Making Connections

The essence of memory is linking one thought to another

By Anthony J. Greene

Many people wish their memory worked like a video recording. How handy would that be? Finding your car keys would simply be a matter of zipping back to the last time you had them and hitting "play." You would never miss an appointment or forget to pay a bill. You would remember everyone's birthday. You would ace every exam.

Or so you might think. In fact, a memory like that would snare mostly useless data and mix them willy-nilly with the information you really needed. It would not let you prioritize or create the links between events that give them meaning. For the very few people who have true photographic recall—eidetic memory, in the parlance of the field—it is more burden than blessing.

For most of us, memory is not like a video recording—or a notebook, a photograph, a hard drive or any of the other common storage devices to which it has been compared. It is much more like a web of connections between people and things. Indeed, recent research has shown that some people who lose their memory also lose the ability to connect things to each other in their mind. And it is the connections that let us understand cause and effect, learn from our mistakes and anticipate the future.

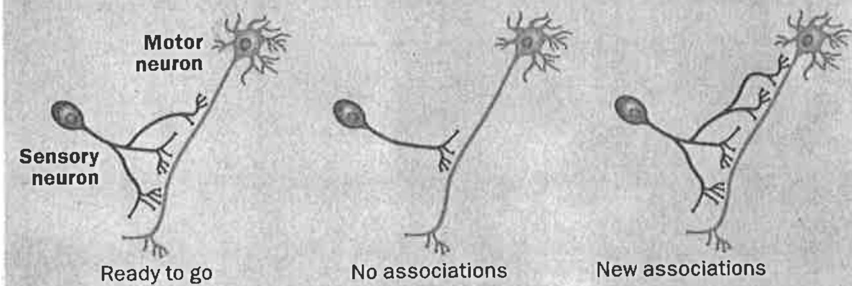
The things we remember are the ones that experience teaches us will help us make predictions; the newest work in our laboratory reveals how we make use

PHOTOILLUSTRATION BY AARON GOODMAN

To a mind that can't make connections, each instant fleeting and unrelated, each precept without relevance,

Creating Memories

When a memory forms in the brain, it alters the connections between nerve cells, such as these from a sea slug, *Aplysia*. A sensory neuron (*left*) loses most of its connections, or synapses, to an adjacent motor neuron when the slug learns that two things or events are no longer related (*center*). New synapses form when repetition reinforces an association (*right*), creating a memory as neurons that fire together wire together.



FROM AN INTRODUCTION TO BRAIN AND BEHAVIOR, THIRD EDITION, BY B. KOLB AND I. Q. WHISHAW, WORTH PUBLISHERS, 2009

of this predictive ability. Other recent studies show that imagining the future involves brain processes similar to, but distinct from, those involved in conjuring the past. We also tend to remember the people and events that resonate emotionally, which is why forgetting an anniversary is such an offense: it is fair evidence that the date is not as important as the ones we do remember.

The discovery that memory is all about connections has revolutionary implications for education. It means that memory is integral to thought and that nothing we learn can stand in isolation; we sustain new learning only to the degree we can relate it to what we already know. The modern theory of memory can help us as we organize our experiences, teach our children and support those with learning problems.

The History of Memory

For millennia, metaphors for memory have marched in lockstep with the technology for recording thought. References in ancient Greece likened memory to tracings in a wax tablet, in the Middle Ages to parchment, and later to books, files, photos, videos, audio recordings and computer hard drives. Modern scientific dialogue still sometimes refers to memory as a trace (as in a wax imprint or a rubbing). Lately we compare human memory to computer memory, and we draw from the same taxonomy. We speak of encoding and storage for the learning of new memories, retrieval for the act of remembering, address for the location of a memory in the brain, and output for a remembered event—metaphors that persist even as our understanding of memory evolves.

The modern view of memory has its roots in the 1930s and 1940s, when a series of discoveries, most notably by psychologist Karl Lashley of the University of Chicago and later Harvard University, revealed that learning and memory are not sequestered in their own storage banks but are distributed across the entire cerebral cortex. Lashley set out to discover the location of the learning center of the brain by systematically disconnecting different regions of the cerebral cortex in a number of different rats. To his surprise, all the rats showed some degree of mild learning impairment, but none was seriously impaired.

