually at the proper level of difficulty. Tasks that are too difficult are frustrating and impossible to connect with prior knowledge, and tasks that are too easy have no challenge in them and often result in boredom. In between these two extremes lies what cognitive scientists call "**desirable difficulty**."

When activities remain at the desirable level, learners have the opportunity to experience **flow**. Psychologist Mihaly Csikszentmihalyi called flow an optimal condition that "can result in deep learning and high levels of personal and work satisfaction."[15] Said another way, the right level of challenge keeps learners engaged and focused.

One way to help learners find the right level of desirable difficulty is to provide the proper scaffolding. **Scaffolding** creates support while recognizing a learner's roles in their own learning process.[*] Scaffolding provides the structure they need to successfully engage in, and learn from, more complex tasks than they could otherwise handle. Scaffolding includes hints, prompts, conceptual frameworks (like advance organizers), process support, focus support, and strategic guidance. The goal is to provide just enough support to make tasks achievable without losing useful complexity or context.

Most adults are already familiar with scaffolding. Parents often scaffold learning for their infants in ways similar to those used by effective educators.[16] For example, they may:

- arrange the environment to promote learning,
- give cues to guide understanding about how to behave in new situations,
- use labels to classify objects and events,
- frame or model language and behavior,
- help the child connect a new situation to a more familiar one,
- interest the child in the task,
- reduce the number of steps required to solve a problem,
- maintain pursuit of a goal by directing activity and motivational feedback,
- control frustration and risk, or
- demonstrate an idealized version of the act to be performed.

The list above gives examples of supporting knowledge and skill as well as frustration and motivation. Some scaffolding focuses on cognition, such as making

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[*] *A popular misconception is that the function of education is to pour information into the learner's mind. The truth is that learning takes focused effort on the part of the learner. Learning doesn't happen without some level of effort or attention.*

a task easier for a learner. Other scaffolding can focus on, for example, drawing a learner into a task, sequencing steps for desirable challenge, or creating structure to help a learner reach their objectives.

Not only must a learner be an active participant for effective learning, what a learner thinks about themselves—and about learning—makes a difference. Helping learners understand that many aspects of successful learning, such as strategy and effort, are under their own control fosters a sense of **self-efficacy**. And a related concept for learning engineering is **learner agency**, the "methodological development of both the capacity and the freedom of learners to exercise choice regarding what is to be learned and to co-create how that learning is to take place."[17] Learner agency assumes that learners have some role in:

- Setting goals
- Initiating action toward those goals
- Reflecting on and regulate progress toward those goals

Like many aspects of learning engineering, there are trade-offs in balancing the benefits of learner agency with the agency of education and training providers. Later in the chapter we will explore the importance of cultural contexts for learning, including the role of a safe environment and nurturing relationships. When learners feel safe, they're more likely to see failure as an opportunity to find out what they still need to learn and adjust learning strategies; that is, learners are more likely to persevere.

[6]

Let's fast-forward in the lives of our fictional learners Mia and Kai. Mia is entering middle school, and Kai is in elementary school. Mia is an 'A' student and an avid reader. She loves reading mysteries, and her favorite subject is mathematics.

Kai has had some difficulty in the early grades. The policy and culture of the school tends to support a teach-to-the-middle approach; it doesn't optimize the learning experiences based on the learner variability, and Kai isn't an average student. His abilities and disabilities don't fit the teach-to-the-middle approach. He takes longer to do writing assignments and is a slow reader. He developed faster than his peers in other areas such as executive function, deeper understanding of mathematics concepts, and critical thinking, but the grading system didn't reflect those abilities. **Executive function** is the group of complex mental processes and cognitive abilities needed for goal-directed behavior.[18]

For Kai, it was frustrating every time the teacher said, “time’s up; turn in your assignment,” when he was half finished, but he struggled through it for several years, doing just well enough to get average grades.

By fifth grade, he was at risk of needing to repeat the year. He was struggling with reading, writing, and memorizing math facts. Until then, he was able to fumble along, eking out passing grades in the mold of group instruction. However, one incident in fifth grade brought the disconnection between the instructional model and Kai’s learner differences to a head. The teacher wrote on the board several columns of facts for the class to transcribe and then, presuming the class was done with the first column, erased it to write more facts. Kai wasn’t finished with the first column. The teacher noticed this time that Kai was frustrated and struggling—not lazy.

Kai was diagnosed with a learning disability and given some extra help with reading. Still, most of the time he was stuck in the fixed-pace and non-differentiated group instructional model.

One bright spot in this part of Kai’s life was playing chess. It was something he could feel good about. His uncle taught him the basics of the game, and he was able to beat his sister Mia most of the time, even though she was a year older and “smarter” (meaning she did much better in school). For Kai, chess was challenging but not frustrating.

[7]

Learning is dependent on cognitive capacities such as attention, executive function, working memory, and processing skills. Cognitive science research on grandmaster chess players and other experts helps us understand how the expert brain can do things faster and easier than novices. It also helps us understand how novices can become experts. The difference between a novice and an expert brain has a lot to do with how each uses two kinds of memory:

- **Short-term, working memory** is slower, error prone, more deliberate, has limited retention, requires greater mental effort, and is the place where new learning starts.
- **Long-term memory** has long retention, is efficient, operates automatically (without effort), and when trained error-free; it’s what experts use to do complex tasks effortlessly.

Both kinds of memory are used to make sense of new information. Experts, however, have been able to rewire their brains over time so that long-term memory can make sense of, and act on, even very complex information without consciously thinking about it.

Renowned psychologist Daniel Kahneman in *Thinking, Fast and Slow* describes two systems that drive the way we think. System 1 that uses long-term memory is fast, intuitive, and emotional. System 2 is slower, more deliberate, more logical, lazier, and easily distracted.[19]

SENSORY MEMORY	WORKING MEMORY (SYSTEM 2)	LONG-TERM MEMORY (SYSTEM 1)
👁 👂 ☝ Combining senses, e.g., audio and visual, aids memory	• Short retention • Verbal, conscious • About 5 things at once • Slow • Error prone • Highly flexible • Can generate new insights • More discriminating	• Long retention • Nonverbal, not conscious • Highly parallel • Fast • Error-free recall (with training) • Rigid (decisions must “fit”) • Biased (doesn’t challenge what seems to “fit”)

FIGURE 2.10. General comparison of memory types

Figure 2.10 illustrates the relationship among working memory, long-term memory, and sensory memory. **Sensory memory** is very short-term retention of impressions of sensory information such as seeing an image or hearing a sound. That sensory information may be passed easily to working memory (conscious memory) if used for immediate processing. With effort (practice, study) a learner may move information from working memory to long-term memory. This multi-store or modal model of memory was first proposed by Atkinson and Shiffrin in 1968.[20]

A novice chess player uses System 2 and working memory to try to think about the consequences of each move, two or three moves out. This is hard work. It creates what cognitive scientists call cognitive load. On the other hand, using System 1, an expert chess player can recognize patterns automatically and with far less cognitive load. This pattern recognition gives the expert a kind of intuition to sense the level of risk and opportunity of a given move.

