Learning and Memory Series

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101

THE PSYCHOLOGY OF LEARNING AND MEMORY

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CONTENTS

Poor Solomon Shereshevsky couldn't help but create detailed memories of nearly everything that entered his unusual brain. He never forgot. He could be given long lists of numbers, words, and non-sense syllables and remember them perfectly years later—and backwards, no less.

While that talent seems like a blessing, and it certainly was responsible for his career as a mnemonist and showman, the neuro-physiologist Alexander Luria, who studied Shereshevsky in the 1920s, found that he was handicapped by this remarkable ability. Every experience, even the most mundane, consisted of the reliving of countless associated details. The simple act of asking a street vendor for a scoop of ice cream brought forth remembered imagery of such intensity that the transaction was quickly brought to a halt. Intelligence tests revealed an average IQ, yet interestingly, Shereshevsky could not easily create abstract thought. The level of detail that plagued his conscious attention precluded him from forming general principles by which to conduct a normal and happy life.

So, why do the rest of us forget? Why is memory transient —here today, faint in a few weeks, gone in a year or two? Is transience due to faulty wiring or to the cellular limitations of the brain? Maybe it's just like the old marketing joke about bad software code, except in this case it's true—forgetting is not a bug, it's a feature. Are there different types of memory? How does a brain store memory and what can be done to improve it?

Beginning with psychological research in the 1870s and leading up to the very latest theories and working models, this paper examines the key discoveries of the most influential experimental psychologists. Over many decades of toil, their work has revealed how we learn and remember—perhaps the biological activity that makes us most human. As Noble Prize winning neurobiologist, Eric Kandel proclaims,

> *"For me, learning and memory have proven to be endlessly fascinating mental processes because they address one of the fundamental features of human activity: our ability to acquire new ideas from experience and to retain these ideas in memory. In fact, most of the ideas we have about the world and our civilization we have learned so that we are who we are in good measure because of what we have learned and what we remember."*
> *—Erik Kandel, Nobel Prize Lecture, 2000*

The new synthesis

In the last few decades, psychology and neuroscience have been joined together in a search for an understanding of the workings of the human brain. The wealth of theoretical confirmation from observation and experimentation of this unbelievably complex structure (approximately 100 billion neurons forming about 1,000 trillion connections) is a profound accomplishment. As predicted by Harvard biologist, E.O. Wilson, a consilient view of human mind and human nature is forming at this very moment—a new synthesis. Incredibly, it connects the outside world with the molecular machinery in nerve cells, and to the behavior of people (and, of course, our animal cousins). The work will not be complete for another century, if ever, but we can now discuss memory and learning at the deepest levels beginning with the molecules that regulate gene expression. From there, we can see how genes control neurons that change their structure during learning to form memory. Continuing up the physical hierarchy, we discover that modular regions of the brain are tasked with specific functions. Lastly, we see how the overall integration of the functional regions create the psychology of people, their myriad behaviors, and the memories that constitute a life reflected upon. From genes, to neurons, to brain, to behavior and personality; this spectacular and humbling new knowledge is the foundational science from which the Amplifire learning architecture was built.

To grasp the innovations contained in Amplifire, it is necessary to get a handle on the basic principles of learning from the perspective of psychology and neuroscience. It's not as intimidating as it sounds since the journey is really one of self discovery. After all, we have all learned countless things through the act of living, and every bit has been perceived and interpreted through a mind. How that happened and continues to happen is both fascinating and enlightening. This paper will concentrate on the view from psychology. It will then hand off to the view from neuroscience.

A memorable history

The four stages of memory

To begin with, the science of memory breaks down the process of learning into four sequential components that are easily understood in the first instance yet contain a wealth of detail if one cares to explore the terrain. The basic operations that turn information into memory are *encoding, storage, retrieval,* and *forgetting*.

Encoding can be thought of as the transformation of the sensory inputs coming in from the real world into signals stored as memory in organic tissue. A human being's task is to somehow convert activity in the real world into a format that is suitable for storage in a brain composed of 100 billion neurons. To truly learn something, we must pay attention to the stimulus and go over it in our minds from multiple perspectives while trying to associate it with other, already-learned information. This activity forms a *memory trace* that is stored in patterns of neurons bound by their synapses—the language of encoding.

Storage consists of changes in patterns of neurons at various locations throughout the brain. As we'll see, the evidence suggests that there is no one place that any memory is stored for the long term. Rather, it is distributed among the many sensory pathways and brain structures that initially encoded the information. So, if you remember the orange you had for breakfast, the color is distributed at many points in the vision regions, the flavor resides in regions devoted to processing tastes, and the texture of the fruit is stored in the tactile processing regions.

Retrieval is the conscious or unconscious act of reassembling all the disparately stored components of a memory into a consistent whole—like reassembling the memory of the whole orange from the many locations where different aspects of it are stored.

Forgetting seems like an error in the brain's design, but as we'll see, it's really a feature with many advantages. Life without forgetting would be nearly intolerable, as Solomon Shereshevsky showed you. On the other hand, forgetting important things like the rules for solving algebra equations during an SAT exam can be quite detrimental to attaining one's life goals. The task at hand is to find methods that encode important information into long-term memory storage so retrieval is effortless, while letting the less important bits fall away in due course.

Amplifire is designed to enhance the encoding, storage, and retrieval processes while slowing the forgetting process. These processes are native to the brains of normally functioning human beings and are capable of modification by the appropriate technology. To see how, we must acquire a bit more detail on the ways that brains learn and remember.