The significance of these findings is profound. It means that memory is dispersed, forming in the regions of the brain responsible for language, vision, hearing, emotion and other functions. It means that learning and memory arise from changes in neurons as they connect to and communicate with other neurons [*see illustration above*]. And it means that a small reminder can reactivate a network of neurons wired together in the course of registering an event, allowing you to experience the event anew. Remembering is reliving.

Another piece of the puzzle fell into place in the 1950s, after some surprising observations of a few individuals

FAST FACTS
Linking and Learning

1» Brain cells that fire together during an experience can form permanent connections.

2» Those connections let the same network of brain cells refire later on, which we experience as memory.

3» New experiences can lead a network of cells to develop further connections, adding to a memory and helping us learn but sometimes modifying a recollection and creating false memories.

4» Because knowledge derives from connections, the optimal strategy for learning involves making meaningful associations among topics.

is an isolated event without continuity, each thought each person a stranger, every event unexpected.

with almost complete amnesia. In the most compelling case, a 27-year-old Connecticut man, known as HM but identified as Henry Gustav Molaison after his death in 2008, had severe epilepsy that was not responding well to medication. It was a sadly common practice in those days to treat epilepsy by removing or disconnecting substantial portions of brain tissue. The performance of a brain resection on HM resulted in one of the most extreme cases of amnesia ever recorded. His case and others revealed that damage to the hippocampus, a wishbone-shaped structure located deep below the surface folds of the cerebral cortex, leaves people almost completely unable to acquire new memories or to learn complex associations. Their minds remain frozen at the time of the neural insult; the greater the damage, the more severe the amnesia.

At first, this finding appeared to contradict the discovery that learning and memory are distributed across the brain. The hippocampus, though, turned out to be not the source or storehouse of memory but rather an essential mediator in its formation. In a very small brain, every neuron might be connected to every other neuron. But a human brain that worked on this model would require that each of hundreds of billions of neurons be linked to every other neuron, an impossibly unwieldy configuration. The hippocampus solves this problem by serving as a kind of neural switchboard, connecting the distant cortical regions for language, vision and other abilities as synaptic networks take shape and create memories [*see illustration below*].

Recent amnesia research paints an even bleaker picture of the condition, while yielding some startling insights into what memory really is. Hippocampal amnesiacs appear to have impairments that go well beyond the loss of memory creation. They also have severe difficulty imagining future events, living instead in a fragmented, disconnected reality. In a study published in 2007 psychologist Eleanor Maguire and her research team at University College London asked participants with amnesia and those with normal memories to elaborate on hypothetical scenarios of short, simple vignettes. (The researchers gave participants a cue card summarizing the main dramatic elements to ensure that no one would forget the setup.)

In one scenario, participants were to imagine they were standing in the main hall of a museum with many exhibits. Those with normal memory could generally develop a coherent narrative about people and their activities. Amnesic participants typically could visualize only a few details, which were often disconnected and lacking in spatial and temporal coherence. One typical narrative: "Well, there's big doors.... There'd be the exhibits.... I don't know what they are.... There'd be people." What is lost in amnesia, then, is the capacity to connect things to one another and find any meaning in them. To a mind that cannot make connections, each instant is an isolated event without continuity, each thought fleeting and unrelated, each precept without relevance, each person a stranger, every event unexpected.

A Neural Switchboard

From its central location, the hippocampus (*yellow*) connects far-flung regions of the cortex (*red*) that are involved in a particular recollection. The image, in which the brain is rendered semitransparent, superimposes a functional MRI image of the cerebral activity on an MRI of its structure.

