A NEUROSCIENCE PERSPECTIVE ON LEARNING

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In 1997-98, J.M. Haile wrote in this journal[1-3] a series of three articles entitled "Toward Technical Understanding." The first article described brain structure and function and indicated that the mind is what the brain does. The second and third articles discussed a seven-step hierarchy to understanding and the importance of the transitions between each step. Since Haile's original articles, several major neuroscience advances have become common in both experimental techniques (*e.g.*, functional magnetic resonance imaging [fMRI]) and brain learning mechanisms (*e.g.*, protein synaptic growth) that have changed the paradigm for learning applications.

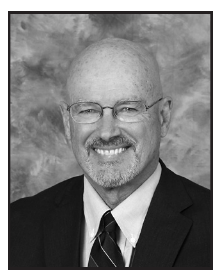
This work builds on Haile's brain-pedagogy foundation by applying principles of neuroscience research, as summarized for example, by Rudy.[4] Recently a review[5] has stated the fallacies of applying neuro-myths in teaching. Instead, we suggest neuroscience foundations of well-established, familiar pedagogical principles, which may enable new extensions, and present a few non-intuitive surprises. In other words, it is our thesis that neuroscience provides a helpful new perspective for thinking about learning. After a brief exposition of memory, the work is bifurcated into three principles and four applications.

THREE TYPES OF MEMORY AND FORGETTING

Initially let us define three types of memory. Short-term memory is remembering some fact for a few seconds, *e.g.*, long enough to remember to "Carry the 2" when adding a column of numbers. It is quickly analyzed for value and can be quickly forgotten. In contrast, long-term memory is information that is remembered for long stretches of time, like the name of one's kindergarten teacher or the words to the Mickey Mouse Club song. It is something that has been remembered, either due to repetition or its connection with other memories. Between the short-term and long-term memories there is working memory. This is the information one pulls from short-term and long-term memory to help with problem solving. Working memory is limited in size, much like a person's workspace. One can only hold a limited amount of information (*i.e.*, four items, perhaps abetted by "chunking") in working memory. But much like a workspace, one can access other files and reference material when wanted. Working memory can rapidly sift through information to discern the useable information.

When memory is moved from short-term to long-term, the process is called consolidation. Reconsolidation occurs when memory is pulled out from long-term to working memory, then put back into long-term memory. Reconsolidated memories are never exactly the same as the original memory. Both time and context have changed since the original consolidation. Pulling up a formula to working memory and deciding it does not solve the problem may be laced with frustration as it is reconsolidated. One might remember that the next time one pulls up that equation.

Another important aspect of memory is forgetting. In Haile's second article,[2] he writes about the hierarchy of learning, which sometimes requires forgetting previous knowledge. Learning that babies come from mommy's tummy will need to be relearned as a person ages. Erroneous information must be forgotten and simple explanations must be augmented to further the learning process to increase the level of understanding. These are the transitional states in Haile's understanding hierarchy.



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THREE NEUROSCIENCE PRINCIPLES

There are differences in the definitions of memory, learning, and understanding. The difference between learning and understanding is at the foundation of the Haile articles. Learning comes with the establishment of long-term memory and the ability to retrieve that memory at a later time. Understanding is being able to take the previously mentioned long-term memory and apply it to a new situation or novel setting.

