Ask the Cognitive Scientist: Inflexible Knowledge: The First Step to Expertise

By Daniel T. Willingham

Question: So often, even if I inventively present new material or emphasize applying the new knowledge in various situations, what I get back from my student seems "rote." Why is this? What can I do about it?

Answer: Cognitive science has shown us that when new material is first learned, the mind is biased to remember things in concrete forms that are difficult to apply to new situations. This bias seems best overcome by the accumulation of a greater store of related knowledge, facts, and examples. To understand this bias, we need to first distinguish between what I would call genuinely "rote" knowledge and the much more common "inflexible" knowledge. Second, we'll look at a number of experiments that strongly suggest the mind tends to remember new concepts in terms that are concrete and superficial, not abstract or deep. Third, we'll review experiments designed to illuminate the nature of expertise, which can be thought of as consisting of "flexible" knowledge. Fourth, we'll consider what this means for teaching.

What is Rote Knowledge?

Much of what is commonly taken to be rote knowledge is in fact *not* rote knowledge. Rather, what we often think of as rote is, instead, *inflexible* knowledge, which is a normal product of learning and a common part of the journey toward expertise.

In his book *Anguished English*, Richard Lederer reports that one student provided this definition of "equator": "A managerie lion running around the Earth through Africa." How has the student so grossly misunderstood the definition? And how fragmented and disjointed must the remainder of the student's knowledge of planetary science be if he or she doesn't notice that this "fact" doesn't seem to fit into the other material learned?

All teachers occasionally see this sort of answer, and they are probably fairly confident that they know what has happened. The definition of "equator" has been memorized as rote knowledge. An informal definition of rote knowledge might be "memorizing form in the absence of meaning." This student didn't even memorize words: The student took the memorization down to the level of sounds and so "imaginary line" became "managerie lion."

"Rote knowledge" has become a bogeyman of education, and with good reason. We rightly want students to understand; we seek to train creative problem solvers, not parrots. Insofar as we can prevent students from absorbing knowledge in a rote form, we should do so. I will address what we know about this problem, and how to avert it, in a future column.

But a more benign cousin to rote knowledge is what I would call "inflexible" knowledge. On the surface it may appear rote, but it's not. And, it's absolutely vital to students' education: Inflexible knowledge seems to be the unavoidable foundation of expertise, including that part of expertise that enables individuals to solve novel problems by applying existing knowledge to new situations—sometimes known popularly as "problem-solving" skills.

The Difference Between Rote and Inflexible Knowledge

Let's consider another example. In one of my classes, I teach the concept of classical conditioning. A student might memorize this definition: "Classical conditioning occurs when repeated pairing of an unconditioned stimulus (which leads to an unconditioned response) with a conditioned stimulus comes to elicit a conditioned response upon presentation of a conditioned stimulus." The student with rote knowledge might be able to produce the definition but would not understand it. This student, who learned the form without the meaning, wouldn't connect this definition to the familiar example: Pavlov's dog repeatedly hears a bell (conditioned stimulus) before getting food (unconditioned stimulus), whereupon the bell elicits salivation (conditioned response).

Another student might memorize the definition of classical conditioning and how each term (e.g., conditioned stimulus) relates to Pavlov's experiment (the conditioned stimulus is the bell). The student, therefore, understands the relationship of the terms (the dog salivates when it hears the bell because it expects the food). We would be more prepared to say that this student had learned the meaning of the term "classical conditioning," and that her knowledge was not rote.

Now suppose you present some new examples to the student:

1. Every time a red light comes on, I put water in the bowl of a thirsty cat. In time, the cat learns to approach the bowl when the light comes on. Is this classical conditioning?

2. Every time a rat pushes a button, it gets fed. In time, it learns to push the button when hungry. Is this classical conditioning?

3. To cure bed-wetting, I put a pad under a child's mattress attached to an alarm that is rigged to ring when the pad gets wet. In time, the child learns to wake up before the alarm goes off. Is this classical conditioning?

Most likely, she will confidently say that example one is classical conditioning (it is); will hesitantly say that example two is (it is not*); and will be stumped by example three (it is†). The student successfully recognizes example one, which is new to her, as classical conditioning. That seems to indicate that her knowledge is not rote. On the other hand, does the failure to recognize example three as classical conditioning mean that the student doesn't really get it? Has this student acquired mere rote knowledge?