MATHEW VERBER *Medical College of Wisconsin*

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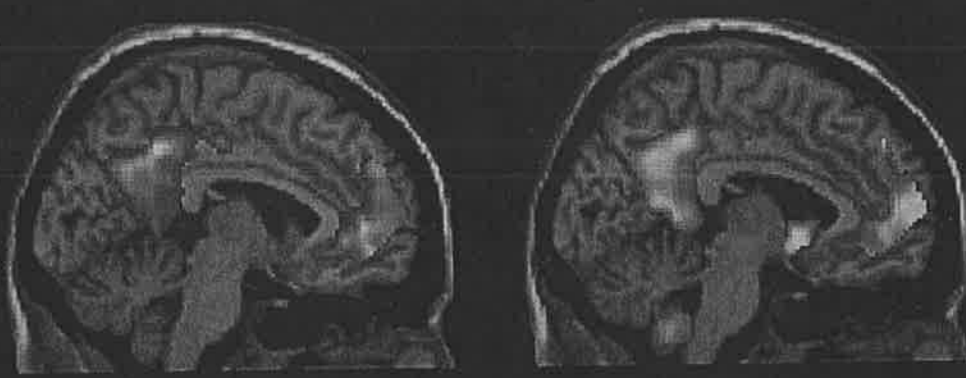
The ability to form and retain connections makes this critical aspect of learning: "I put two and two

Reimagining Is Reliving

These two fMRIs show a few differences but great overlap in the regions of the brain involved in recalling a past event and imagining a future one. In each case, a network of neurons fires across the cerebral cortex.



Remembering the past

Imagining the future

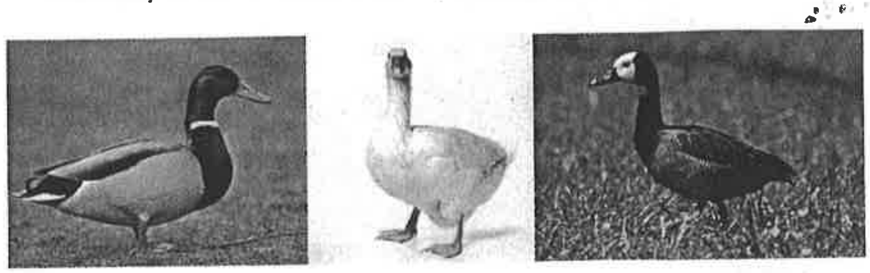
The connections across the brain also help us conceive the future, as recent imaging studies have shown. Functional magnetic resonance imaging detects changes in blood oxygen in various regions of the brain. When participants perform memory tasks, the areas of the brain that use more oxygen are assumed to be involved. In 2007 a team led by psychologist Kathleen McDermott of Washington University in St. Louis and, separately, by psychologist Daniel L. Schacter of Harvard and his colleagues showed that a mosaic of brain areas similar to those involved in memory is active when participants imagine details of hypothetical or prospective events. In McDermott's study, participants were told they would be asked to imagine some future event. Once the subjects were inside the scanner, a researcher would announce a keyword—"birthday," say—and the participants would then think (to themselves; talking is not permitted during a scan) about how and where and with whom they would celebrate a future birthday. Just as memories do, those imaginings elicited activity in the hippocampus as well as multiple regions of the cerebral cortex.

In a 2009 experiment with a similar setup, Schacter's team asked people to recall an experience instead of inventing a new one. The researchers found that although the subjects' brain activity was similar to that of people imagining a new scenario, the patterns were clearly distinct, suggesting that anticipating the future is not simply a matter of recasting past experiences into a novel or hypothetical form [*see illustration above*]. Every new event has some novel element to it even if experienced under similar circumstances, so the pattern of neuronal firing will be different each time. Our brain has evolved not just for learning and memory but for the management of relations: past, present and future.

Memory as Connection

The ability to form and retain connections gives us not just a record of events but also the foundations of comprehension. We have plenty of clichés to express this critical aspect of learning: "I put two and two together" or "I just connected the dots." We make use of these connections thousands of times a day. And knowing how they work is crucial to understanding how we learn.

Connections progress from simple relations between things to ever more complex cascades of inferences. Links between things, events, people and our actions—so-called item associations—are the reason certain objects evoke reminiscence and become keepsakes. Visiting your alma mater, catching a whiff of burning leaves or finding a letter from a loved one can bring back vivid memories



The neural connections that make up our memories also help us generalize and discriminate. Generalization helps us see the common elements in, say, all waterfowl but blinds us to the differences between the mallard (*left*), the goose (*center*) and the white-faced whistling duck (*right*). In time, we learn to tell one similar creature from another.