> *"Whether or not something that is perceived will be remembered later is determined by a number of factors, the most important of which operate around the time of learning: the number of times the event or fact is repeated, its importance, the extent to which we can organize it and relate it to knowledge that we already have, and the extent to which we rehearse the material after it has first been presented."*
> Kandel & Squire—Memory, from Mind to Molecules—2008

The "problem" of memory - transience

In a well-known experiment, students were asked to write down their location and circumstances upon hearing about the O.J. Simpson verdict on the very day he was found not guilty. Just three years later, they were only 30% accurate when recalling those circumstances. From nature's survival perspective, why should they remember since their location in space and time on that day is now far removed from the needs of the present? On the other hand, no one forgets the outcome of the case. That chunk of memory, due to it's emotional content, will likely be with us for life. You'll never hear, "What was the verdict in that O.J. trial?"

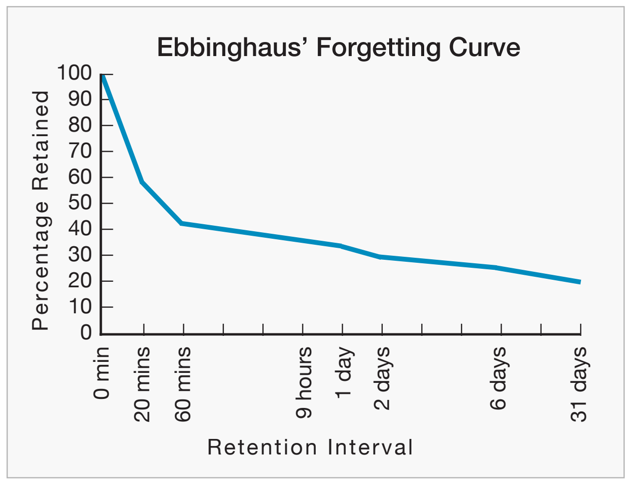
As these students nicely demonstrate, transience exists because nature has made a bet that the things that aren't used in day-to-day living are unlikely to be useful in the future. Those unused items fall out of memory.

Ebbinghaus launches psychology

The formal study of how we remember and forget was launched in 1878 with the pioneering work of Professor Hermann Ebbinghaus in Berlin. He was the first person to use the principles of science to study memory. It is not an exaggeration to propose that, before Ebbinghaus, a truly scientific method was missing from psychology. At the time, the sanctioned method of investigation was introspection. The only equipment needed was an armchair and a quiet place in which to think.

Ebbinghaus changed psychology by introducing an elegant yet rigorous methodology. He invented 2,000 nonsense words and created random lists of between 6 and 30 words. Then, he set about to memorize them. He discovered that learning a list of six or seven new words took place very quickly, often in just one session. Longer lists, however, required repeated sessions. There seemed to be a perfect correlation between the number of times he repeated the word lists and his ability to recollect them later. In effect, Ebbinghaus was the first scientist to empirically demonstrate that practice makes perfect.

He then plotted out the rate at which words fell out of memory and made another set of discoveries. First, that memory seemed to fade in two distinct stages—a steep decline that takes place in the first hour after learning and then a far more gradual decline that takes place over a period of a month or so.



Second, Ebbinghaus discovered that re-learning an old list of forgotten words was much easier than learning a new list of words. Somehow, the brain remembered an echo of the former learning (he called it *savings*) even after the material seemed to have been completely forgotten.

Short and long-term memory

In 1890, the great American psychologist William James contemplated Ebbinghaus' results that showed two phases of forgetting and then correctly hypothesized that memory must exist in two discrete forms—what we now call short-term and long-term memory. In his seminal work, *The Principles of Psychology*, James described long-term memory as secondary memory, but considered it vital, calling it "memory proper."

> *"Memory proper, or secondary memory as it might be styled, is the knowledge of a former state of mind after it has already once dropped from consciousness."*
> *—William James, The Principles of Psychology, 1890*

Consolidation

In 1900, two Germans, Muller and Pilzecker, having conducted over forty memory experiments across an eight-year period, expand on James concept of short and long-term memory (LTM) by showing that memory is surprisingly fragile for the first few minutes after learning. In experiments much like those of Ebbinghaus, they demonstrate that a critical process of "consolidation" takes place during this interval. Subjects could not remember a first list of syllables if a second was presented within a few minutes. Within that short period, consolidation is vulnerable to disruption if an attempt is made to learn additional information.

> *"..after reading a list of syllables, certain physiological processes continue with decreasing intensity for a period of time. These processes and their facilitating effects are being weakened to a greater or lesser extent if the experimental subject experiences further mental exertion immediately after reading a list…"*
> *—Muller and Pilzecker, 1900*

Neurologists of the day were quick to see a similarity with brain injury. They realized that consolidation is also interrupted if the brain experiences trauma. Following a concussion, a patient is unable to remember the events that occurred just before the blow to the head although their long-term memories remain intact and retrievable.

The process of consolidation is critical in our understanding of how the brain learns and remembers. Somehow, short-term memory is modified within a window that is open for only a few minutes and converted into a more stable form—LTM.

(note: Technically, there are two types of consolidation. Here we are talking about the version that refers to the fairly rapid conversion of short term memory into LTM in an area of the brain called the hippocampus. This is called synaptic consolidation. The other type of consolidation refers to a slower process whereby the hippocampus is distributing LTM into the cortex for final storage. This is systemic consolidation. Both will be discussed further in *Paper 102* dealing with the organic structures of learning and memory.)

Working memory

By the 1950s, another useful memory distinction begins to come to light. Researchers show that people will forget three syllables within a mere 20 seconds if also given another task like counting backwards from 100. This observations made clear the fact that a short-lived memory process was operating in the brain during this 20 second window. .

That process, came to be known as *working memory* and it is distinct from its cousin, *immediate memory*. Immediate memory is concerned only with the stream of information as it is being experienced in real-time. Working memory is an internal, and mostly unnoticed rehearsal process that is critical for carrying out everyday activities.

Working memory allows for the simultaneous analysis of the components in a stream of data. A sentence is a good example. Imagine that you have no working memory and are therefore unable to hold in your mind the beginning of this sentence and, now, at this point, you have absolutely no idea that the subject is working memory.