No, the learning is deeper than rote knowledge defines. But at the same time, clearly the student has not completely mastered the concept. The characteristic of concern here is *flexibility*. Knowledge is flexible when it can be accessed out of the context in which it was learned and applied in new contexts. My student understands classical conditioning, and she understands the *meaning*, but this understanding is somehow tied to the surface features of the example learned: dogs, food, and bells. When I switch to bed-wetting, her knowledge is rendered unavailable.

Notice that inflexible knowledge is quite different than rote knowledge. Neither memorizing a definition as a string of words, nor memorizing "managerie lion," carries any accompanying meaning. In contrast, inflexible knowledge is meaningful, but narrow; it's narrow in that it is tied to the concept's surface structure, and the deep structure of the concept is not easily accessed. "Deep structure" refers to a principle that transcends specific examples; "surface structure" refers to the particulars of an example meant to illustrate deep structure. For example, the deep structure of commutativity in addition or multiplication is that order is irrelevant in these operations. One example of surface structure that captures this principle might be 3+4=7 and 4+3=7. Another surface structure would be 9+3=12 and 3+9=12. One could easily imagine that a student would recognize commutativity when presented with a number of problems in this form, but that student would not recognize, for example, that a cash register embodies commutativity because the order in which purchases are rung up is irrelevant to the total. Such a student has a narrow knowledge of commutativity. His knowledge is inflexible because it is tied to a particular type of surface structure.

I would argue that most of the time when we are concerned that our students have acquired rote knowledge, they have not. They have actually acquired inflexible knowledge.

All right. You may accept my argument that student knowledge is usually not so devoid of meaning as to be properly classified as rote. But isn't inflexible knowledge almost as bad? One point of education, after all, is to enable students to apply new learning to situations outside of the classroom, not simply to remember the examples learned in school. Mustn't we fight inflexible knowledge every bit as hard as we would fight rote knowledge?

Inflexible Knowledge is the Normal Foundation for Expertise

Flexible knowledge is of course a desirable goal, but it is not an easily achieved one. When encountering new material, the human mind appears to be biased towards learning the surface features of problems, not toward grasping the deep structure that is necessary to achieve flexible knowledge.

Here's an example of the inflexibility of newly learned knowledge from an experiment by Mary Gick and Keith Holyoke (1983). Subjects were asked to solve this problem:

> Suppose you are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed, the patient will die. There is a kind of ray that can be used to destroy the tumor. If the rays reach the tumor all at once at a sufficiently high intensity, the tumor will be destroyed. Unfortunately at this intensity the healthy tissue that the rays pass through on the way to the tumor will also be destroyed. At lower intensities the rays are harmless to healthy tissue, but they will not affect the tumor either. What type of procedure might be used to destroy the tumor with the rays, and at the same time avoid destroying the healthy tissue?

This problem is quite difficult, and only something like 10 percent solved it in the 15 minutes allotted. At the end of that time, the experimenters told all the stumped subjects the solution. The solution is to use a number of weaker rays coming from different directions, but all focused on the tumor. The weaker rays can pass through the healthy tissue, but they combine at the site of the tumor to destroy it. Next, the experimenter gave subjects this problem:

> A dictator ruled a small country from a fortress. The fortress was situated in the middle of the country and many roads radiated outward from it, like spokes on a wheel. A great general vowed to capture the fortress and free the country of the dictator. The general knew that if his entire army could attack the fortress at once, it could be captured. But a spy reported that the dictator had planted mines on each of the roads. The mines were set so that small bodies of men could pass over them safely, since the dictator needed to be able to move troops and workers about; however, any large force would detonate the mines. Not only would this blow up the road, but the dictator would destroy many villages in retaliation. How could the general attack the fortress?

The structure of the second problem and its solution has what seems like an obvious parallel to the first: The solution calls for the dispersal of strength with regathering of strength at the point of attack. And yet only 30 percent of subjects solve the second problem. It's not that subjects can't understand the analogy. By merely presenting the second problem with the instruction that the first problem may help, the solution rate for the second problem rockets to 90 percent. The difficulty students have is not in applying the analogy, but in thinking of using the analogy between the first and second problem. Why is this such a problem?