FROM "REMEMBERING THE PAST AND IMAGINING THE FUTURE: COMMON AND DISTINCT NEURAL SUBSTRATES DURING EVENT CONSTRUCTION AND ELABORATION," BY DONNA ROSE ADDIS, ALANA T. WONG AND DANIEL L. SCHACTER, IN *NEUROPSYCHOLOGIA*, VOL. 45; 2007. REPRINTED WITH PERMISSION FROM ELSEVIER (*brain scans*); GETTY IMAGES (*mallard*); GK HART/VIKKI HART *Getty Images* (*goose*); HERBERT SPICHTINGER *Corbis* (*whistling duck*) comprehension possible. Plenty of clichés express together" or "I just connected the dots."

Getting the **Most** from Your Memory

Rather than cluttering your mind with arbitrary facts, try these techniques for using your memory more effectively. You will understand concepts in greater depth and have more confidence in what you know.

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- Think about relevant connections between what you wish to learn and what you already know. Build as many meaningful connections as you can.
- Make sure you thoroughly understand what you want to learn. If you try to memorize a formula, a foreign phrase or a passage you have not fully grasped, you will soon forget it and will create a cul-de-sac for future learning.
- Explain things to yourself as if you were teaching them to someone who was unfamiliar with the subject. You will clarify and consolidate your own understanding.
- Organize your thinking, outlining complex topics. Ensure that the outline is as logical as you can make it.
- Summarize what you wish to learn so that you establish the main points. Then elaborate on them to establish depth and breadth.
- Never cram or rush yourself. Spread out your learning. There are no known upper limits on how much human beings can learn, but there are significant limits on how much they can learn at the last minute.
- Practice early and often. —A.G.

of events you might not have thought about in years. Item associations let us remember that Italy has good wine, and they help us connect people's names to their faces. Items can also be retrieval cues. A buzzer reminds us that dinner is still in the oven. The sight of a co-worker in the hall prompts us to mark a meeting on the calendar.

Put enough of these item associations together, and you will create a web of connections that can help you make predictions and navigate the world more effectively over time. At their simplest, predictive associations remind us that wet snow will clog the snowblower and that lewd humor will upset some people. But many predictive associations are more nuanced. Your boss might get upset if you tell a crude joke in the office but not when you are out for a beer and even then may check to see who else is there before deciding to laugh. Making predictions requires us to weigh multiple variables, which in turn takes a brain big enough to learn all the relations involved. Indeed, social interactions can pose our greatest predictive challenges and may well have been a major impetus, among our prehuman ancestors, for the evolution of astounding learning abilities.

At the root of the flexibility of learning and memory is generalization. My one-year-old son recently had a wonderful time feeding some ducks and soon was able to point out a duck with no trouble, whatever its color or age. He also overgeneralizes: in his lexicon, geese and swans are also ducks. Eventually he will learn to discriminate among waterfowl and perhaps in time among different types of ducks, as he will later learn to tell a cabbage from a lettuce and one sort of lettuce from another. Generalization and discrimination are the yin and yang of learning and memory—complementary processes that ultimately work together to shape our associations.

As we amass knowledge over the course of our life and connect events in our memory, we learn to model complex contingencies and make inferences about novel relations. In my own lab, we have been exploring the ways people use learned relations to make predictions. In one experiment, published in 2006, participants lying inside a functional MRI machine viewed a computer screen on which we displayed various pairs of unfamiliar shapes, drawn from the Japanese *hiragana* alphabet [*see top illustration on next page*]. For each pairing, we asked participants to click on one shape or the other, eliciting a message—"correct" or "incorrect," depending on the choice—letting them learn which symbol in a given pair was preferred. Then we showed them novel pairings and asked them to click on the one they thought was correct,

Experiments reveal how easy it is to create false incorrect information about a car accident, many

Symbol Solutions

ゑ>ま>か>め>せ

People were trained to recognize which of these symbols from the Japanese *hiragana* alphabet was the "preferred" one in a series of pairings. Then the participants tried to pick the "correct" symbol in new pairings. The learners who were able to *infer* a hierarchy of symbols from the original symbol sets made more correct choices later on and displayed greater activity in the hippocampus.

based on the hierarchy implied during the learning phase. Those who scored well—the ones who used inference—displayed much greater activity in the hippocampus than those who scored nearer the level of chance—the ones who merely guessed—suggesting memory networks are fully engaged across the brain when people use what they know to make predictions. This study and others like it give insight into how we cobble together bits of information learned over many years and use them to navigate our course through life.