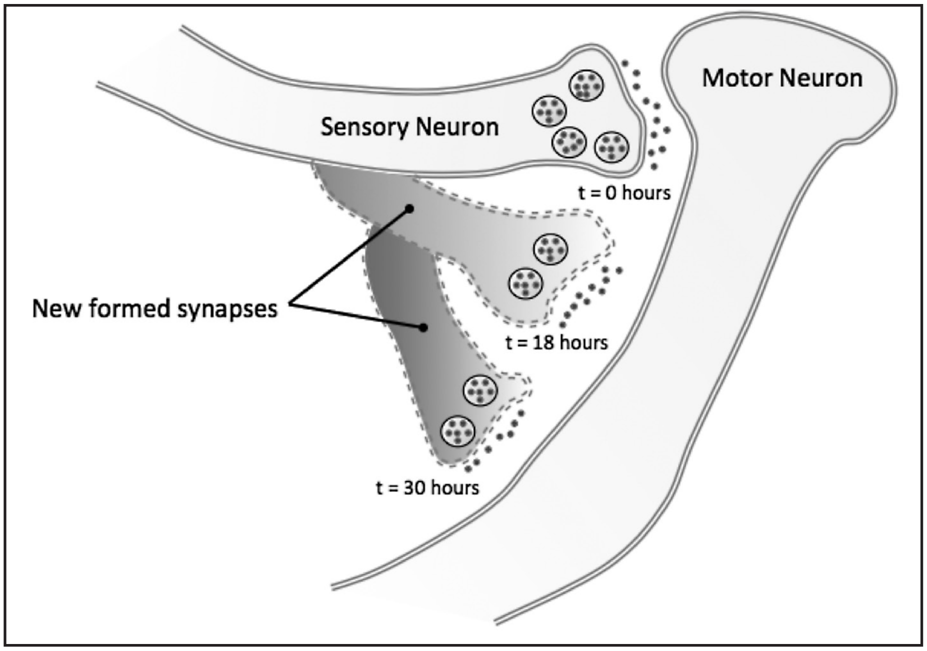

Figure 1. Short-term memory requires neurotransmitter release (dots) occurring at 3-4 hours, but long-term memory requires new protein growth (dashed lines) over 18-30 hours, as new experiences are partially consolidated (copyright 2013 by Sloan and Norrgran,[10] used with permission)

Man has been interested in thought processes before the brain was even acknowledged as the organ producing these thoughts.[6] Thus, "thinking and memory" started in the realm of philosophers such as Aristotle[7] in the fourth century B.C.E., before transitioning to the cognitive psychology by such thinkers as William James[8] at the end of the 19th century. With current technological advancements, thinking, memory, and understanding have moved to the world of neurobiology. As one pedagogical indicator, many university psychology departments have evolved to psychology/neuroscience departments.

Memory is the basis of learning. Without the production of memories, learning and understanding cannot progress. The brain hierarchy is first memory, then learning, then understanding. To comprehend the biology of memory and learning, one needs to understand the structure of the brain. As a first approximation, this requires comprehension of three concepts: the synapse, the three-brain theory, and the prefrontal-hippocampus-neocortex interplay, outlined in the next three subsections.

1. The synapse: biological basis of memory

Memories exist due to the biological network between the brain cells, known as neurons, in the spaces between them, called the synapses. There are 10^{11} neurons in the brain (approximately the number of stars in our galaxy) and each neuron has thousands of synapses. Such a large number, despite each memory requiring thousands of synaptic connections, is sufficient for memories over our lifetime.

In Nobel prize-winning work Kandel[9] and co-workers determined microbiologic pathways for establishing long-term memory, as protein growth in the synapse between neurons, as shown in Figure 1, for signal transmission between a sensory and a motor neuron.[a] This growth process enables more area for enhanced transmission of electrochemicals (neurotransmitters) at the beginning of long-term memory (or long-term potentiation).

Such protein growth requires a significant time, typically 18–30 hours. As one encounters new experiences, with repetition and connection to other memories, the brain physically changes by growing proteins. Remarkably, this is one molecular reconciliation of the nature versus nurture dichotomy, combining both as we grow memories in a new environment.

Suppose a student is first presented with the concept of chemical potential. If she recognizes the importance, and believes she can understand the concept, she may spend the energy necessary to grow protein to understand this new concept. She searches her memory to determine what the new concept can be compared to. Her thinking stimulates new synaptic buds in an effort to connect to existing synapses. The locations of these budding synapses depends on the success of the teacher, relating them to existing neural synapses,

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a *Recently some research[11,12] has suggested that new protein is not required until existing, available protein has been depleted, and molecules at the synapse have been rearranged.*