The reason is that people store the first problem in memory in concrete terms. The subjects take the first problem to be about rays and tumors, not dispersal and regathering of strength. The second problem is about armies and fortresses, and hence the rays and tumor problem doesn't come to mind as relevant. Note that the problem here is slightly different than in the classical conditioning problem. In the rays/fortress problems, the subject does not spontaneously think of drawing an analogy between the problems, but can easily draw the analogy if prompted. In the classical conditioning example, a new problem with different surface features (baby, alarm, waking) can't be mapped to an old problem (dog, bell, salivation) even when the student is prompted to draw the analogy. Thus, to apply old knowledge to new situations, one must both recognize that the analogy is appropriate and successfully map the new problem to the familiar problem. Knowledge is often inflexible because to be widely applicable, it needs to be stored in terms of deep structure, but people tend to store it in terms of surface features.

Can't We Teach Deep Structure Directly?

Inflexible knowledge might be normal, but its usefulness is limited. Can't we circumvent the mind's tendency to store information in terms of surface features and get students to learn the deep structure? As I've outlined the problem, the solution seems rather obvious. The difficulty is that problem solutions are stored in terms of the specifics of the problem (rays and tumor) instead of the deep structure (strength dispersal and regathering). So, to fight inflexible knowledge, it would seem that we should encourage students to think about material in deeper, more abstract terms, which will then generalize to other contexts.

This is a marvelous idea that cognitive scientists have tried to make use of many times. But, the problem with such direct instruction is that the mind much prefers that new ideas be framed in concrete rather than abstract terms. Consider this classic example (Wason, 1968). Each of the four figures below represents a card. There is always a letter on one side of the card and a number on the other side. Your job is to verify whether or not the following rule is true: If there is a vowel on one side of the card, then there must be an even number on the other side. What is the minimum number of cards you must turn over to test the truth of the rule?

A	**2**	**X**	**3**

The answer is that you must turn over the A card and the 3 card. Most people choose the A card, but most fail to select the 3. You must choose the 3 because if there is a vowel on the other side, then the rule has been violated. Something like 20 percent of college undergraduates get this problem right. The percentage goes up very little even when subjects have just completed a one-semester course in logic that includes learning the logical form *Modus Tollens*, on which this problem is based (Cheng et al., 1986).

Now consider another version. You are an officer at the border of a country. Each of the four cards that follow represents a traveler. One side of the card lists whether the person is entering the country or is in transit (just passing through). The other side of the card shows what vaccinations the person has received. You must make sure that any person who is entering the country is vaccinated against cholera (Cheng & Holyoak, 1985).

ENTERING	**TRANSIT**	**CHOLERA** **MUMPS** **TYPHOID**	**FLU** **MUMPS**

About which travelers do you need more information? You need to check the "entering" person (to ensure that he has the cholera vaccination), and you need to check the "flu mumps" person (to ensure that he is in transit).

This question has exactly the same formal structure (*Modus Tollens*) as the previous problem, but people are much more likely to get it right. Why? Because this problem has a concrete structure that makes sense—it doesn't use letters and numbers—and the rule about disease and entry is sensible, not arbitrary. The idea that the human mind prefers to consider novel concepts in concrete ways should ring true to every teacher. When presented with a new abstract idea or formula, students clamor for examples.

So How Does Inflexible Knowledge Become Flexible?

You can probably think of many instances where your own knowledge seems quite flexible. For example, if you know how to find the area of a rectangle, that knowledge is probably generalizable; you can apply it to any rectangle, and the formula is not tied to the specific examples in which you learned it. You think of using the formula in novel situations, such as determining the total square footage of a hallway, kitchen, and dining room. Why is this knowledge flexible?

Knowledge tends to be inflexible *when it is first learned*. As you continue to work with the knowledge, you gain expertise; the knowledge is no longer organized around surface forms, but rather is organized around deep structure. That principle was nicely captured in an experiment by Michelene Chi et al. (1981). She gave expert physicists and novices a set of physics problems and asked that they put them into categories of their own devising. The novices categorized the problems based on the surface features of the problems—that is, they formed one category for problems involving inclined planes, another for problems involving springs, and so on. The experts, however, created categories based on physical principles: one category for conservation of energy, another for Newton's first law of motion, and so on. Similar experiments, using knowledge of dinosaurs, have likewise shown that experts' memories are organized differently than novices', whether the experts are children or adults.