Working memory—where new learning starts—has limited capacity and requires greater mental effort. **Cognitive load** is the effort used in working memory. In some cases, a heavy cognitive load can impede learning. **Cognitive load theory** suggests that learning experiences should be designed so that they don’t overload working memory.

Another kind of cognitive load has to do with the number of sensory inputs a person has to process at a single moment. It's more difficult to think and learn in a chaotic and distracting environment or when too much information is presented for processing at once. A novice chess player sees the position and rank of up to thirty-two pieces on the sixty-four squares of the board as separate inputs. The expert has learned to see patterns that *chunk* information to be processed as fewer sensory inputs.

Building expertise takes deliberate practice with feedback. Newly learned skills or knowledge are generally forgotten over time if not reinforced with practice and applied. Even if the goal were only to pass a test, cognitive science has found that short practices spaced out over time are better for learning than cramming. Spaced learning or the spacing effect and related findings about the lag time in between practice sessions (lag effect) helps inform mathematical models for optimizing the amount and frequency of practice a learner needs to gain and retain knowledge.

> The **spacing effect** is the observation that people tend to remember things more effectively if they use spaced repetition practice (short study periods spread out over time) as opposed to massed practice (for example, cramming). The phenomenon was first documented by Ebbinghaus (1885), using himself as a subject in several experiments to memorize verbal utterances. In one study, after a day of cramming, he could accurately recite twelve-syllable sequences (of gibberish, apparently). However, he could achieve comparable results with half as many practices spread out over three days.
>
> The **lag effect**[21] is the related observation that people learn even better if the spacing between practices gradually increases. For example, a learning schedule might begin with review sessions a few seconds apart, then minutes, then hours, days, months, and so on, with each successive review stretching out over a longer and longer time interval.[22]

Different kinds of learning, such as learning a word in a new language versus learning how to solve a kind of mathematical problem, may have different optimum practice schedules. The best time to practice is when you're on the verge of forgetting, but that time may be different for every new word you're trying to learn or every step in a procedural process. A learner can't possibly keep track of when they're on the verge of forgetting every possible thing they want to retain, so learning engineers develop solutions that use **formative assessments** to help keep track and schedule practice for them.

Building expertise is about making new mental models, and spaced learning is about making what you know more accessible; *retrieval practice* combines the two. After many hours of practice, the expert brain is *conditionalized* to recognize and respond[23] effortlessly.[24] The expert mind also has developed more sophisticated mental models for addressing novel problems. The chess master recognizes a pattern and knows what to do based on the patterns wired into long-term memory. This quick retrieval of relevant information from long-term memory is effortless, not necessarily faster; experts might take longer to answer a question because they want to fully understand a problem. The same kind of process applies to learning to read, learning to code, or becoming a star athlete.

> Learning high-level chess can be compared to learning to read. A first grader works hard at recognizing individual letters and assembling them into syllables and words, but a good adult reader perceives entire clauses. An expert reader has also acquired the ability to assemble familiar elements in a new pattern and can quickly “recognize” and correctly pronounce a word that she has never seen before. In chess, recurrent patterns of interacting pieces play the role of letters, and a chess position is a long word or sentence.[25]

At the most basic level, learning engineering is about facilitating this overall learning process—helping a learner move from novice to a greater level of expertise for any given skill, knowledge, or ability.

[8]

Carnegie Mellon University professor Ken Koedinger is an inventor of intelligent tutoring software for mathematics, founder of the Pittsburgh Science of Learning Center known as LearnLab, and co-founder of Carnegie Learning, Inc.[26] His work builds from John Anderson’s ACT-R theory of cognition (adaptive control of thought–rational), a theory for simulating and understanding human cognition. Anderson’s theory, in turn, builds from the work of Allen Newell and Herbert Simon, who received the Association for Computing Machinery’s A. M. Turing Award in 1975 for contributions to artificial intelligence and the psychology of human cognition.

Influenced by generations of thought leaders at the roots of learning engineering, Ken developed the **Knowledge-Learning-Instruction (KLI) Framework**[27] with Albert Corbett and Charles Perfetti. It helps people apply cognitive science research to practice. (See Figure 2.11.)

A **learning sciences framework** like KLI organizes discrete facts from the learning sciences into a model that can be practically applied in the design of learning experiences and solutions. It recognizes that we can't know exactly what thought process is going on inside a learner's head. However, we can build an approximate model of what a person knows and how they think by measuring how they respond to specific prompts. The more precisely we can define what a learner knows, the better we can measure their strengths, weaknesses, specific knowledge, and skill gaps. With that and other data, we can infer what conditions and experiences might help that learner fill those gaps.

One of the authors interviewed Ken in his office at the Human Computer Interaction Institute in Newell-Simon Hall on the Carnegie Mellon University campus. (The building was named after Herb Simon and his colleague Allen Newell, both pioneers in artificial intelligence and the psychology of human cognition.)

"From my experience," Ken said, "you can't just take the science and apply it. There are a lot of decisions I'm making for which science provides me little to