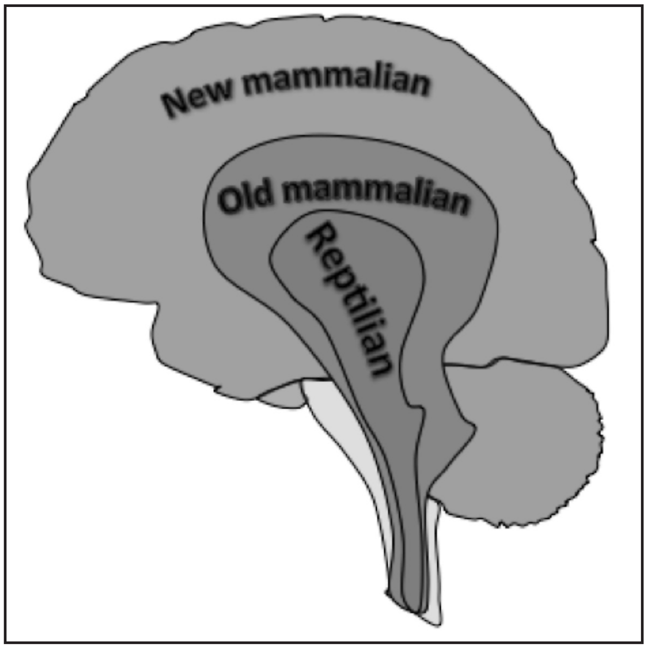

Figure 2. *The three brains build upon one another, from the reptilian brain (archicortex), to the old mammalian brain (paleocortex), to the new mammalian brain (neocortex). (copyright 2013 by Sloan and Norrgran,[10] used with permission)*

or existing memories, *e.g.*, concentration, temperature, and pressure. If the initial exposure misguides the synaptic connections (*e.g.*, to potential energy), then synapses will bud on the wrong neurons, and the student will be faced with unlearning, in order to establish correct synaptic memories. With subsequent practice and familiarity, chemical potential will be connected to other neural networks involving phase equilibria and chemical reaction equilibria memories.[b] The professor might suggest motivating applications, *e.g.*, connections to separations and chemical reactions, to help guide the initial, correct synaptic connections.

2. Three brain portions build upon each other

The three-brain theory provides an approximate foundation for the evolution of memory, learning, and understanding. The brain is divided into three parts according to both the histological structure and physiological function, shown in Figure 2. The least evolved part of the human brain is termed the reptilian brain or archicortex and is found in all animals to some extent. The archicortex is a brain section between the spinal cord and the neocortex, containing three layers of gray-matter cells that control the basic physiology of the organism, *e.g.*, heart rate, breathing rate, digestion, hormonal release, body temperature, etc. The reptilian brain takes care of the processes that we don't have to think about. It runs autonomously and takes orders from the feedback of higher centers of the brain.

Further along the evolutionary pathway the paleocortex arose. This component of the brain is what some call the instinctive brain; its concern is with the survival functions of food, fighting, fleeing, and reproduction. According to LeDoux,[13] the brain must learn what to be afraid of, but not how to be afraid. The paleocortex area called the amygdala is the center of our strongest emotions such as fear, anger, rage, excitement, etc. All incoming sensory information is automatically shunted to the amygdala to be analyzed for survival significance. The amygdala adds emotional value to the input. Since the amygdala works with strong feeling, the input that has added emotional valence will be connected in the upper, long-term cortical memory without necessarily requiring repetition. Post-traumatic stress and flashbacks can be initiated in this manner. This added valence can be important to the learning process, stressing certain facts and information quickly, especially for survival. The sensory input-amygdala pathway is known as the rapid, low road of memory processing.

The third, most evolved part of the brain is the neocortex, or brain surface, which makes us human. The gray matter of the neocortex has an area of 1 m^2 and a thickness of 2 mm containing six layers of neurons, distinguishing the neocortex from the lower two brain structures that consist of three to four neural layers each. Undulation maximizes the neocortex area per unit volume by crumpling this brain surface into our cranial volume, and the neocortex sends output downward to the lower two brain portions and to the spinal cord. The neocortex contains numerous association areas that take sensory input and compare it to previous experience and memory. Routine functions are often ignored, such as when you arrive at work but don't remember the route you drove to get to work. Novel inputs attract our attention and are more memorable. When the input progresses through the sensory input-hippocampus-neocortex it is somewhat slower than the low road, and is called the high road for memory processing. All memory ends up in the neocortex, roughly where it was first sensed, localized in the neural network of the brain.

