by Jonah Lehrer • Posted July 19, 2006 12:32 AM

Credit: Adam Billyeald
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In 1982, when Maisha Moses was in middle school, her father Bob became her math teacher. Her public school didn't offer algebra, so Bob, who had studied the philosophy of math at Harvard, decided that he was going to teach the subject himself. Maisha was mortified. "I had the usual adolescent reaction," she remembers. "I was just so embarrassed that my dad was there." But her father wouldn't relent. Walking in to Maisha's Cambridge, MA classroom that first day, Maisha recalls, Moses assumed that teaching a few kids about quadratic equations would be relatively easy.

It wasn't. Moses quickly realized that most students couldn't grasp the basic concepts of algebra. "That first year was tough," Maisha says. "Your dad is teaching your friends, and your friends don't get what he's talking about. I mean, nobody likes learning algebra." Bob, too, could see the students were hopelessly lost. But he realized that the problem wasn't algebra, and it wasn't Maisha and her friends. It was the way they were being taught algebra.

Moses spent the next five years developing a completely new curriculum. He called it the Algebra Project. Instead of confronting students with abstract equations, Moses took them out into the real world, traveling around Boston in search of experiences that could demonstrate the practical uses of math. A ride on the T became a lesson in coordinate graphing and negative numbers. Neighborhood landmarks stood in for integers. When Moses taught students about displacement, he had them measure the dimensions of their own bodies. The first rule of Moses' math class was that students always had to "participate in a physical event."

His unconventional methods changed the way the students felt about math. "When you take a trip on the subway and learn about algebra," Maisha says, "what you're really doing is developing a new way of thinking. Instead of just trying to memorize these strange equations, you're busy relating the math to your own experiences. All of a sudden, you find math spilling over into other areas of your life."

How to Get to Carnegie Hall

Two obvious rebuttals to the argument that talent is just a matter of learning by doing are Mozart and Tiger Woods. Mozart famously began composing symphonies as an eight-year-old, and Woods was the world's best golfer at 21. But do they really contradict the "learning by doing" principle?

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Before long, the Algebra Project curriculum began to spread. Lynne Godfrey, Maisha's old math teacher, was one of the first to try out the new approach. "It was just astounding the results we were getting," Godfrey remembers. "We would take the Red Line, and then turn the subway stops into symbolic representations. It didn't feel like math class, which was a good thing. For the first time, every kid in the class understood the concepts of algebra. The students retained the knowledge. They were really learning."

Follow-up studies have confirmed the benefits of Moses' experiential curriculum. 92% of Algebra Project graduates in Cambridge went on to upper-level math courses, twice the rate of students not in the program. Similar results were reported at middle schools in San Francisco. Before the Algebra Project came to Lanier High School in Jackson, MS, it wasn't uncommon for every student in a math class to fail the state math exam. After just two years, the pass rate among its graduates was 55%.

The Algebra Project is a rare success story in the troubled field of math education. More kids drop out of US high schools because they fail introductory algebra than for any other academic reason. Of the 48,000 ninth-graders who took beginning algebra in the Los Angeles Unified School District in the autumn of 2004, 44% failed—nearly twice the failure rate of English in a district that's 43% non-native English speaking. (An additional 17% finished with Ds.) The vast majority of these students will never graduate. They will fail algebra again and again, and then they will throw up their hands in defeat, convinced that they'll never be able to solve for *x*.

"From the perspective of our brain, learning and doing are just two different verbs that refer to the same mental process."

Bob Moses' insight was that the math curricula these schools follow misunderstand the mind. The same abstraction that many educators celebrated -- algebra is often touted as an introduction to symbolic logic -- stifled learning for many students. By taking his students outside the classroom, Moses made math a part of everyday life: He realized that the brain wasn't designed to deal with abstractions it doesn't know how to use, or to solve variables while sitting at a desk. Our knowledge, Moses intuited, is a by-product of activity. What we end up knowing is what we can learn how to use. We learn by doing.