This is a rather important function. Working memory allows a person to keep one chunk of information in mind while additional sensory data is streaming in. Information can be held in working memory for seconds and sometimes minutes, but at some point it drops away when rehearsal is no longer possible or when another, more attention-getting stimulus is perceived.

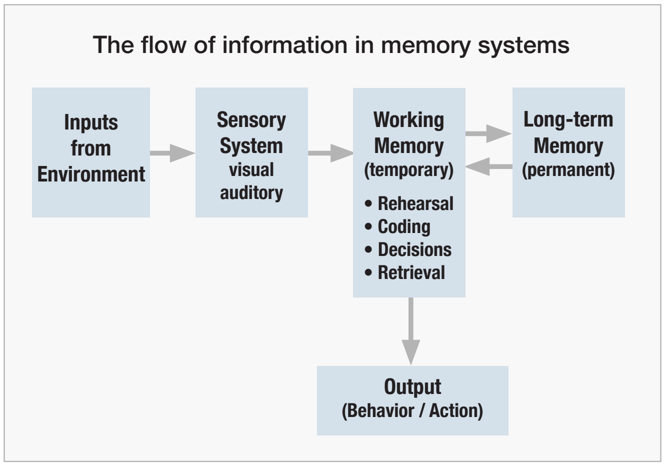
In 1956, George Miller demonstrated that most people can hold seven numbers in working memory (plus or minus two either way) but are generally incapable of holding more.

You can test out working memory on yourself. Read each number sequence and then close your eyes and repeat it back. Continue with the sequences until you fail. Your working memory span for numbers is one digit less than the point at which you fail.

8 3 4 6
7 9 7 1 5
5 7 9 3 5 1
8 1 6 8 3 7 2
3 9 7 5 1 8 3 4
6 8 1 5 9 3 2 7 4
2 8 6 4 8 7 1 2 9 5
9 1 5 7 4 1 2 3 9 5 4
4 9 7 2 6 6 4 2 8 1 6 8
8 2 6 5 7 3 1 2 8 6 4 8 6
9 5 7 2 6 4 1 5 9 8 3 5 1 7
6 7 3 2 9 4 8 2 4 6 2 3 7 1 5
3 4 8 1 6 5 7 9 2 7 1 6 8 4 6 2

The limitation of one's working memory make itself known regularly and rather unpleasantly. The reason that most of us have difficulty remembering the name of a person that we are introduced to for the first time is because other processes overwhelm one's working memory of the new name. The smiling new face, the body shape and size, and the apparel covering it, are all being visually analyzed alongside other mental processes that consider emotional affect, social rank, and the overall circumstances of the social setting. Without concerted conscious focus, working memory doesn't have the capacity to hold onto that information or consolidate it into LTM while so many other inputs demand attention.

By the early 1970s, the concepts regarding memory could be summed up in this illustration which ran in Scientific American.



Notice that information from the environment flows into the nervous system through the senses and into both working memory and LTM. Behavior, however, emanates from working memory, not from long-term memory. In this model, working memory draws information out of LTM and the sensed environment, and then integrates both with decision-making processes to tell us how to act in the present moment.

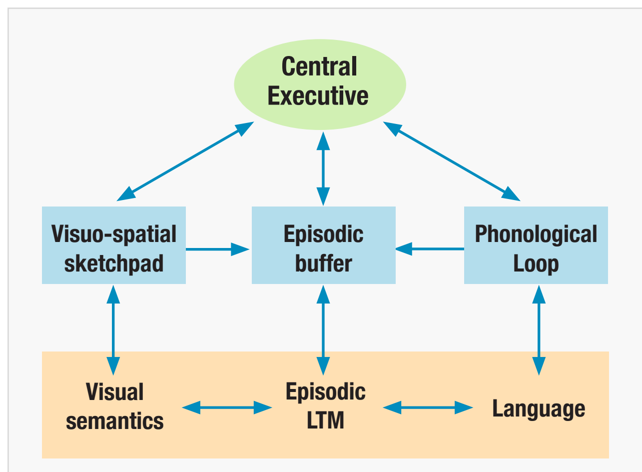
The multi-component model

Further refinement arrived in 1974. The experimental psychologists Baddeley and Hitch fine-tuned working memory into a multi-component model that uses two "slave systems" plus an executive control function that binds them together. The general idea is that the brain utilizes a variety of mechanisms to temporarily store and rehearse memory before moving it into long-term memory. The first slave system is called the phonological loop. It holds onto spoken words and meaningful sounds. The second is the visuo-spatial sketchpad which temporarily stores images like faces and places.

> *"The model we proposed had three components. One of these, the phonological loop, is assumed to be specialized for holding sequences of acoustic or speech-based items. The second sub-system, the visuo-spatial sketchpad performs a similar function for visually and/or spatially-encoded items and arrays. The whole system is controlled by the central executive, an attentionaly-limited system that selects and manipulates material in the subsystems, serving as a controller that runs the whole show."*
> *Alan Baddeley—Memory, 2009*

Additional refinement occurred to Baddeley in 2000 when he realized from experimental evidence that working memory must be somehow integrated with LTM in a more fundamental and important manner. Among other issues, it was noted that people can remember far more words in a sentence than working memory would predict—only seven or so. Therefore, working memory must be drawing on elements like vocabulary, grammatical rules, and various associations stored in LTM. To accomplish this, working memory contains another component—a buffer to store information drawn out of LTM—the *episodic buffer*. As Baddeley notes:

> *"The episodic buffer is assumed to be a storage system that can hold about four chunks of information in a multi-dimensional code. Because of its capacity for holding a range of dimensions, it is capable of acting as a link between the various subsystems of working memory, also of connecting these subsystems with input from LTM and from perception."*
> *Alan Baddeley—Memory, 2009*



The multi-component model of working memory.

The central executive in this working-memory model is responsible for directing attention to relevant information and suppressing irrelevant information. It coordinates the focus of thinking processes when more than one task must be done simultaneously. Attention is one of the key triggers that allow content in the outside world to become converted and stored as long term memory. There are two kinds of attention. One is driven by the central executive from the top down, while the other, known as salience, emerges from the bottom up. The structure of the cortex and related modules allows for this extremely useful function.