Inflexible Knowledge in Perspective

The examples above should put this problem of inflexibility in context. Understanding the deep structure of a large domain defines expertise, and that is an important goal of education. But if students fall short of this, it certainly doesn't mean that they have acquired mere rote knowledge and are little better than parrots. There is a broad middle-ground of understanding between rote knowledge and expertise. It is this middle-ground that most students will initially reach and they will reach it in ever larger domains of knowledge (from knowing how to use area formulas fluently to mastering increasingly difficult aspects of geometry). These increasingly large stores of facts and examples are an important stepping stone to mastery. For example, your knowledge of calculating the area of rectangles may have once been relatively inflexible; you knew a limited number of situations in which the formula was applicable, and your understanding of why the formula worked was not all that clear. But with increasing experience, you were able to apply this knowledge more flexibly and you better understood what lay behind it. Similarly, it is probably expecting too much to think that students should immediately grasp the deep structure beneath what we teach them. As students work with the knowledge we teach, their store of knowledge will become larger and increasingly flexible, although not immediately.

What Does This Suggest for Teachers?

1. Use examples: The fact that students seem to get stuck on examples does not mean that teachers should refrain from providing examples. Certainly, examples help students understand the abstract concepts and some researchers (e.g., Gick & Holyoak, 1983; Gentner et al., 1993) believe that by providing multiple examples, one encourages students to compare the examples and to thereby consider what they have in common; what they have in common, of course, is the deep structure we would like students to learn. Thus, it is probably helpful to tell them not just about

Pavlov's dog, but about a number of wide-ranging examples.

2. Make a distinction between rote and inflexible knowledge: This might be the most important point. Rote knowledge is meaningless. But inflexible knowledge is a natural consequence of learning. We should neither despair when it appears, nor take drastic measures to eliminate it when its elimination could cause collateral damage to our students (i.e., diminished factual knowledge).

3. Appreciate the importance of students' growing knowledge, even if it's inflexible: Don't be reluctant to build students' factual knowledge base. Some facts end up in memory without any meaning, and other facts have meanings that are quite inflexible, but that doesn't mean that teachers should minimize the teaching of facts in the curriculum. "Fact" is not synonymous with rote knowledge or with inflexible knowledge. Knowing more facts makes many cognitive functions (e.g., comprehension, problem solving) operate more efficiently. If we minimize the learning of facts out of fear that they will be absorbed as rote knowledge, we are truly throwing the baby out with the bath water.

4. Remember that inflexible knowledge is a natural step on the way to the deeper knowledge that we want our students to have: Frustration that students' knowledge is inflexible is a bit like frustration that a child can add but can't do long division. It's not that this child knows nothing; rather, he doesn't know everything we want him to know yet. But the knowledge he does have is the natural step on the road to deeper knowledge. What turns the inflexible knowledge of a beginning student into the flexible knowledge of an expert seems to be a lot more knowledge, more examples, and more practice.

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*Example two, rather, represents operant conditioning, in which the animal learns that an action on the environment (pressing the bar) has consequences (being fed) that change the probability of performing the action in the future. In classical conditioning, the animal learns that two stimuli (e.g., bell and presentation of food) are associated.

†The feeling of a full bladder (conditioned stimulus) becomes associated with the alarm (unconditioned stimulus), which causes waking (unconditioned response). With practice, the full bladder (conditioned stimulus) causes waking (conditioned response).

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About this column

How does the mind work—and especially how does it learn? Teachers' instructional decisions are based on a mix of theories learned in teacher education, trial and error, craft knowledge, and gut instinct. Such knowledge often serves us well, but is there anything sturdier to rely on?

Cognitive science is an interdisciplinary field of researchers from psychology, neuroscience, linguistics, philosophy, computer science, and anthropology who seek to understand the mind. In this regular American Educator *column, we consider findings from this field that are strong and clear enough to merit classroom application.*

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