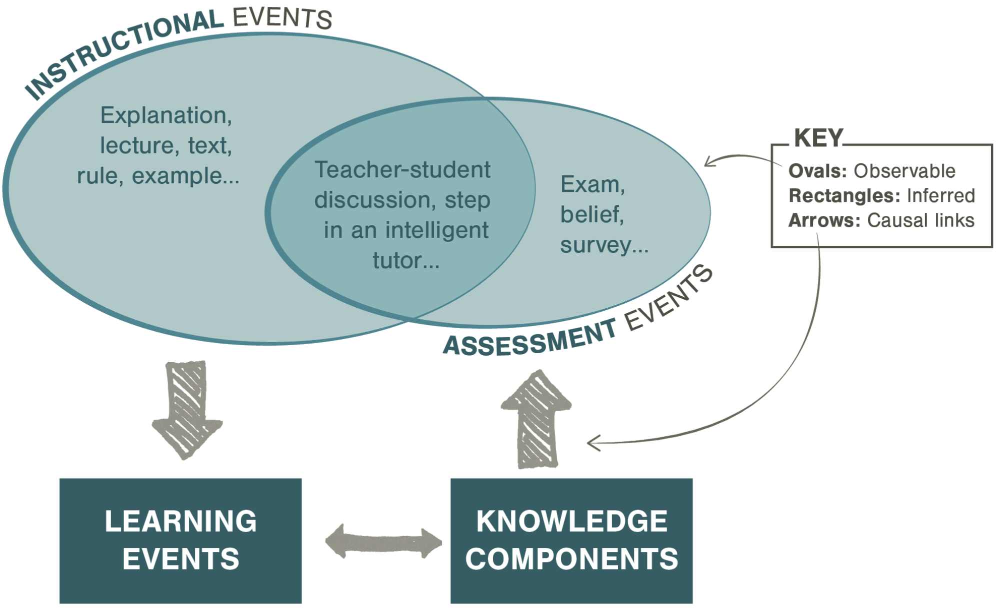


FIGURE 2.11. The KLI Framework defines observable instructional and assessment events, and unobservable learning events. Knowledge components are the competencies that cause learner performances, which can be observed/measured with assessment events.

no guidance. So that led me to believe, well, maybe I can do some of my own little studies on these and then other times we'll just guess. And then, when we had the opportunity to test whether those guesses worked, maybe 50 percent of the time—maybe—they did."

The KLI Framework defines observable **instructional** and **assessment events** as well as unobservable **learning events**. Performances observed and measured with assessment events tell us something about a person's learning.

Instructional events are changes in the learning environment or learner experiences intended to cause learning events. Sometimes an assessment event is an instructional event, such as with formative assessments where the learning measures are instrumented into the learning experience, for example, tracking what a learner does during an online simulation or instrumented classroom activity. Other times, an assessment event is just an assessment.

KLI identifies three broad classes of learning events:

1. memory and fluency processes,
2. induction and refinement processes, and
3. understanding and sense-making processes.

Different learning events call for different kinds of learning experiences. Learning experiences can include externally directed **formal** instructional and assessment events or learner-directed **informal** events. Mia and Kai playing store was an observable informal learning experience that led to an unobservable learning event (Mia gaining conceptual understanding of negative numbers).

If the goal is to help learners rewire their brains to know, think, and perform closer to the way that an expert thinks and performs, then a learning engineering challenge is to understand what's going on inside expert brains when they demonstrate a complex skill or ability. What facts do they use? What mental strategies do they employ? What does mastery look like? It turns out this is a big challenge because experts often can't tell you why they know something or how they get something done. Experts conditionalize their mental processing to be automatic. Expertise is often wired so deeply into long-term memory (the System 1 brain) that to the expert it may seem like intuition. *They just know the answer!*

Another problem is that experts tend to forget how their brains worked as novices. Ken Koedinger and his learning scientist colleagues call this the **expert blind spot** in which "advanced content knowledge without well-developed knowledge of the learning and teaching of novices can lead to expert-based views of curricula that are at odds with the learning process." Their research showed that "people with greater expertise tend to make assumptions about what novices know that turn out to be in conflict with students' actual performance and developmental propensities."[28]

The learning sciences community that discovered challenges such as the expert blind spot also developed processes for unpacking expertise and understanding what competencies learners must develop on the path toward it. Here, a **competency** defines any skill, knowledge, ability, attitude, habit of practice, or disposition that a person can possess. Broadly defined, it's any learning outcome.

Learning engineering can take advantage of methodologies developed by learning scientists to unpack competency definitions to an atomic level. This allows us to develop finely grained assessment items and learning supports based on the set of competencies that make up complex tasks. This level of specificity makes it possible to use observable instructional and assessment events to infer learning events (unobservable changes in a learner's brain that impact performance).

In KLI, an atomic competency definition is called a **knowledge component**. Competency definitions can be defined at a higher level of granularity for assessing complex tasks that involve coordination or synthesis of many knowledge components. However, best practices for formative assessment call for unpacking that competency definition into its parts and designing assessment items or performance tasks with scaffolding, such as hints, that also measure those more granular components. If a learner doesn't succeed with a complex learning task, the more granular items can be used to discover the root cause of the failure, for example, which knowledge components need further development and support.

Competency definitions used for purposes such as job descriptions or academic standards are necessarily defined broadly and leave room for interpretation. For example, an academic standard for mathematics specifies that a student should be able to "solve word problems involving addition and subtraction of fractions referring to the same whole, including cases of unlike denominators." A job description may include the requirement that the candidate has "knowledge of arithmetic, algebra, geometry, calculus, statistics, and their applications."[29]

Learning engineering calls for competency definitions with data-justified specificity, meaning we want to be able to prove that the competency is at the atomic level with data. A common mistake is to assume a competency definition addresses a single measurable skill when it represents two or more skills that need to be further unpacked to be reliably taught or assessed.

To get to well-defined competency definitions with data-justified specificity we can employ two sets of approaches:

1. The first approach is a systematic process to understand the cognitive elements of a more broadly defined competency. One such methodology is called **cognitive task analysis**.
2. The second tool is a data analytics methodology using student learning data to either validate or discover the human errors inevitably in the initial version of a set of competency definitions.

Learning engineers assume that the first draft of a set of competency definitions won't be perfect. Data expose those imperfections and allow us to iteratively fix competency assumptions as well as fix any learning activities and assessment items that were designed to teach or assess based on those flawed competency definitions. A story in Chapter 6 covers **learning curve analysis**, one data analytics method used to check assumptions about data-justified specificity.

[9]

Our fictitious characters Mia and Kai are now in college. Mia is studying cybersecurity, a good fit for her, inspired by her love for mystery novels and proficiency in mathematics.

Kai realized sometime along the way that he didn't fit the mold of school but he could learn to be successful academically. Sometimes that involved figuring out for himself a mental workaround, such as on-the-fly calculating a math fact that he hadn't memorized or visualizing a problem in a different way for deeper understanding rather than just using the rote method presented by a teacher or textbook. Although he struggled with reading as a child, his reading fluency grew with practice, and motivated by natural curiosity, he grew to love reading. He learned to love history, especially figuring out what circumstances affect other circumstances. He reads history well, now, because he has enough understanding of factors that might affect other factors to draw inferences as he reads. He had to spend a lot of time working on developing that competency.

By developing his **metacognitive strategies**—that is, actively reflecting on and adapting his own mental processes—Kai was able to overcome what was diagnosed as a learning disability when he was younger. In fact, he's found that his learning differences and metacognitive strategies often put him at an advantage over his peers. He excels in some areas, such as chess and other strategy games.