The concept of the central executive brings to mind notions regarding the unsolved problem of consciousness. We will examine the idea of executive function and consciousness in the next paper on the biology of memory.

Working memory is an area of intense interest and research at this very moment. Other models are attempting to further distill the ways in which it integrates with LTM.

• Cowan has proposed the embedded process theory which allows working memory to utilize an LTM addressing system. In this model, working memory is a form of LTM.

• Randy Engle, et al, have shown that an important difference among human intellectual ability lies in the length of time that working memory can run, specifically in a measure called *operation span*. In this model, better working memory derives from the capacity to inhibit interference from other stimuli. A knack for shielding working memory from extraneous distraction appears well correlated with cognitive performance.

• In the time-based resource sharing models, rehearsal is the predominant source of working memory. In this theory, attention is intermittently re-focused on the memory trace as it fades. External inputs that affect the ability of working memory to hold information are called the "cognitive load."

• Other researchers have shown that a longer-working memory semenatic

span predicts a variety of human capabilities. High-span people are better at taking notes, composing essays and complex prose, obeying difficult instructions, and performing reasoning tasks from an IQ test. Some researchers have found a link between working memory and "fluid intelligence."

These findings are giving educators a better model for diagnosing and dealing with attention deficit disorders in children. Kids with ADD can be seen to have deficits in some aspects of the multi-component model of working memory. It is becoming increasingly clear that the attention element of ADD is connected to a child's working memory facility. Happily, teachers now have methods for adjusting their teaching style to the vagaries and limitations of a child's working memory.

Long-term memory

Broadly speaking, you can see how working memory and LTM are integrated. Long-term memory is, in many ways, the faculty that makes us who we are.

> *"Most of what we know about the world is not built into our brains at birth but is acquired through experience and maintained through memory—the names and faces of our friends and loved ones, algebra and geography, politics and sports, and music... As a result, we are who we are in large part because of what we can learn and remember. "*
>
> *Eric Kandel—Memory, 2009*

Two kinds of LTM—explicit & implicit

To get a sense of how we remember the past, we must first distinguish among the kinds of LTM that people make. Foremost is the distinction of *explicit* and *implicit* memory.

Implicit memory is very often called procedural or non-declarative memory. Driving a car is a good example. It is a skill that happens automatically, but not at first. When we first learn to drive, attention is intensely focused on every aspect of the vehicle. By consciously manipulating the gas pedal, the steering wheel, and the brakes, over time driving becomes a mostly unconscious act. It is a memory retrieved automatically and it is actually performed best when NOT thinking about it too much. When driving becomes a skill, the memory that drives the driving is implicit memory.

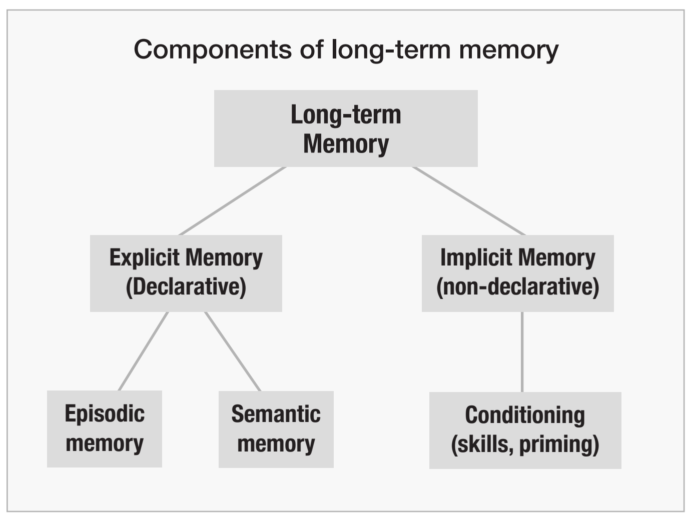
Explicit memory, on the other hand, is a kind of memory that can be talked about. It is often called declarative memory. It consists of faces, places, names, objects, events, processes, and facts. The information that is transformed by the brain into explicit memory is produced through parental training, social interaction, media exposure, the internet, classroom instruction, books, and so on.

There is one last distinction within explicit memory that one must understand to grasp the kind of information students learn.

Two kinds of explicit memory—episodic & semantic

Is a tomato a fruit? Is the Dalai Lama a Buddhist? Is the tongue of a blue whale the size of an elephant? What is the name of your favorite uncle? Does ungulate describe a kind of plant? Is San Diego north of Los Angeles?

Since you have made it this far, it's likely that you had trouble with only a couple of those questions. There is a massive amount of information just like that, encoded, stored, retrievable, and not yet forgotten in your brain. This is semantic memory. It is a certain class of explicit memory and contrasts with the other type of explicit memory called episodic memory. That distinction was formulated and proven out by the great experimental psychologist, Endel Tulving in 1972.



Episodic memory is the recollection of events. This type of explicit memory encompasses the autobiographical elements of where, when, and what—the day you graduated from college, a first kiss, last year's Thanksgiving dinner, and so on.

Semantic memory, on the other hand, contains the facts, figures, and data that one learns over a lifetime of experience and study—that Abe Lincoln was the 16th American president, that the pilgrims ate the first Thanksgiving dinner, that Darwin discovered evolution.

It is semantic memory that is the focus of Amplifire's special abilities. The importance of semantic memory cannot be overstated for it is the acquisition of facts and data that allows people to assemble higher order thinking, intelligence, and some would argue, greater consciousness as the final outcome. For example, thinking about memory, as we are doing now, is producing a chunk of semantic knowledge that can be combined with other chunks from one's life experience to form wholly new ways of seeing and interacting with the world.

Semantic memory—how is it stored?