A special portion of the neocortex is the prefrontal cortex, residing roughly above the orbital region. The prefrontal cortex is the portion of the brain that gives us judgment, indicating how our memories should best be used. For example, when our amygdala provides a startle (or "flee") reflex at the sight of a rubber snake, our prefrontal cortex draws upon neocortical memories of real snakes, the sight of non-movement, and the

b *The idea for this example was kindly suggested by self-identified reviewer J.M. Haile.*

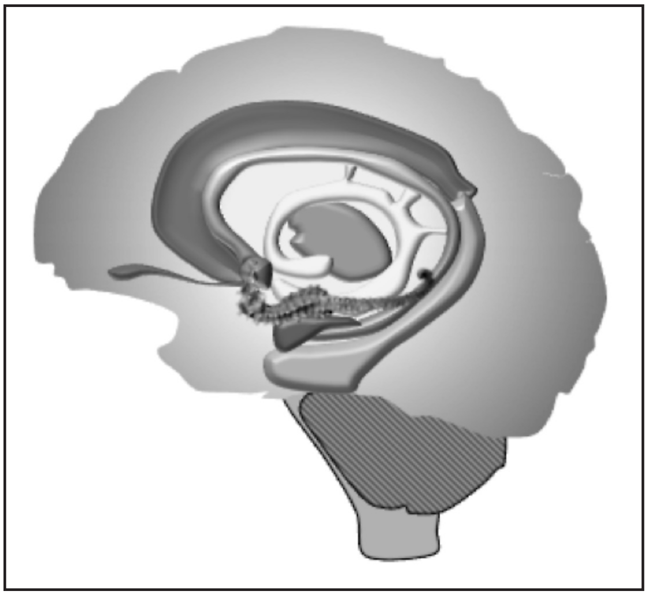

Figure 3. The hippocampus is cartooned as an upward-facing seahorse, midbrain, relative to the outer brain cortex (copyright 2013 by Sloan and Norrgran,[10] used with permission)

smell of rubber, to overcome the startle reflex. Because maturity of the prefrontal cortex may require as much as 30 years, much of adolescent behavior may be of biological origin. Removal of the prefrontal cortex doesn't endanger life function, but the person's judgment becomes severely impaired.

LeDoux[14] summarized the three-brain theory. Without the neocortex, we could not be human; for example we could not think like a student. Without the neocortex we would behave much like a cat, with similar impulses driving our lives. Without the paleocortex, we would be physically but not psychologically alive, behaving much like a reptile or lower animal. Without the archicortex we would die.

3. Memory as a dialogue between the hippocampus and the cortex

In the macroscopic brain, information first arrives through sensory structures such as vision, audition, and touch. After preliminary analysis of the input in the dedicated region of the neocortex, information will transfer to the hippocampus, a small seahorse-shaped structure deep in the temporal lobe, shown in Figure 3. There the input will be prioritized into the important and/or the forgettable.

An eidetic memory is rare; we do tend to forget and we do not generally reproduce the memory-related event like a photograph, video, or computer file. Our brains store our own context and significance to the memory as it forms, recording the gist of the memory, rather than an exact replication. This all takes place in the hippocampus, and is called short-term memory. From here, the memory moves to other portions of the brain and is stored as interconnections among certain neurons, often termed a neural network. One neuron can play a part in several networks, and it is the triggering of the distributed network or connectome[15] that causes memory recall. Thus, there is no single area of the brain that stores memory, but there is one place that moves short-term memories into long-term memories, and that is the hippocampus.

The hippocampus organizes short-term memories for long-term storage. The short-term memories are moved to the neocortex where they are arranged, connected, associated, compared, contrasted, discriminated, and consolidated into long-term memory. This uses past experience, past learning, and emotion in the scaffold of building long-term memory. Time is required: proteins must be constructed, receptors must be built, and transmitters must be produced. This happens at the speed of life, not at the speed of computers. It requires repetition, connection to existing memories, and time.

The prefrontal cortex also plays a role in the storage of memory, adding considered value to the memory, but not the emotional value of the amygdala. The prefrontal cortex adds content such as social appropriateness, judgment, usefulness, and connectedness. The hippocampus, neocortex, and prefrontal areas of the brain all have input into explicit, declarative memory formation—the remembering of facts. Implicit memory formation may bypass the prefrontal area when it is consolidated, in instances like episodic events and motor skills.