While Kai had to overcome some differences that didn't fit the mold of school, some apparent learning struggles that children have early on when compared to peers may be due to normal development. Children progress developmentally at different paces. If you plan to develop learning solutions for specific age groups, it's helpful to understand something about how the brain develops and functions at different stages of life, from birth through late adulthood. Figure 2.12 shows stages of brain development over the course of human life.

We previously discussed how the brain is wired and how learning, in a sense, rewires your brain. **Neuroplasticity**, also known as brain plasticity or neural plasticity, is the ability of the brain to change throughout an individual's life.[30] At the single cell level, synaptic plasticity[31] refers to changes in the connections between neurons, whereas non-synaptic plasticity[32] refers to changes in their intrinsic excitability, for example, how responsive they are to the chemical signals they receive.[33] The structure of the brain can change throughout life but may be more "plastic" during developmental periods from prenatal to early 20s. For more detailed explanations of what researchers have discovered about changes that occur with age and learning across the life span, see *How People Learn II.*[34]

[10]

As an adult, Mia is a cybersecurity expert for the Institute for Defense Analyses, an American nonprofit corporation that helps the US government address national security issues. Part of her success is that in addition to being a subject-matter expert, she's an expert life-long learner. Like many professions in the twenty-first century, Mia's job requirements for what she has to know and be able to do change continually.

Learning works best when the learner has "learned how to learn" and takes an active role in the learning process. Learning how to learn includes developing knowledge about learning strategies and practicing skills that apply those strategies. It also involves developing productive mindsets (what the learner thinks about learning) and dispositions, including habits of practice. People can learn to become **expert learners**. As an adult, Kai is an expert learner and historian working as a strategy analyst for governments and corporations.

Learning to learn often involves so-called **noncognitive factors**. A report by the University of Chicago Consortium on Chicago School Research identified five noncognitive factors:[35]

<table>
<tr>
<td>The PRENATAL brain develops new neurons, synapses, and myelinated axons at an astounding rate. At birth it has more structural elements than it needs.</td>
<td>The brain increases fourfold during PRESCHOOL YEARS and by age six is about 90% of adult brain volume. Synaptic connections (gray matter) and myelination of nerve fibers (white matter) dramatically increase. Growth and synaptic pruning are shaped by experiences.</td>
<td>Explosive growth continues AGE SIX TO ADOLESCENCE offset by synaptic pruning. The structure of the brain is shaped by experiences.</td>
<td>Growth and pruning continues from ADOLESCENCE TO EARLY ADULTHOOD. The brain reaches a size of about 86 billion neurons and 84 billion non-neuron cells.</td>
<td>The ADULT BRAIN continue to add and maintain synapses and generate myelin in response to new learning. As the adult learner acquires new knowledge, regions of the cortex develop specialization of function known as experience-dependent learning.</td>
<td>LATE ADULTHOOD is associated with declines in memory, speed of cognitive processing and ability to learn new information. However, it is associated with increased skill in solving social dilemmas.</td>
</tr>
<tr>
<td colspan="4">Synaptic Pruning (birth to mid-to-late twenties)—use it or lose it! During this period the brain lets some synapse connections die off while adding and strengthening others. Synapses continually used are retained, those that are not used are eliminated. Both axon (transmitter) and dendrite (receiver) completely decay and die off. This sculpting of the brain improves the networking capacity of the brain and is associated with a heightened ability to learn. Some of the most significant “brain remodeling” happens during adolescence from pruning and the laying down of myelin sheaths that make the transfer of information about 3,000 times faster for those connections. Through practice the learner’s brain lays down myelin to enable a skill.</td>
<td colspan="2">Effects of aging on the brain: The outer layer of the brain (cortex) starts to thin after age forty. It is not clear if this means a decrease in brain tissue or is the result of some other factor such as lower hydration. It does, however, seem to correspond to the start of cognitive decline often observed in older adults. Older adults are more likely to remember the important implications of an event while younger learners will likely remember more details about the event. Conditions such as life satisfaction and having strong social networks can reduce the speed of age-related cognitive decline.</td>
</tr>
</table>

FIGURE 2.12. Life-long brain development

CC-BY Jim Goodell

Sources: (a) Siegel, D. J. “Dr. Dan Siegel - BRAINSTORM: Brain Remodeling, Pruning and Myelin.” November 8, 2013. Video, https://youtu.be/s_MJg5zofOo. (b) Siegel, D. J.” Pruning, Myelination, and the Remodeling Adolescent Brain.” Psychology Today, February 4, 2014. (c) How People Learn II. (ibid.) (d) O’Rourke, M., Gasperini, R., & Young, K. M. (2014). Adult Myelination: Wrapping up Neuronal Plasticity. Neural Regeneration Research, 9(13), 1261–1264. https://doi.org/10.4103/1673-5374.137571.

1. Academic Behaviors
   Going to class, doing homework, organizing, participating, studying
2. Academic Perseverance
   Grit, tenacity, delayed gratification, self-discipline, self-control
3. Academic Mindsets
   I belong in this academic community. My ability and competence grow with my effort. I can succeed at this. This work has value for me.
4. Learning Strategies
   Study skills, metacognition, self-regulated learning, goal-setting
5. Social Skills
   Interpersonal skills, empathy, cooperation, assertion, and responsibility

These factors point to learning-to-learn competencies that can be developed in and by learners. Learning engineering teams should keep in mind that productive mindsets and behaviors can be reinforced or undermined by their designs. Helping learners understand that many aspects of successful learning, such as strategy and effort, are under their own control fosters agency to learn. A productive mindset may be encouraged by giving process-focused feedback in an environment that treats mistakes as an opportunity to reflect and learn.

Not only is it important what the learner thinks about learning in general. It's also important how the learner thinks about their own learning while learning. **Metacognition** is thinking about one's own thinking; it's where learners actively reflect on activities and their own mental processes.

Metacognition in learning includes knowledge of one's own learning strengths and weaknesses as well as the demands of the learning at hand. It also includes self-regulation—the ability to correct errors when appropriate and the ability to reflect on one's own learning.[36] Learners need insight into their own learning before they can effectively plan or self-regulate.

Metacognition is often a learned behavior; it doesn't come naturally to everyone. Learners may not be aware of their own internal dialogue or how important it is for the learning process unless explicitly taught to attend to it. Like other learned behaviors, that internal dialogue is influenced by culture and previous experiences, and the type of self-monitoring that's most productive will vary by academic or professional discipline.