How are facts, events, and places organized in the brain? A host of reasonable theories have come and gone. One initially attractive notion had a memory stored in a discrete location in the brain. In this early model, all the components that make up an orange—its taste, texture, and appearance would be found in a collection of neurons in a particular location—one location for any one thing. This turned out to be wrong.

Hierarchical model

An improvement came in 1969 that began to explain some of the observations of real people retrieving semantic memories. The hierarchical model of semantic memory was proposed by Collins and Quillian. In this theory, information about things and concepts is stored in many branching networks of categories that hold generalized descriptions that apply to each. For example, a canary and eagle are different sizes and color but they share important traits—both have feathers and fly, and are consequently categorized in the hierarchy as birds.

The hierarchical model feels right but it had a problem highlighted by experimental observations of people retrieving semantic memory. The model couldn't easily explain why it takes more effort to retrieve the fact that a penguin is a bird than it does to retrieve the fact that a canary is a bird. What became clear is that people really group items based on their *typicality*. A penguin has many bird qualities but it doesn't fly—a typical trait of the organism we call a bird.

Multi-property model

The hierarchical model, along with others that were proposed throughout the 20th century, have been found inadequate. The theory that appears to fit the data, including observations of people who have suffered brain damage and show semantic-memory deficits, is called the *multi-property approach*. In this model, presented by Cree and McRae in 2003, the knowledge of things, facts, places and people is conceived as a combination of seven features—color, function, taste, smell, parts, sound, and motion. Each feature type is stored in a region of the brain that specializes in processing information of that type.

This model must be closer to a true description of the organization of semantic knowledge because it is confirmed by three other observations. First, fMRI images show that memory is distributed throughout the brain. The archetypal orange is stored in areas that specialize in vision, taste, and shape. Second, it is certainly true that the one's knowledge of the world is based on the various physical qualities of its constituent parts at varying scales. At this moment, the room you are in can be conceived as an interior space, or you can focus on the color or function of your desk, or you can get in close and notice the textured grain of the wood and the matte finish of the lacquer. These combined properties together form a sensory/functional model of general and specific information about the room you currently occupy. Third, the multi-property model accounts for brain damaged patients who exhibit difficulty naming an object like a hammer. In these unfortunate cases, the region of the brain that specializes in understanding an object's functionality is impaired. Complimentarily, patients who exhibit impairment in sensory areas of the brain that handle components of vision (there are roughly 50 regions that contribute to vision) will have difficulty grasping the subtleties of an orange.

Schemas

Semantic knowledge is more than just simple facts and concepts. It is obvious that people can develop extremely deep, nuanced, and integrated knowledge in disparate activities and knowledge domains. They do so by assembling smaller units of information into a greater whole—schemas, as first proposed by Sir Frederic Bartlett. Low level schemas are like the automatic process of getting food in a restaurant. High level schemas are mental constructs such as sophisticated models concerning world history, scientific theories, and even the structures that form political points of view.

Low-level schemas are wonderfully useful for navigating the world without elaborate calculation. The process of ordering food in a restaurant is an example of an automatic semantic procedure that is composed of many remembered parts. In the fast food schema, you order at the counter, find a table yourself, wait for your number to be called, and pick up your own food at the counter. In the fancy restaurant schema, you wait to be seated by the host(ess), order through the waiter, and wait for food to be brought to your table. A certain decorum is part of that schema. There are countless schemas that allow for the effortless recall of procedures and processes.

Schemas let us make inferences that connect many dissimilar parts into cohesive wholes. Consider the following story:

> A newspaper is better than a magazine. A seashore is a better place than the street. At first, it is better to run than to walk. You may have to try several times. It takes some skill, but it is easy to learn. Even young children can enjoy it. Once successful, complications are minimal. Birds seldom get too close. Rain, however, soaks in very fast. Too many people doing the same thing can also cause problems. One needs lots of room. If there are no complications, it can be very peaceful. A rock will serve as an anchor. If things break loose from it, however, you will not get a second chance.

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Notice that meaning is painfully elusive as your mind sorts for a way to make sense of the parts. An overall schema is necessary and it can be quickly obtained by the word "kite." Knowing that one concept makes every disjointed observation fall in place. Try reading the passage one more time.

High-level schemas are constructed from rudimentary chunks of semantic knowledge that are learned in school, from parents and society, and from exposure to media. The expertise of specialists is a high-level schema formed from extremely well-integrated memory in a specific domain of semantic knowledge. Examples of schema expertise exist in realms such as the political history of Bolivia, the uses of quadratic equations in bridge design, and the role of proton pumps in mitochondrial energy production. In these cases, a portion of the real world is so well encoded and represented in the brain as memory, that easily retrieved knowledge can then be re-fashioned into new models, theories, and understanding.

Built-in genetic and personality biases will also influence how complex high-level schemas are formed. An interesting, and in ways, dispiriting aspect of schemas is that once people form them, they are highly resistant to modification through new, more accurate, but contradictory information. Bartlett showed that cultural influences bias the way that new information is organized in the brain so that it fits comfortably into the pre-existing schema. New information that doesn't match the schema is either quickly forgotten or altered in fundamental ways to fit the existing framework.

Certainly, this explains the resistance and even disgust that people experience in the company of new ideas, worldviews, and economic or political points of view. While schemas are extraordinarily useful, and indeed, we couldn't navigate the world without them, the downside is that over-reliance on them makes us vulnerable to old, incorrect, and biased habits of thought.

Retrieving memories

Cues

Both experimental evidence and common experience show that a memory is retrieved using cues from the environment. The brain integrates sensory information coming in from the world (cues) into working memory and actively looks for the desired trace in LTM. For example, if you are trying to remember where you parked your Volvo in a crowded parking lot, various physical landmarks are the cues that will guide you to the vehicle. If you didn't pay attention to these spatial cues while leaving your car (and get them into LTM), then you are likely to have a difficult time remembering its location.