The brain builds connections of consolidated memories to form patterns.[16] Pattern establishment and pattern recognition are the fastest, most efficient ways to organize information for later retrieval.[17] Patterns allow the individual to see relationships between bits of information that might not be the product of formal teaching or learning. This organization of memories in patterns is what produces the understanding of the subject that professors want to instill in their pupils.

Pattern establishment is not a memory technique such as repetition. It is also not a technique for recall, such as mnemonics. Pattern establishment is the scaffolding to the building of organized and easily processed information. The implication is that memories are connected to other memories in a hierarchical manner, the way the foundation provides support for the upper structures of a building.

Instead of computing, the brain retrieves patterns from the hierarchical patterns of memory, in a process much faster, for example, than a computer algorithmic search.[18] Patterns are the fundamental currency of intelligence and our certainty of

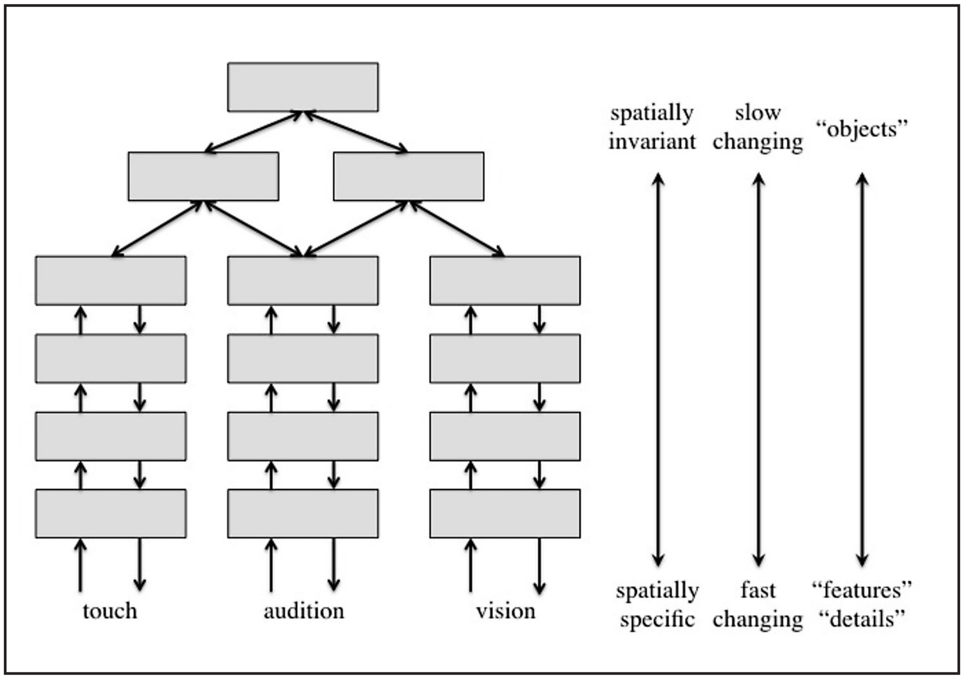

Figure 4. *Hierarchical classification of patterns ascending the neocortex, proceeding upward from detailed structure, to more global pattern structure. Most neurons in the cortex are devoted to touch, audition, and vision, in the ratio 25:25:50 (modified from Hawkins and Blakeslee[18]).*

the world is based on pattern consistency, and our interpretation of them. As an illustration, consider the cartoon diagram of six neocortical layers in Figure 4.

In Figure 4, when specific signals come in at the lowest level, electrochemical input data are in the same form from the dominant three senses of touch, audition, and vision. Taste and smell are relatively underdeveloped senses in humans. Ascending the cortical levels, the association areas of the brain classify the data into patterns, which enable the prediction of incomplete data. That is, while you are still sensing part of the incoming information, your brain rapidly attempts to fill in the remainder of the data, consistent with its stored patterns. At higher levels, the crossover between the senses confirms the patterns.

However, the retrieval of data is much different and relies on the fact that the highest level of the neocortex has horizontally distributed memories. These can reach across many neural column outputs, as shown in the cartoon of Figure 4. The descending pattern retrieval is less direct than the ascending pattern.