Scaffolded metacognition as learners are learning may prompt them to reflect on or articulate what and how they're learning. *Did I already know that? How would*

I explain that to someone else? Does it conflict with what I thought I knew or thought I could do? How well do I know this? How well do I know how to do this? On what parts of this do I need help or more practice?

> An emphasis on metacognition must accompany instruction in each of the disciplines because the type of monitoring required will vary. In history, for example, the student might be asking himself, "who wrote this document, and how does that affect the interpretation of events," whereas in physics the student might be monitoring her understanding of the underlying physical principle at work.[37]

When designing learning experiences, it's equally important to understand subject-matter experts' internal dialogue and to model that thinking for novices. Such domain-specific thinking supports domain-specific **chunking** (sorting and grouping of knowledge into long-term memory). Learning engineering teams can bundle a learning experience with metacognitive coaching and modeling, such as contextually appropriate conceptual frameworks and reflective exercises. This can help learners recognize and evaluate their own conceptualizations or practices.

In August 2020, Laura Fries, Ji Li Son, Karen Givvin, and James Stigler published the paper "Practicing Connections: A Framework to Guide Instructional Design for Developing Understanding in Complex Domains." Based on what research suggests about how experts are able to organize and connect chunks of knowledge, they suggest a practical framework for helping learners practice connections:

> The building blocks of this transferable knowledge, sometimes referred to as schemas [or mental models], emphasizes the connections between abstract relations (such as hierarchies, embedded categories, and functional systems) rather than lists of discrete facts and procedures. For example, expert physicists' schemas for a range of problems situations are organized by fundamental relationships [for example, the relationship of work to energy] rather than by superficial surface-level details specific to problem contexts. Experts also have fewer and more interconnected schemas.

To help learners think more like experts, the authors suggest incorporating features of scaffolding and instruction that explicitly prompt learners to build connections between a domain's core concepts, key representations of those concepts, and the contexts and practices in the world, for example, how physics is used in the real world by physicist and engineers.

[11]

Mia and Kai each had individual experiences that led to their own learning as well as shared experiences and cultural influences that likely had some common impact on those unique journeys. Every experience that a learner has influences their brain and their ability to learn new things. At a macro level, the culture in which the learner is situated can also impact learning—in positive and negative ways. **Culture** refers to the shared beliefs, social forms, and material traits of a racial, religious, family, or other social group; and the integrated pattern of human knowledge, belief, and behavior that depends upon the capacity for learning and transmitting knowledge to succeeding generations.[38]

> Learning does not happen in the same way for all people because cultural influences pervade development from the beginning of life. – *How People Learn II* [39]

The bottom line is that people bring a set of beliefs, behaviors, motivators, feelings, prior knowledge, prior misconceptions, and mindsets to every new learning experience, and these are influenced by the experiences formed in the communities in which they live. People can compartmentalize their cultural identities, adopting more than one set of cultural norms. For example, a student may reflect one set of behavioral habits and beliefs when in a school or work setting and a different set at home. However, while this tendency to compartmentalize may be helpful to counteract negative external influences on learning, it can also hinder the transfer of learning to new contexts.

Learning takes place within a social context. Even independent learning where a learner isn't interacting with another person is influenced by social and cultural expectations. Remember, there's no learning from scratch. Mia's understanding of elementary school mathematics was shaped by her prior experiences of playing with blocks and playing store.

> An individual's development is affected by the environment in which she lives—including not only the family and other close relationships and circumstances but also the larger contexts in which families and communities are situated.[40]

In addition to culture, the contextual conditions during learning experiences matter. Disruptions, such as forced remote learning in 2020 due to the COVID-19 pandemic, can have positive impacts for some learners and negative impacts for others. Learning engineering includes creating conditions that promote learning. That goes beyond just creating instructional materials. Some learning engineering challenges involve creating an appropriate culture and context of learning within an institution, organization, or school.

- Does the learner feel safe?
- Is the learner hungry, too cold, too hot, sick, stressed?
- Is the environment distracting?

The conditions don't need to be perfect, and the environment doesn't need to be comfortable for people to learn. Air conditioning and three meals a day aren't prerequisites. However, a person experiencing severe hyperthermia or malnutrition probably will need some food and a lower body temperature before doing any productive learning.

Similarly, while stress is a necessary and important factor in human development, chronically high levels of stress, without buffering, derail healthy brain development and impact school and work performance.[41] In the wake of the September 11, 2001 attacks on the United States, Pamela Cantor co-authored a study that found more New York City school children were traumatized by their experience of growing up in poverty than by what they had witnessed on that terrifying day. Her organization, Turnaround for Children, applies learning science to help schools counter such negative influences. According to Cantor, "It's impossible to feel curious, for example, while also feeling threatened." The good news, she says, is that science also tells us that the brain is malleable and given the right environment, children and adults can learn the skills and mindsets for success in learning and in life.

[12]

The **learner model** is a dynamically updated profile of the learner used for diagnosis, feedback, coaching, and prescription of learning activities. In one-on-one tutoring, the tutor mentally constructs a learner model based on observations and interactions with the student. Data-driven learner modeling in adaptive instructional systems similarly uses student interaction data to build explanatory models of a learner's cognition, metacognition, and motivation. No matter the time in their life, this type of adaptive data-driven support could have provided both Mia and Kai with the types of feedback and learning experiences that would have better supported their individual and collective learning journeys.

Teachers, tutors, learning coaches, and adaptive learning systems can provide good guidance and feedback when they understand where a learner is on the pathway toward mastery, what misconceptions they have, and where there is room for improvement. The right kind of observation and measurement gives the visibility needed to optimize feedback.

> **Data-driven learner modeling** is "use of student interaction data to build explanatory models of elements of learning (e.g., cognition, metacognition, motivation) that can be used to drive instructional decision-making toward better student learning."[42]

A learner model includes not only information about a learner's progress but insights into the learner's thinking, knowledge gaps, and misconceptions. A study of middle school physical science teachers found "that teachers who know their students' most common misconceptions are more likely to increase their students' science knowledge than teachers who do not."[43]

Likewise, learning experiences can be engineered to approximate what's going on inside the learner's mind and respond accordingly. Platforms like Duolingo use data about the difficulty of a task in combination with learner model data to predict the likelihood of a learner answering the next prompt correctly.

Gaining visibility into learner mastery and misconceptions often is achieved through formative performance assessments. A best practice is to embed continual measurement of learning within learning activities rather than present assessments as separate events. Great teachers, tutors, and intelligent tutoring systems first determine if the learner's response indicates mastery of a competency, and then if not mastered, they use follow-up assessment items or metacognitive activities to unpack the misconception or imperfection in the learner's thinking. With this information the tutor or system can provide the right kind of feedback and follow-on learning activities.