The cue phenomenon operates in all memory retrieval even though much of the action is below consciousness and working away automatically. To see cuing at work in your own brain, try the demonstration below that asks you to retrieve the names of capital cities. Cover the letters in the right column which is the first letter of the country's capital city, and then try to name the city. Then, uncover the letters and notice if there is a change in your memory retrieval ability.

Peru	L	Argentina	B
Australia	C	Vietnam	H
Canada	O	Hungary	B
Austria	V	Libya	T
Finland	H	Afganistan	K
Sweden	S	Norway	O
Iran	T	Colombia	B
Kenya	N	Belgium	B

For the capitals where you needed the letter cue to identify the city, the memory trace of the city was clearly already in your brain. Without the cue of the first letter, many of the capitals are surprisingly difficult to retrieve. People can generally only remember about 16% of the cities without the letter cue. With the letter, the retrieval rate jumps to over 50%—a 300% gain.

Various sensory cues can serve to retrieve the trace. Sights, sounds, and smells all activate memory. Who hasn't had the experience of an unexpected aroma taking you back to very early years in a startlingly vivid flashback? We are remarkably competent at using a variety of cues to search the database of memory traces and pull out the correct information that forms the contents of explicit memory.

The mechanism that gives the brain access to this database is called *spreading activation*. Think of activation as the energy level of the associated neurons that form a memory. Recent memories are generally more activated and, hence, are more easily retrieved. Because the brain is wired in a vastly interconnected network, a cue that sends out "energy" into the network will activate associated memory traces and bring the *target memory* into consciousness. A lamppost might suddenly activate the target memory of where your car is parked. The letter L might activate the target memory of Peru's capital city, Lima.

Signal Strength

When recognizing an aspect of the environment as previously encountered (learned, or heard, or seen), memory strength lies upon a continuum. High *signal strength* memories are easily accessed while low signal strength memories are difficult or impossible to retrieve. Utilizing spreading activation, we are able to detect the strength of a memory trace by the signal it transmits and we can describe that strength in language that reflects our perception of it. Memory traces with weak signal strength and poor familiarity lead a person to feel doubt and express it in terms such as, "I'm not sure" or "It's somewhat hazy." When a memory trace is encoded weakly or becomes degraded with the passage of time, a person will feel little familiarity and say things like, "I haven't a clue." A signal that has been encoded deeply will be described as the feeling of certainty and stated in terms such as, "I'm totally positive."

The theory of signal strength has proven useful in explaining much of how we judge familiarity, but it can't be quite all there is to detecting a memory trace. Experiments unexpectedly revealed that recalling a word is easier for certain words that are used infrequently. Signal strength should be low for these rarely used words and recognition should be more difficult. Instead, it's easier.

Familiarity and recollection

To handle observations like this, theorists have developed a *dual-process* model for memory recognition. One part of the retrieval process is *familiarity*. This phenomenon is driven by signal strength, the process that we have just learned about where strong physical signals make the memory seem familiar. The other component is *recollection*. It's the active remembering of the details and particulars of an experience or event. Familiarity is nearly instantaneous—the sense of the memory trace is perceived in near real time. Recollection is slower and demands more attention. Details that represent the memory are recalled bit by bit and recognition is assembled from many parts and from different areas of the brain.

In 1985, Tulving, developed his remember / know procedure in which people express how they recall a study item, either by remembering it (recollecting) or knowing it (familiarity). Continuing research in 2002 has shown that distraction during learning will impact recollection more than familiarity. This finding is born out in studies of brain=damaged patients who have more trouble recalling the details of information than judging its familiarity. The dual-process model of recognition memory takes both components into account. Familiarity corresponds to the signal strength of memory while recollection is the piecing together of details that eventually lead to the whole memory.

Forgetting

Trace decay

A memory trace is composed of a pattern of neurons connected by synapses. The trace decays as synapses weaken and disappear with disuse. As Baddeley has pointed out, this is very likely one main cause of forgetting because neuroscientists can observe synaptic degradation in simple nervous systems like that of the mollusk Aplysia. Although it's impossible to test experimentally in humans, (an experimenter would somehow need to isolate a person from any stimulus that might reactivate the trace) nervous systems in creatures as disparate as mollusks and monkeys work in fundamentally identical ways. Trace decay is undoubtedly one of the reasons that memory is transient with time.

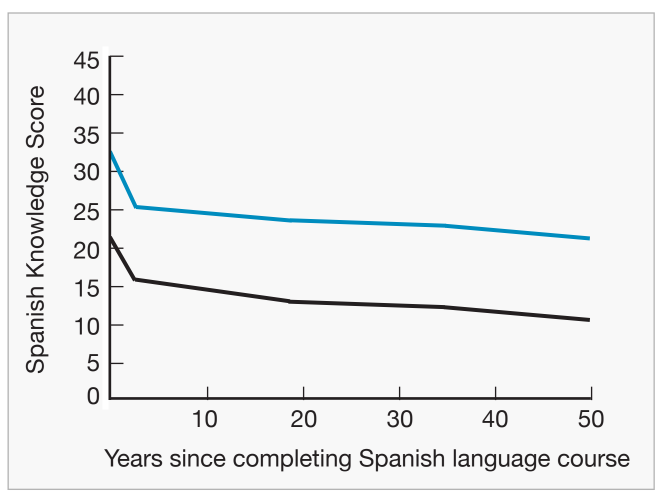
Interference

Beyond trace decay due to synaptic degradation, another form of forgetting is driven by the fact that similar kinds of memories can become jumbled together and impede accurate recollection. This is *interference*—when memory traces that have overlapping characteristics become confused with other traces. We can think of the various traces as competing among themselves for attention and retrieval. This is due to the fact that a single cue may be attached to and activate (via spreading activation) a host of memory traces which are in competition with the *target memory*. As the number of traces attached to any cue increase, the possibility for confusion and/or forgetting arises, a phenomenon know as *cue-overload*.