It takes approximately 10,000 hours[19] of study to become an expert in professions ranging from professional musicians to computer programmers. This time approximates the period for a chemical engineering degree, plus the five years of practice required to become a professional engineer. Extended practice or graduate work may be required to develop in-depth expertise in a specific area. Once one achieves the status of an expert, the information tends to be at one's fingertips and the patterns of information are easily grasped. This leads to understanding the subject. Any new information is simply added to the structure already in place in the brain's memory storage.

Example 1. The use of patterns in learning transport phenomena

Consider pedagogical patterns in the flagship of modern chemical and biological engineering, *Transport Phenomena*,[20] by Bird, Stewart, and Lightfoot. This book is a hallmark of incorporation of science in the discipline, providing an equal complement to the existing pedagogical philosophy of unit operations. Remarkably, the book was only recently revised after more than a half-century of utility to the profession.

The authors first established a pattern for the momentum transfer, starting with simple basics, then increasing both the challenge and the generality, *i.e.*, (1) molecular transport, (2) laminar transport, (3) turbulent transport, (4) interphase transport, and finally, (5) large-scale systems. Thoughtful, challenging problems are given at the conclusion of each chapter, to ensure the student establishes the momentum transport patterns in long-term memory.

Only after the student has mastered momentum transport, do the authors use the same five patterns for energy transfer, a more complicated transport that complements and enlarges the momentum patterns. Mass transfer, the third topic, is yet more complicated, but is introduced with the same five patterns, and builds upon the other two transport patterns.

After the student realizes the molecular transport pattern analogy of thermal conductivity to viscosity, it becomes easier to fit diffusivity into that pattern. The enlarged pattern simplifies the complement of simple diffusivity, with the complications of stagnant film and equimolar transport.

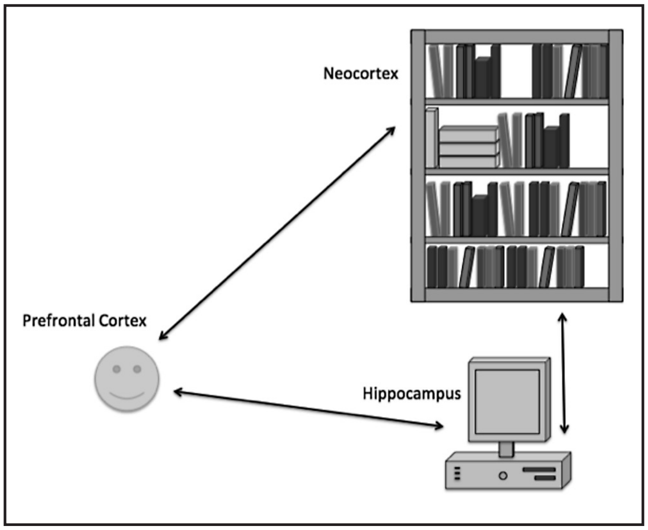

Figure 5. Library analogy for problem-solving interactions between (1) the prefrontal cortex (PFC), (2) the hippocampal (HC) structures, and (3) the neocortex (NC). A person (PFC) takes a problem to an indexing computer (HC) to find references on her topic(s). The computer (HC) shows the problem solver (PFC) where the books (LTMs) are stored in the library stacks (NC) for different portions of the problem. Once in the stacks (NC), the problem solver (PFC) can browse among similar books (LTMs) without returning to the indexing computer (HC), or she can return to the computer for other references. (copyright 2013 by Sloan and Norrgran,[10] used with permission)

Bird, Stewart, and Lightfoot wisely provided similar analogies across all five patterns for the three transport phenomena. Upon completion, the professor might help the student recognize how pedagogical difficulties were avoided to establish long-term memory of transport phenomena. In particular, the difficulty increase in each pattern mimics Figure 4, the ascensions in the three columns of cortex neuron patterns, with crossover analogies at the highest levels.

Consider an extension of the metaphor suggested by Purves et al.,[21] in which the long-term memories in the neocortex are like the books in the upper floors of a library, whereas the hippocampus is like a computer in the library basement, which has an index to all volumes on the upper floors. Without the computer it is impossible to access or index the incoming books, but the shelved books contain references that relate them to other, similar books.