To reach this granular level of understanding—this level of visibility into learners' thinking—requires well-defined competency definitions and a well-defined knowledge base of what can go wrong for learners in mastering each competency.

It's not enough to know if a learner understands or can do something. We also want to know how well they can use their competence to address new kinds of problems (transfer) and how well they've retained their competence for long-term use. We also want to know what barriers exist, blocking the way to mastery, and what possible strategies might overcome those obstacles. Similarly, because part of the journey from novice toward some level of expertise involves the learner's ability to think about their own thinking (and to regulate their own learning), learner models can also contain estimates of learners' metacognitive skills, mindsets, motivations, attitudes, and anything else that impacts learning.

[13]

In summary, the learning sciences form the bedrock of learning engineering. They guide its theories and practices and provide an initial blueprint for designing learning experiences. But as important as the learning sciences are, remember the lesson from the story of penicillin discussed in the introduction: it takes more than scientific discovery to produce innovation at scale.

> Efforts to design effective learning environments and activities cannot be based solely on scientifically validated theories of learning: theoretical advances are often too slow in coming, too blunt, and too idealistic. Engineering and other design-based approaches use faster methods of testing innovation. Design-based approaches are goal directed and contextualized and often employ frequent, formative assessments as part of iterative design-implement-evaluate-redesign methods. This allows for highly responsive, evidence-based course corrections so that it is possible to realign solutions to suit local constraints and to resolve on-the-fly decisions that are underspecified by prevailing scientific models.[44]

Engineers look at everything as a system, and while the learning sciences provide the basis for learning engineering, alone they're not sufficient. Read on, to learn more about how the learning sciences join with the other sub-disciplines of learning engineering to create a complete system. ★

- Many learning science discoveries aren't yet applied at scale.
- People build mental models (also called schemas), which are internal representations of the world. Expertise is the process of continually improving these and connecting different mental models together.
- There is no learning from scratch. All learning builds on prior knowledge and experiences, and these are influenced by culture and context.
- Learning is different for everyone, and different topics and developmental levels call for different kinds of learning activities.
- Optimal learning takes place when the difficulty level is just right. By adding scaffolding (like hints), learners can complete activities they couldn't otherwise. That's when some of the best learning takes place.
- Cognitive factors, such as executive function and metacognition, affect learning. Executive function is related to working memory—or System 2, the more deliberate kind of memory.
- Using working memory takes effort. It creates cognitive load. Too much cognitive load can interfere with learning.
- Over time, experts learn to rely more on the mental models stored in their long-term memory—System 1, the faster, automatic memory.
- Knowledge, skill, dispositions, habits of practice, and even intelligence are trainable to a significant and meaningful degree.
- You can learn to be an expert learner.
- Metacognition refers to "thinking about thinking." Metacognitive skills, like self-regulation, can be learned, and it greatly improves learning outcomes.
- We can't see inside learners' heads to know if they're learning, but we can build learner models from assessments, which let us infer those unobservable learning events. These models can be "built" in a teacher's mind or via data-driven computational methods.
- Learning is different for everyone.

LEARNING ENGINEERING APPLIES THE LEARNING SCIENCES

KEY POINTS

Endnotes

1 Simon, Herbert A. "Job of a College President." *Educational Record 48,* no. 1 (1967): 68–78.

2 Duschl, Richard A. *Taking Science to School: Learning and Teaching Science in Grades K-8.* Washington, DC: The National Academies Press, 2007. https://doi.org/10.17226/11625

3 McLeod, Saul. "Cognitive Dissonance." Simply Psychology. February 05, 2018. www.simplypsychology.org/cognitive-dissonance.html

4 Maskiewicz, April Cordero and Jennifer Evarts Lineback. "Misconceptions Are 'So Yesterday!'" *CBE Life Sciences Education,* 2013. www.ncbi.nlm.nih.gov/pmc/articles/PMC3763002

5 Johnson-Laird, PN. "The History of Mental Models." In *Psychology of Reasoning: Theoretical and Historical Perspectives,* edited by Ken Manktelow and Man Cheung Chung, 179–212. London: Psychology Press, 2004. https://doi.org/10.4324/9780203506936

6 Smith, John P., Andrea A. diSessa, and Jeremy Roschelle. "Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition." *The Journal of the Learning Sciences 3,* no. 2 (1993): 115–63. www.jstor.org/stable/1466679

7 Koedinger, Kenneth R., Albert T. Corbett, and Charles Perfetti. "The Knowledge-Learning-Instruction Framework: Bridging the Science-Practice Chasm to Enhance Robust Student Learning." *Cognitive Science 36* (2012) 757–798. https://doi.org/10.1111/j.1551-6709.2012.01245.x

8 Bransford, John D., Ann L. Brown, M. Suzanne Donovan, and James W. Pellegrino, eds. *How People Learn: Brain, Mind, Experience, and School.* Washington, DC: National Academy Press, 2003, 32. https://doi.org/10.17226/9853

9 Gladwell, Malcolm. "Complexity and the Ten-Thousand-Hour Rule." *The New Yorker,* August 21, 2013. www.newyorker.com/sports/sporting-scene/complexity-and-the-ten-thousand-hour-rule

10 Fries, Laura, Ji Y. Son, Karen B. Givvin, and James W. Stigler. "Practicing Connections: A Framework to Guide Instructional Design for Developing Understanding in Complex Domains." *Educational Psychology Review 33,* no. 2 (2020): 739–762. https://doi.org/10.1007/s10648-020-09561-x

11 Bransford et al., *How People Learn,* 115.

12 Adapted from Wikipedia, "Neuron," last modified August 7, 2011, https://commons.wikimedia.org/wiki/File:Neuron.jpg, and from US National Institutes of Health, "Nerve Tissue," https://training.seer.cancer.gov/anatomy/nervous/tissue.html.

13 Cook-Harvey, Channa. "The Science of Learning and Development and Its Implications for Transforming K-12 Education." International Association for K-12 Online Learning. Aurora Institute. May 2018. www.inacol.org/wp-content/uploads/2018/05/iNACOL-Leadership-Webinar-May-2018.pdf

14 In *Mind in Society,* Vygotsky defined the Zone of Proximal Development as "the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peer" (p. 86).

Vygotsky, Lev Semenovich, and Michael Cole. *Mind in Society: Development of Higher Psychological Processes*. Cambridge, MA: Harvard University Press, 1978.