Modern neuroscience can explain the wisdom of Moses' pedagogy. From the perspective of our brain, learning and doing are just two different verbs that refer to the same mental process. The reach of this discovery extends way beyond eighth-grade math class. In fact, the same technique that improved test scores in Boston and San Francisco and Mississippi is also partly responsible for the runaway success of Toyota and the supernatural-seeming skills of a violin soloist. And even though learning by doing might seem backward—doesn't learning precede doing?—it's how our mind works best.

One hot summer day in 1991, in Parma, Italy, all the scientists in Giacomo Rizzolatti's lab went out to lunch. They had spent the morning studying the motor cortex of a monkey, using fine wires implanted in its brain to figure out which neurons were involved in which bodily movements. The work was tedious and exacting, as it required measuring the activity of individual brain cells. (Needless to say, the experiments were even harder on the monkey.) When lunch was over, one of the scientists decided to get a little ice cream, which he brought back to the lab. The monkey was still there, the wires monitoring its motor cortex. When the scientists returned, the hungry primate started staring at the ice cream cone. As the scientist lifted his cone to his lips, the neurons in the monkey's motor cortex began frantically firing, even though the monkey itself remained completely still.

Rizzolatti was completely confused. "How could this happen, when the monkey did not move?" he wondered. "At first, we thought it to be a flaw in our measuring or maybe equipment failure, but everything checked out okay and the reaction [in the monkey brain] was repeated when we repeated the movement." It was only after methodically demonstrating a similar effect with peanuts, bananas, raisins and a host of other monkey delicacies that Rizzolatti began to believe his results. There really were cells in our brains that mirrored the movements of someone else. Rizzolatti called these cells "mirror neurons" because they became active both when the monkey made a particular action (like licking an ice cream cone) and when it observed another individual making a similar action.

How do mirror neurons do this? Rizzolatti devised an ingenious experiment to figure it out. His lab measured the activity of neurons in the monkey's motor cortex while the monkey watched a second monkey grasp a banana. Most of the time, the second monkey held the banana with its hands, but occasionally it decided to use its mouth or its feet. But the mirror neurons didn't distinguish between these mechanical differences. No matter how the banana was actually grasped, the same network of mirror neurons kept lighting up. These cells just itched to do something; they didn't care how it was actually done.

Before Rizzolatti's experiment, the motor cortex was the dumb jock of the brain. According to this theory, the idea to move and the motion itself were separate mental events, unfolding in different brain areas. Rizzolatti proved this wrong. The motor cortex is really designed to combine the idea—the reason we are moving—with the movement.

This revealed the essential connection between learning and doing. The human mind understands the world by interacting with it. When we see an inanimate object that we are familiar with, our mirror neurons instinctively imagine what they could do with that object. A tennis racquet causes our cells to imagine swinging it; a violin causes our cells to imagine playing it. If you happen to be taught algebra by Bob Moses, a math equation might trigger thoughts of taking the subway. A separate brain imaging study has shown that our mirror neurons can even be activated by the sound of words. When we say "tennis" or "violin" or "algebra," cells in our motor cortex automatically get excited.

What's the point of all this neural activity? Mirror neurons let us comb the world for practical things. Because they translate our ideas into actions, they naturally focus on whatever ideas we know how to use, ignoring the abstract and the theoretical. This makes evolutionary sense. The brain, after all, is an adaptive organ: It evolved to help us cope with a world full of concrete problems, not so that we could excel at metaphysics. (As Goethe quipped, "In the beginning was the deed.") And even though mirror neurons are just a small cluster of cells, their predilection for action is an essential part of the human mind. They have been implicated in everything from the invention of tools to the development of language. Mirror neurons are also why most of our favorite entertainment—from theatre to sports—involve watching other people perform. These active cells even explain why the Algebra Project is so much more effective than conventional teaching approaches. By grounding algebraic abstractions in the real world, it allows kids to learn math with the help of their motor cortex.