Consider once more the problem of finding your Volvo in a crowded parking lot. This is not the first time you have been in a parking lot and they all tend to look similar—either asphalt or concrete, painted lines, support structures, and a payment booth. The cues you will use to find your car are the landmarks of the lot, the Volvo itself, an image of yourself driving it, and so on. Unfortunately, these cues are all attached to many other similar circumstances that have their own memory traces and unless particular attention was paid, so that the new memory trace can out-compete those others, you will soon be hunting about for your car.

Permastore

Studies of a person's memory spanning fifty years have confirmed Ebbinghaus' observation of rapid forgetting within the first hours and days of learning but they have also revealed that memory becomes extraordinarily stable after that initial decline. In topics ranging from geographic memory to recall of a foreign language, Harry Bahrick's studies have shown memory stability that lasts for decades. He calls this kind of long-lasting memory *permastore* and it can be clearly seen in the following graph.



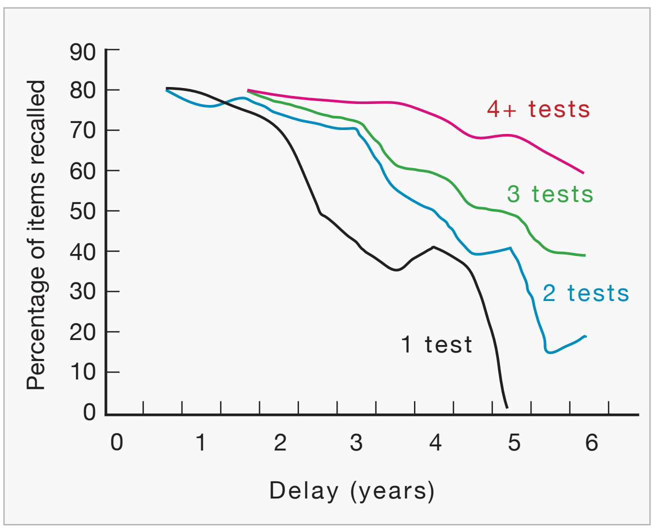
Foreign Language Retention

Notice that the initial depth of knowledge persists over time. If you learned a subject deeply in the first instance, then forty years later, you'll have twice the recall of the material than a classmate whose initial encoding was not as strong.

Retrieval slows forgetting

In a related vein, Marigold Linton's experiments on retrieving episodic memory show that the act of retrieval strengthens the original memory trace and greatly slows forgetting. As we have seen, a memory trace is made stronger by deep encoding at the time of original input. Linton shows that it can also be strengthened by its retrieval.

In this study, Linton made daily entries in her diary that described two events from each day over a five year period. At set intervals, she randomly selected events and tested her ability to recall them. Eventually, the data showed a remarkable pattern—retrieving a memory has a huge effect on whether it will be remembered in the future. For Linton, memories that were retrieved only once became progressively unrecoverable after five years. Memories that were retrieved four or more times could be retrieved about 65% of the time after five years.



The influence of testing on forgetting and recall

Learning

Since we now know a few things about memory, let's consider the problem that students face when learning and using semantic information. The learner's context is irrelevant. This could be a biology student viewing an animation of the organelles that drive the cell interior. It might be a patent lawyer listening to the latest supreme court ruling regarding intellectual property. Perhaps it's a factory manager studying the operations manual for a recently delivered Korean-made robot welder. The processes in the brain of our learner are the same. Let's call him Bill.

- Bill's new memory traces are being encoded through the language of synaptically connected neurons.
- His attention is directed by the brain's central executive to the content that he wants to remember, but other salient environmental inputs, like email, Twitter, and phone calls, clamor for attention
- Bill's working memory holds onto the information in its slave systems—audio is in the phonological loop and sights are in the visuo-spatial sketchpad.
- Working memory is automatically combining information pouring in through the senses with a small portion of long-term memory drawn into Bill's episodic buffer.
- Within minutes or hours, the memory trace is transferred from Bill's working memory to LTM storage via consolidation.
- The memory trace that represents the material is now stored in a distributed manner throughout Bill's brain. Some is in the frontal lobes, other bits are in the sensory cortex that first processed it, some may still reside in the hippocampus, emotional components might be represented in the amygdala.
- Without activating additional mental switches like repetition or elaboration which trigger stronger synaptic connections, the memory trace begins to lose signal strength.
- What memory now remains is associated and integrated with preexisting, higher order schemas. Information that does not fit Bill's schema may or may not be discarded.
- The signal strength of the trace suggests degrees of familiarity with the information. These "feelings of knowing" range from ignorance, to doubt, to certainty.
- Recollection requires that Bill reassemble and retrieve numerous memory trace details to form a complete memory.
- When retrieving the target memory for use two weeks later, spreading activation allows the highly distributed trace to be re-assembled. Bill remembers it and the trace is strengthened by its re-activation.
- But retrieval is occasionally in error because various cues in the environment are activating historic memory traces that overlap and compete with the target. Familiarity might give Bill confidence, but interference retrieves misinformation.
- Despite the many reasons that Bill's studying shouldn't encode, store, or be retrievable later on, some memories can accurately persist for many decades.

Switches and triggers

Memory is a rather staggering invention of nature that allows Bill to remember his studies. Let's briefly touch on a few of the psychological effects that help to encode memory deeply and stave off forgetting.

Repetition

We have already seen how Ebbinghaus originally demonstrated repetition's power to boost encoding and storage, and to slow forgetting. Recently, it has been shown that Ebbinghaus' forgetting curve is a bit steeper and more dramatic than real-world forgetting. This stems from the fact that Ebbinghaus had to use made up syllables so that his learning was not contaminated by previously-learned words or phrases. This gave his experiments rigor, but it also made them somewhat less like reality. Other factors like elaboration also help make memory that sticks in the mind.

Elaboration

Normally, people learn new information that is built upon previously learned information. The new and the old can be elaborated in the mind by forming associations with other material that has meaning for the learner. When people find meaning in information, encoding processes are intensified by elaboration and learning sticks in memory storage.