The accretive and adaptive quality of memory can sometimes cause us problems by altering our memories instead of augmenting them. During the 1990s psychologist Elizabeth Loftus, now at the University of California, Irvine, produced an impressive amount of research showing how easy it is to create false memories of past events. In one study, participants watched a film of a car accident. Researchers asked some subjects how fast they thought the cars were going when they "smashed into" each other and asked other subjects how fast the cars were going when they "hit" each other. The subjects who heard the word "smashed" gave significantly higher estimates of the speed. In other experiments, subjects were fed incorrect information about an accident after watching the film; they might, for instance, be asked repeatedly whether a traffic light had turned yellow before the collision when in fact the light was green. Many then remembered a yellow light that never existed—which is why eyewitness testimony after police interrogation can be so unreliable. To avoid this kind of malleability, smart lawyers tell clients to write down what happened as soon as possible and before discussing it. [For more on the reliability of eyewitness testimony, see "Do the Eyes Have It?" by Hal Arkowitz and Scott O. Lilienfeld; SCIENTIFIC AMERICAN MIND, January/February 2010.]

Teach, Memory

In my own early education during the 1970s, schools often taught through rote memorization. I was told to memorize multiplication tables, the Preamble to the U.S. Constitution, and poetry that I did not understand at all. Although the days of learning by repeating things over and over are finally on the wane, educators still rely on old-school methods such as the arbitrary mnemonic device—an unrelated acronym used as a memory cue. This is not to say that facts need not be learned. Some, such as phone numbers and people's names, are inherently arbitrary, and for them rote learning may be appropriate. But the message of modern memory research is that the brain is wired to recognize and organize coherent connections, not arbitrary ones. By tying new learning to existing associations—by engaging in contextual learning—we greatly improve results.

Say, for instance, you were teaching students about a historical novel such as *The Scarlet Letter.* Before you uttered the name "Hester Prynne," you might first discuss how Puritan society mirrored truths your students already know: religious leaders do not always live up to their convictions; the judgment of peers is weighty and lasting; concealed shame eats at the soul. You could next intro-

New brain insights suggest that rote learning is usually ineffective. Students are more likely to retain new information when they can relate it to what they already know.

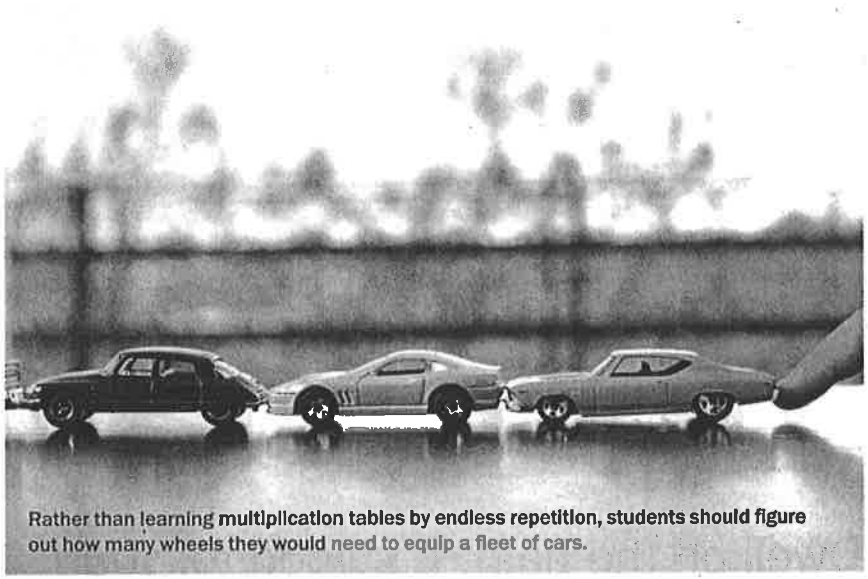
FROM "AN FMRI ANALYSIS OF THE HUMAN HIPPOCAMPUS: INFERENCE, CONTEXT, AND TASK AWARENESS," BY A. J. GREENE, W. L. GROSS, C. L. ELSINGER AND S. M. RAO, IN *JOURNAL OF COGNITIVE NEUROSCIENCE*, VOL. 18; 2006 *(top)*; WILL & DENI McINTYRE *Corbis (bottom)*