Some of the most convincing experimental evidence that learning and doing are inseparable comes, ironically, from the study of sleep. Numerous studies have now demonstrated that sleep is an essential part of the learning process. Before you can know something, you have to dream about it.

This outlandish notion began with a scared rabbit. In the early 1950s, scientists at UCLA discovered that the rabbit hippocampus, when aroused by some fearful stimulus in its environment (a coyote, for example), would start pulsing with a very distinctive beat, its neurons firing exactly six times a second. They dubbed this odd phenomenon the "theta rhythm." Subsequent studies found the same beat in several species, but only when the animals were extremely excited or scared. Rats exuded a theta rhythm whenever they were exploring their cage. Cats had it stalking prey. But what was this rhythm's function? Why did the hippocampus—a brain structure involved in learning and memory—become active in this way during moments of intense awareness? Stumped, the UCLA scientists shelved their work and moved on to other things.

Years later, Case H. Vanderwolf of the University of Western Ontario made an even stranger discovery: Theta rhythm was also present during sleep—activity and rest provoked the same strange brain activity. Nobody could figure out the meaning of this.

The breakthrough came in 1972, when psychologist Jonathan Winson came up with a simple theory: The rabbit brain exhibited the same pattern of activity when it was scared and when it was dreaming because it was dreaming about being scared. The theta rhythm of sleep was just the sound of the mind processing information, sorting through the day's experiences and looking for any new knowledge that might be important for future survival. They were learning while dreaming.

Winson's theory was ridiculed. At the time, most scientists assumed that our dreams were accidents of the brain stem, nothing more than a Dadaist montage of meaningless hallucinations. But Winson maintained that this hypothesis made no sense. For one thing, our dreams don't seem random. Instead, they unfold in intricate narrative scenarios, which tend to reflect our daily activities. According to Winson, these nighttime stories—that flurry of theta rhythm—were actually carefully scripted events, in which our new knowledge was put to the test. Did our new learning help us solve our invented problems? Was it a good "survival strategy?" If the answer was yes, then the knowledge was woven into the brain. We woke up a smarter person. The rabbit figured out how to escape its predator. We also, therefore, learn by pretending to do.

Whatever the elegance of Winson's theory, he lacked conclusive evidence. What he needed was a study that directly linked a brain's real-world experience with its manufactured dreams. That study arrived in 2001, when Matthew Wilson, a professor at MIT, published a paper in *Neuron* about the dreams of rats.

Wilson began his experiment by training rats to run through mazes. While a rat was running through one of them, Wilson measured clusters of neurons in the hippocampus with multiple electrodes surgically implanted in its brain. As he'd hypothesized, Wilson found that each maze produced its own pattern of neural firing. To figure out how dreams relate to experience, Wilson recorded input from these same electrodes while the rats were sleeping. He was astonished by his results. Of the 45 rat dreams recorded by Wilson, 20 contained an exact replica of the maze they had run earlier that day. "During REM sleep, we could literally see these rat brains relive minutes of their previous experience," Wilson says. "It was like they were watching a movie of what they had just done."

But why would rats dream of running through a maze again? What's the advantage of replaying the activities of the day at night? According to Wilson, dreaming is a form of mental cleaning. The brain is figuring out what information it needs to keep. Since Wilson rewarded the successful rats with food, their brains were re-encoding the route, making sure they remembered how to find their way.

Like rats dreaming of a maze, the mind is designed to remember useful knowledge. Dreams are just a practical filter; they help figure out what knowledge we might need, and what is just a waste of neuronal space. "When you are having these vivid dreams," Wilson says, "what you are really doing is testing out all your new learning. You are recapitulating your old experience, but in a new situation. Dreaming is a way of figuring out what ideas you might actually need in the future."

The corollary is that everything we learn has to pass through this REM filter. If our knowledge fails the dreaming test—if it doesn't prove to be an "adaptive behavior" that helps us cope with our nighttime scenarios—then the brain lets it go.