A compelling demonstration of the process can be shown with simple lists of words. Subjects are asked to remember a list containing words like lion, CAR, table, Tree. They are asked to note if the words represent things that are living or nonliving, or if they are in uppercase or lowercase letters. The living-non-living aspect creates elaboration and people easily remember those words. After all, it takes real thought to categorize objects in that way. One is forced to picture the thing itself, the environment it inhabits, and other associated concepts. Conversely, letter case is irrelevant to the meaning of the word and one's previous knowledge about the thing is not brought to bear. There are no associative concepts with which to elaborate.

Emotion

The neuroscientist Robert Burton has argued that a previously unrecognized emotion is associated with semantic knowledge. He calls it the "feeling of knowing." Conventionally, the core human emotions have been mental states like anger, sorrow, and joy (mad, sad, and glad). Burton explains that people can describe how they feel about their internal knowledge by using words like doubtful, positive, no clue, and so on. He argues that these feelings are a basic emotion. Psychologists call these internal appraisals, "judgements of learning" and they have now been imaged by fMRI scanners. Those images show judgements of learning operating in the brains of people as they try to access information stored as semantic memory. Experiments at MIT and Stanford are revealing that accessing these "feelings of knowing" makes for better learning and deeper LTM.

Attention

Attention, as common wisdom teaches, is a vital component of learning. Much like emotion, it encodes a strong trace memory by recruiting more synapses into the pattern. Attention is an evolved trait for producing memory because the bearer of a strong memory can adjust its future behavior appropriately the next time a similar attention-getting circumstance arises. One type is under executive, top-down control. The other, *salience*, involves bottom-up processes that arise from the sub-conscious.

Retrieval

As we have seen from the Linton studies, the mere act of recalling a memory into consciousness strengthens its trace. In some circles, this is known as the testing effect. Retrieval strengthens the memory trace by re-activating it. Study habits that refresh memory by asking for its retrieval are an effective method for making memories stick. This memory feature works when re-reading the events in a diary or testing ones knowledge of macro-economic fundamentals. In both cases, memory will be amplified.

Summing up

The view from psychology has shown us many useful descriptions of the memory processes that give rise to learning. With that knowledge now in our own minds, it is possible to modify our personal schemas if we care to. This knowledge gives us the opportunity to know ourselves more accurately and to understand others far better. All of us hope for unbounded potential but we clearly face limitations.

Let's briefly review the concepts.

- *Encoding* converts sensory information into a format suitable for storing in organic tissue.
- *Storage* takes place through a pattern of connected neurons that form a *memory trace* that is widely distributed.
- *Retrieval* re-assembles disparate memory traces to build a coherent memory.
- The *forgetting curve* shows how *repetition* slows the *transience* problem.
- C*onsolidation* moves working memory into LTM.
- *Working memory* is a complex integration of buffers, loops, sketchpads, and LTM, all bound by a central executive.
- *Attention deficit disorder* appears to be an issue involving components of working memory.
- *Long-term memory* can be implicit or explicit.
- *Implicit memory* drives unconsciously performed skills.
- *Explicit memory* can be consciously talked about.
- *Episodic memory* is about autobiographical events.
- *Semantic memory* is facts, places, faces, and data. It is information received from parents, peers, media, and school.
- *Sensory perceptions* or *functional utility* appear to be the categories in which semantic memory is stored in a multi-property model.
- *Schemas* arrange many smaller bits of semantic memory into higher order constructs—from procedures in a restaurant to one's view on the proper role of government.
- *Cues* guide the retrieval of a target memory. Cues can be attached to more than one memory trace. Cue-overload makes a trace difficult to retrieve.
- *Spreading activation* energizes associated neurons that form a memory trace.
- *Signal strength* determines familiarity.
- *Recollection* assembles the details that form a whole

memory.

- *Trace decay* happens because synapses fade with disuse.
- *Interference* occurs when a cue activates overlapping and competing memory traces that share the cue.
- *Permastore* memories can exist for many decades.
- Certain *psychological switches* cause memory to be encoded more strongly in storage and less easily forgotten.

Next up

In the next paper, The View from Neuroscience, we'll examine the biological and structural basis for the psychological models of memory and learning we have just covered. An astounding general proposition is that all this memory-making activity happens through physical changes in living tissue. Signals arriving from the outside world alter the living structure of our interior selves.

A series of remarkable discoveries about the biology of the brain has formed an alliance between psychology and biology. Scholars consider it a 'new synthesis." For the first time, the behaviors and actions of creatures as complex as people can be causally linked to underlying physical phenomenon at various scales—from genes and molecules all the way up to large collections of neurons that form functional regions with specific tasks.

Perhaps Eric Kandel, whose discoveries we'll be reading about next, says it best:

> *"The convergence of psychology and biology has led to a new synthesis of knowledge about learning and memory. We now know that there are many forms of memory, that different brain structures carry out specific jobs, and that memory is encoded in individual cells and depends on changes in the strength of their interconnections. We also know that these changes are stabilized by the actions of genes in nerve cells, and we know something about how the molecules inside nerve cells change the connection strength between nerve cells. Memory promises to be the first faculty to be understandable in a language that makes a bridge from molecules to mind—that is, from molecules to cells, to brain systems, and to behavior."*
>
> *Eric Kandel—Memory*

Further Reading:

Memory—Baddeley, Eysenk, Andeson,

Memory: from Mind to Molecules—Eric Kandel & Larry Squire

Knowing What Students Know—National Research Council / National Academies

The Blank Slate—Steven Pinker

How the Mind Works—Steven Pinker

The Seven Sins of Memory: How the Mind Forgets and Remembers—Daniel Schacter

Descartes Error: Emotion, Reason, and the Human Brain—Antonio Damasio

On Being Certain: Believing You Are Right, Even When You're Not—Robert Burton amplifire

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