As quoted from Shabani, Karim, Mohamad Khatib, and Saman Ebadi. "Vygotsky's Zone of Proximal Development: Instructional Implications and Teachers' Professional Development." *English Language Teaching 3,* no. 4 (2010): 237–248. https://files.eric.ed.gov/fulltext/EJ1081990.pdf

15 "Flow (Csíkszentmihályi)." *Learning Theories.* February 4, 2017. www.learning-theories.com/flow-csikszentmihalyi.html

16 Bransford et al., *How People Learn,* 104.

17 Poon, Jennifer Davis. "Part 1: What Do You Mean When You Say 'Student Agency?'" *Education Reimagined,* September 11, 2018. https://education-reimagined.org/what-do-you-mean-when-you-say-student-agency

18 Merriam-Webster. "Executive Function." Accessed November 27, 2021. www.merriam-webster.com/dictionary/executive%20function

19 Kahneman, Daniel. *Thinking, Fast and Slow.* New York: Farrar, Straus and Giroux, 2011, 20.

20 McLeod, Saul. "Multi-Store Model of Memory." Simply Psychology. January 1, 1970. www.simplypsychology.org/multi-store.html

21 Melton, Arthur W. "The Situation with Respect to the Spacing of Repetitions and Memory." *Journal of Verbal Learning and Verbal Behavior 9,* no. 5 (1970): 596–606.

22 Settles, Burr, and Brendan Meeder. 2016. "A Trainable Spaced Repetition Model for Language Learning." In *Proceedings of the 54th Annual Meeting of the Association for Computational Linguistics, Berlin, Germany, August 7–12, 2016,* 1848–1858. Stroudsburg, PA: Association for Computational Linguistics. https://aclanthology.org/P16-1174.pdf

23 IGI Global. "What is Conditional Knowledge." Accessed December 29, 2017. www.igi-global.com/dictionary/conditional-knowledge/5277

24 Bransford et al., *How People Learn,* 44–49.

25 Kahneman, *Thinking, Fast and Slow,* 238.

26 "Timeline of Cognitive Tutor History." Cognitive Tutor Authoring Tools: Timeline of Cognitive Tutor History. Carnegie Mellon University. Last modified 2015. http://ctat.pact.cs.cmu.edu/index.php?id=timeline

27 Koedinger, Corbett, and Perfetti, "The Knowledge-Learning-Instruction Framework."

28 Kessler, Aaron, Melissa Boston, and Mary Kay Stein. "Exploring How Teachers Support Students' Mathematical Learning in Computer-Directed Learning Environments." *Information and Learning Sciences 121,* no. 1/2 (2019): 52–78. https://doi.org/10.1108/ILS-07-2019-0075

29 "15-1132.00 - Software Developers, Applications." O*NET OnLine. US Department of Labor. www.onetonline.org/link/summary/15-1132.00

30 Goodell, Jim and Janet Kolodner. "Learning Sciences: Concepts for Learning Engineering." Prototype Card Deck Prepared for the IEEE ICICLE 2019 Conference on Learning Engineering. https://drive.google.com/file/d/13XqSu3BMMHWd0_pRut7cuoijG6vK1pHC/view

See also: Goodell, Jim and Janet Kolodner. "Learning Science Cards." In *Proceedings of the 2019 Conference on Learning Engineering,Washington, DC, May 20–23, 2019.* http://sagroups.ieee.org/icicle/wp-content/uploads/sites/148/2020/07/ICICLE_Proceedings_Learning-Engineering.pdf

31 Wikipedia. "Synaptic Plasticity." Last modified September 21, 2021. https://en.wikipedia.org/wiki/Synaptic_plasticity

32 Wikipedia. "Non-Synaptic Plasticity." Last modified November 16, 2011. https://en.wikipedia.org/wiki/Non-synaptic_plasticity

33 Wikipedia. "Neuroplasticity." Last modified December 8, 2021. https://en.wikipedia.org/wiki/Neuroplasticity

34 National Academies of Sciences, Engineering, and Medicine. *How People Learn II: Learners, Contexts, and Cultures.* Washington, DC: National Academies Press, 2018. https://doi.org/10.17226/24783

35 Farrington, Camille A., Melissa Roderick, Elaine Allensworth, Jenny Nagaoka, Tasha Seneca Keyes, David W. Johnson, and Nicole O. Beechum. 2012. *Teaching Adolescents to Become Learners: The Role of Noncognitive Factors in Shaping School Performance: A Critical Literature Review. Consortium on Chicago School Research*. Chicago, IL: The Chicago University Consortium on Chicago School Research. https://files.eric.ed.gov/fulltext/ED542543.pdf

36 Bransford et al., *How People Learn,* 97.

37 Bransford et al., *How People Learn,* 21.

38 "Culture." Merriam-Webster. Accessed November 18, 2021. www.merriam-webster.com/dictionary/culture

39 National Academies, *How People Learn II*, 22.

40 National Academies, *How People Learn II*, 21.

41 "The Science." Turnaround for Children. May 3, 2018. https://turnaroundusa.org/what-we-do/the-science

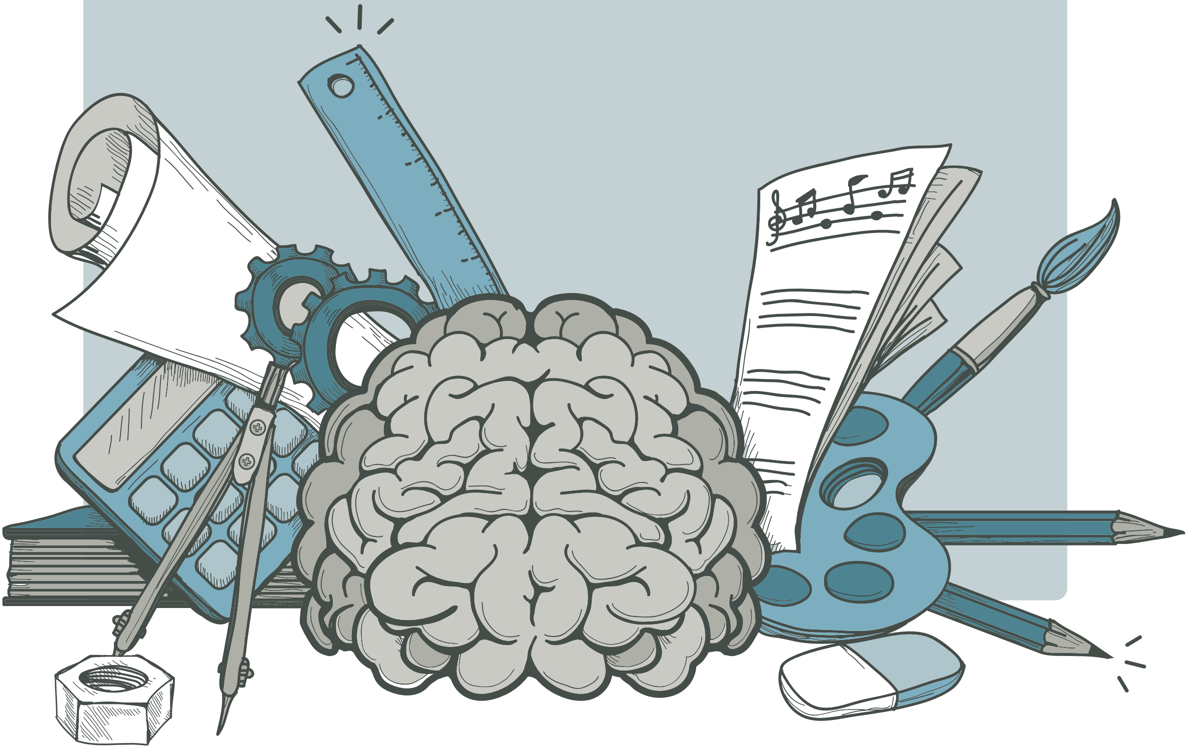
42 Koedinger, Kenneth R., Elizabeth A. McLaughlin, and John C. Stamper. "Data-Driven Learner Modeling to Understand and Improve Online Learning: MOOCs and Technology to Advance Learning and Learning Research." *Ubiquity,* May (2014): 1–13. https://doi.org/10.1145/2591682