Bob Moses was right: Algebra is best learned in the context of the real world. If students know what practical problems algebra can help them solve, then they might actually remember the lesson plan. Nobody dreams about abstract equations.

The Toyota Motor Company has profited handsomely from the understanding that doing leads to learning. Its manufacturing plant in Georgetown, KY is, in many ways, a school that happens to produce cars. The essence of Toyota's manufacturing philosophy—that it doesn't distinguish between learning and doing—is most evident in its willingness to halt production if a problem crops up on the floor.

Because an idle factory is a money pit, most car companies insist that the assembly line never stop. But Toyota defines success in terms of self-improvement, and turning out slightly fewer engines is a small price to pay for educating its workers in turning out better engines. "If some problem occurs...then the whole production line stops," Teruyuki Minoura, former President of Toyota Motor Manufacturing North America, wrote in the book *The Toyota Way*. "In this sense it is a very bad system of manufacturing. But when production stops everyone is forced to solve the problem immediately. So team members have to think, and through thinking, team members grow and become better."

This is in complete contradiction to the mode of manufacturing established by Henry Ford, in which there is no assimilation of information about the process as a whole. In contrast, a sign over the doors at Georgetown reads "When something goes wrong, ask WHY five times." Toyota wants its employees always to wonder how they may do things better. If a worker isn't learning, he isn't doing his job. As Steven Spear and H. Kent Bowen of Harvard Business School wrote in the *Harvard Business Review*, "The key is to understand that the Toyota Production System creates a community of scientists...the Toyota system actually stimulates workers and managers to engage in the kind of experimentation that is widely recognized as the cornerstone of a learning organization. That is what distinguishes Toyota."

Unlike most manufacturers, at which executives dispense instructions to workers, Toyota sees learning as an essential part of what it does: The best ideas about how to make cars, the thinking goes, are most likely to originate from the people actually making them. Turning its factory workers into "scientists" makes for a better production system--because they are the ones doing, they are the ones learning. The raison d'être of a Toyota plant is to harness the knowledge generated on the assembly line, and the company's results speak to the truth of this philosophy. It is valued at more than seven times as much as GM and Ford combined; by the end of 2006 it is expected to replace GM as the world's largest car manufacturer. Last year, it reported an annual profit of over $12 billion. The company has never reported an operating loss.

John Dewey, the pragmatist philosopher and originator of progressive education, harnessed the power of learning by doing three decades before Toyota. In 1895, he founded the Laboratory School at the University of Chicago. His mission was to "reinstate experience into education"; as a result, Laboratory students spent most of their day outside the classroom, engaging in activities such as sewing, carpentry and cooking. But these activities weren't simply exercises in manual labor. Rather, they were demonstrations of "active learning." "If a child realizes the motive for acquiring a skill," Dewey argued, "he is helped in large measure to secure the skill."

The purpose was to make education seem indivisible from action. "Absolutely no separation is made between the 'social' side of the work, its concern with people's activities, and the 'science,' regard for physical facts and forces," Dewey wrote in 1899, in his best-selling pamphlet "The School and Society."

Dewey's insights are needed now more than ever. His curriculum, by collapsing what he called "the invidious distinction between learning and doing," took full advantage of our mirror neuron circuit. Unfortunately, in the age of standardized testing, US schools have given up on Dewey's experiential approach—and the difficulties faced by the Algebra Project exemplify this trend. Even in districts where the curriculum has been an unambiguous success, it has fallen victim to standardized testing. Not long after the Cambridge public schools reported two-fold increases in advanced math enrollment among Algebra Project graduates, the project was quietly shut down. "It's really a tragedy," says Lynne Godfrey, who is still a math teacher in Cambridge. "Even though we were getting these great results, we were under pressure to standardize the math curriculum, so that we could conform with MCAS [Massachusetts' standardized tests] and No Child Left Behind. It's such a shame." Maisha Moses, who went on to work as a math teacher in Mississippi, remembered other teachers telling her, "I know my lesson plan isn't working, but I just have to get ready for the test."