memories of past events. When people were fed remembered a yellow light that never existed.

duce ways in which the Puritan universe was different: living on the verge of survival necessitated collective conformity; technology was primitive; religious convictions were a community affair. Your students can then engage their imaginations to paint a picture of the characters' way of life, from family relations to dogs chasing pigs down the streets. As their knowledge of the story's setting deepens, they can begin to take in abstract ideas, such as the political and legal structures of Puritan society. By this time, the students will have formed an intricate web of associations that will let them weave the lessons of the book into their own thinking. They can live the story and grasp its significance.

Contextual learning can even help with tasks that seem intractably a matter of rote memorization, such as learning the times tables. You can better teach a child that 3 times 4 equals 12 by bringing the idea into the real world. Ask a girl who likes cars how many wheels she would need for three racers with four wheels apiece. As she memorizes the tables, she will learn what multiplication actually does, which will help her solve related problems later on. When rich in context, science becomes an extension of a student's natural curiosity to figure out how things work, just as history, as collective memory, connects students to the continuum of civilization, and fine arts connects them to the mind of the artist. If the connections between subject matter and students are relevant and personal to them, the learned material becomes part of their beings.

The lessons of associative learning can also give educators a fresh approach to early learning and to teaching children with learning deficits. Simplified contingencies can help everyone in the first stages of learning. For example, a young child who thinks that all swimming birds are ducks may later learn conditions that distinguish one kind of swimming bird from another, and from there exceptions to those conditions, and in time more complicated relations still.



Rather than learning multiplication tables by endless repetition, students should figure out how many wheels they would need to equip a fleet of cars.

JEFFREY COOLIDGE Getty Images

Connections help us anchor an ever more complicated body of knowledge about how the world works and negotiate the complex structures all around us. Memory is a dynamic aspect of our intellect. And as our understanding of memory grows deeper, we see that the connections we make between the people, places and things in our lives, between the past, present and future, do not themselves spring from memory. Memory springs from the connections.

Despite our imperfect metaphors, we must have long known that memory was more than a mere repository of experience. Consider the ancient Greeks. The muses were not simply the goddesses who inspired poetry, music and all forms of artistic creativity and for whom temples were erected. They were also patrons of the liberal arts and the wellspring of philosophy, knowledge, thought and wisdom. And the mother and queen of all the muses? Mnemosyne, the muse of memory. **M**

(Further Reading)

- **Metaphors of Memory: A History of Ideas about the Mind.** Douwe Draaisma. Translated by Paul Vincent. Cambridge University Press, 2000.
- **Contextual Teaching and Learning: What It Is and Why It's Here to Stay.** Elaine B. Johnson. Corwin Press, 2002.
- **Synaptic Self: How Our Brains Become Who We Are.** Joseph LeDoux. Penguin Books, 2002.
- **What's New with Amnesic Patient HM?** Suzanne Corkin in *Nature Reviews Neuroscience*, Vol. 3, pages 153–160; 2002.
- **From Conditioning to Conscious Recollection: Memory Systems of the Brain.** Howard Eichenbaum and Neal J. Cohen. Oxford University Press, 2004.
- **The Science of False Memory.** C. J. Brainerd and V. F. Reyna. Oxford University Press, 2005.
- **The Hippocampus Book.** Edited by Per Andersen, Richard Morris, David Amaral, Tim Bliss and John O'Keefe. Oxford University Press, 2007.