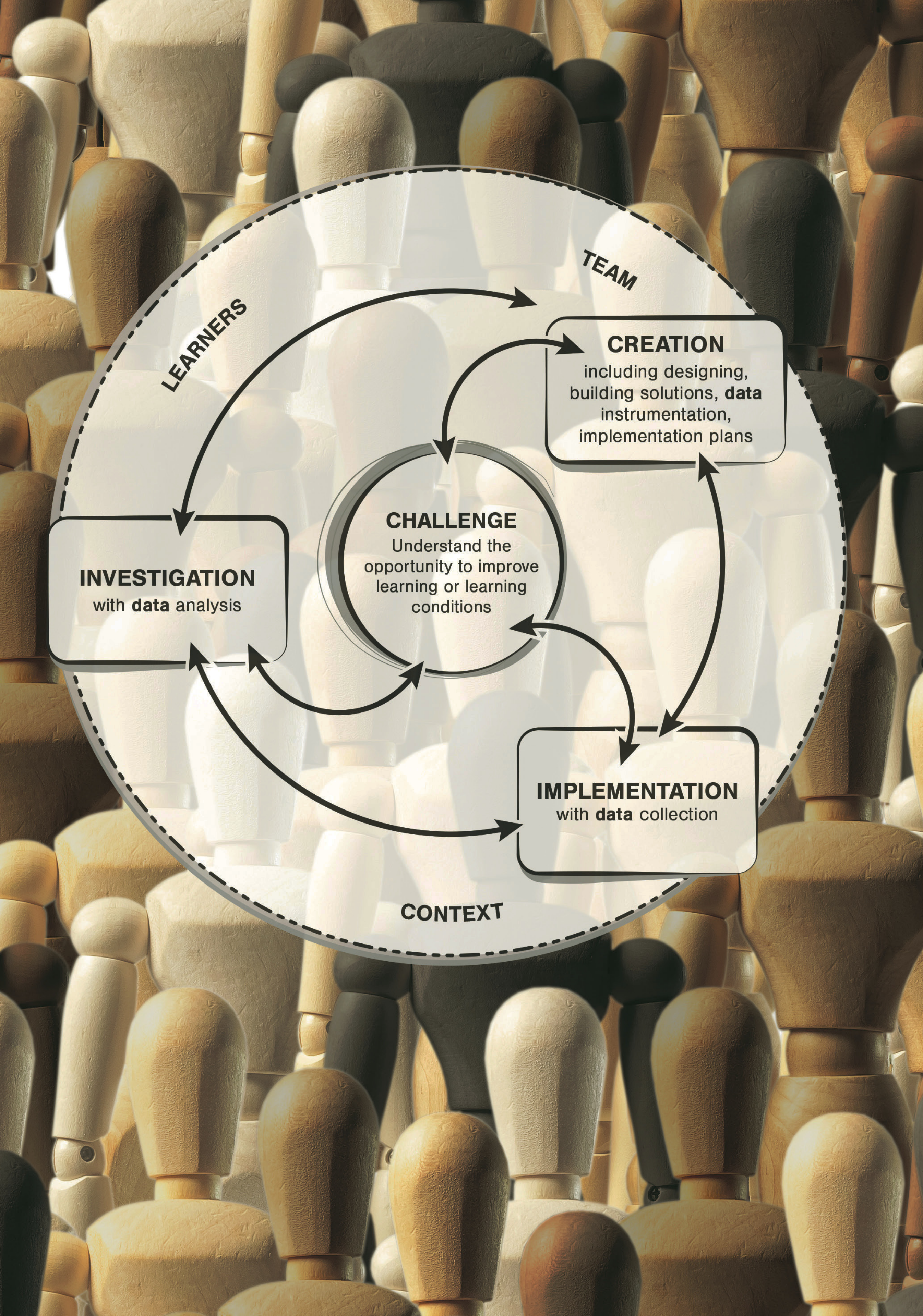
43 Sadler, Philip M., and Gerhard Sonnert. "Understanding Misconceptions: Teaching and Learning in Middle School Physical Science." *American Educator.* September 27, 2016. www.aft.org/ae/spring2016/sadler-and-sonnert

44 Sawyer, R. Keith, ed. 2014. *The Cambridge Handbook of the Learning Sciences.* Cambridge University Press, 23. https://doi.org/10.1017/CBO9781139519526

45 Closing quotation from Hess, Frederick M. and Bror Saxberg. *Breakthrough Leadership in the Digital Age: Using Learning Science to Reboot Schooling.* Thousand Oaks, CA: Corwin Press, 2013, 32.

> Trying to reengineer learning without being versed in the basics of learning is like trying to improve brain surgery without knowing much about the brain.
>
> – *Breakthrough Leadership in the Digital Age*[45]




LEARNERS
TEAM
CREATION
including designing, building solutions, **data** instrumentation, implementation plans
CHALLENGE
Understand the opportunity to improve learning or learning conditions
INVESTIGATION
with **data** analysis
IMPLEMENTATION
with **data** collection
CONTEXT