This is the paradoxical flaw of standardized testing—in the rush to quantify learning, it discourages the sort of teaching that actually gets results. Instead of learning by doing, children are forced to memorize a random-seeming body of knowledge. Even if students pass the test, they never learn what to do with all their new information. As a result, they quickly forget the lesson plan—probably while dreaming at night.

The connection between Toyota, John Dewey and the Algebra Project lies in the research of K. Anders Ericsson, a psychology professor at Florida State University, who has shown that doing leads to learning, and learning by doing leads to doing better.

Ericsson has spent the last 30 years probing the implications of the first experiment he ever conducted as a professional. The year was 1976, and he was studying the limits of memory. At the time, it was believed that the brain could only remember about seven random numbers at a particular moment. Ericsson thought he'd try to increase this capacity through rigorous training. "I was really surprised when, after about 20 hours of training, we could expand the short term memory for digits from seven to 20," Ericsson recalls. "Then [the experimental subject] just kept on improving. After about 200 hours of training, he could remember over 80 numbers. It was very surprising."

Ericsson wondered what other human talents were malleable. After all, if memory ability wasn't innate, then it seemed hard to imagine what was. What else could people learn to do better?

Ericsson started studying a range of "expert performers." He investigated chess grandmasters and the stars of the PGA tour, Scrabble champions and brain surgeons, concert pianists and circus acrobats. After putting these peak performers through a battery of cognitive tests, Ericsson realized that their talent wasn't genetic. They weren't born with better brains. In fact, the average IQ of people at the top of their field, no matter what it is, equaled that of the average college student. In other words, their expertise is very specific, confined to a particular "cognitive domain." Craig Barrett of Intel made great strides when he worked as a scientist at the company, but when he was promoted to CEO they had to teach him how to read a spreadsheet.

But if talent isn't innate, then where does it come from? Ericsson's answer was so simple it was shocking: Practice makes perfect. Talent comes from learning by doing. For example, when Ericsson studied classical pianists, he found that the winners of competitions had practiced over 10,000 hours by the age of 20, while less accomplished performers only practiced between 2,000 and 5,000 hours. This same effect was apparent across a range of fields. "From the outside, it seems like talented people don't have to put in a lot of effort," Ericsson says. "They make it look so easy. But when you look closely, the opposite is actually true. The best performers are almost always the ones who practice the most. I have yet to find a talented person who didn't earn their talent through hard work and thousands of hours of practice."

But how does practice make perfect? And why are some people so much better than their peers, even if their peers put in just as many hours of practice? This might be called the Tiger Woods problem. After all, it's not like everyone else on the PGA tour is a slacker. Ericsson's solution arrived when he began looking in detail at the way people practice. He noticed that the best performers had a unique training style. They tended to downplay mindless drills and rote repetition. Instead, their practice sessions were deliberate, creative and thoughtful, like the outings of the Algebra Project or the progression of a rat through a maze. They set specific goals for themselves, continuously analyzed their progress and focused on process. "A crucial part of practicing well is that you are always learning while practicing," Ericsson says.

According to Ericsson, this is how elite performers always practice. It is the secret trick of their talent, the way they become the best. Instead of treating practice as separate from the learning process--doing is what you do when you are done learning--they constantly find ways to integrate learning into their doing process, and the payoff is immense. The brain is designed to learn in a very particular way, consistently favoring the concrete over the abstract, the practical over the theoretical. If something can't be done, then we probably aren't interested in learning about it. The individuals and organizations that take advantage of this psychological principle are the ones that excel, getting the most out of themselves and their charges. If people can learn the right way--algebra on the subway, practice sessions and factory floors transformed into experiences that broaden the mind--neuroscience indicates there is little the mind can't accomplish. But if we remain ignorant of Dewey and the Laboratory School, of Rizzolatti and his monkeys, of Bob Moses and newly-accelerated math students, of the winners of musical competitions and major golf championships, we will plod along in mediocrity, and fail algebra.