The long-term memories, represented by the books, are the synaptic connections discussed in Section 1. In some cases, the memory may have deteriorated, just as pages or books are occasionally lost, but the neighboring pages/books may help the reader to fill in the missing material. Purves, et al., suggest three main memory features are in the metaphor: (a) small cortical lesions (missing books or pages) produce mild memory deficits, (b) cortical damage produces selective memory loss, and (c) damage to the hippocampus spares much earlier memories (books in upper stacks).

Extending the metaphor slightly, the books on the upper floors are arranged in categories (or long-term memory patterns) so that books on similar shelves relate to each other. In this analogy extension, the prefrontal cortex is like a person who wishes to solve a problem using the information in the library of his long-term memories (LTM), illustrated in Figure 5. After the books (LTM) have been initially located, the person (PFC) may access them without going through the index (hippocampus).

Example 2: The use of memory to solve a chemical engineering problem

As a concrete example, consider a person (PFC) who would like to design a chemical process. She uses an indexing computer (hippocampus) to determine the location of some appropriate books. The indexing computer sends PFC to various library shelves (neocortical memory patterns) that contain books in the major categories of (1) chemical kinetics, (2) fluid flow, (3) heat transfer, and (4) mass transfer. Some of the initially referenced books in the stacks may be missing or misplaced, but PFC can find other similar books in the same topic-area shelves. She could also use references in the originally referenced books, or return to the indexing computer for other references. PFC then combines the information on the four topics to successfully design her process.

FOUR APPLICATIONS TO LEARNING

The above principles lead to a number of learning applications. Of course the experiences of multitudes of bright students and professors make it difficult to determine new applications, because pedagogy has been thoroughly explored. However, if we understand the underlying bases of some existing applications, it may be possible to perturb old applications, or perhaps we might evolve new applications, if we're lucky. Here we present four well-known applications, as examples to get our thinking started in the neuroscience direction.

1. Three physiological bases of learning[22]

Every learner has had the experience of being "stuck"—being stymied on the way to a learning goal, when time and concentration resources were limited. Three fundamental brain physiological principles suggest strategies to become unstuck, when time is of the essence.

First, eat. We know that while the brain cannot store glucose, it is by far the organ which consumes the most energy;

2% of the body's mass consumes 20% of the body's energy —an order of magnitude greater than predicted, based upon mass. We've all had the experience of walking exhausted from an examination after consuming all of our energy while thinking. While calories are important to maintain our ability to concentrate, it is clear they must be of the correct type, *i.e.*, not high in fats.[23] While we wouldn't suggest that students eat during class, it is important to be well-fed (and well-digested), to prevent distractions by hunger pangs.

Second, exercise. Keep blood flowing with a high metabolism to supply the brain with oxygen to combine with the glucose for the high-energy cost of thinking. Chemical engineering *éminence grise* Bob Bird[24] advocates going for a hike to refresh your brain, reinforcing Hippocrates' ancient dictum that, "Walking is man's best medicine." Since the heart is also a much-studied organ, one can take advantage of the heuristic, "If it is good for the heart, then it is good for the brain."

Third, nap. In a study of astronauts, NASA has determined that a 26-minute nap can increase efficiency by as much as 34%,[25] with further increases up to about 45 minutes. Such periods refresh our mental energy, without providing substantial periods for memory consolidation during REM sleep. It is restorative to find a secluded, shady glade on a spring lawn or a quiet chair or library cubby in cooler weather. We do not advocate sleeping in class, or if sleeping is an absolute necessity, the student should not snore loudly enough to awaken neighboring students.

THE PROFESSOR'S ROLE

However, the student can still be stuck even if well-fed, rested, and active. Helping the student to get "unstuck" is often laid at the teacher's feet. Consider the case in which a student has not developed an understanding of the learned concepts, when the student cannot adapt the learned material to a new or novel setting. The teacher must evaluate where understanding is impeded, to help the student fully realize the concept. This is part of the process of helping the student to build a scaffold to make connections between differing learned material, perhaps pulling concepts together from previous courses.

The building of a scaffold for interconnections between learned material can be addressed in the classroom, or in a smaller setting such as office hours. In the classroom, active student engagement has been shown to enhance the learning process.[26] Students will often come to class better prepared if they think they might be called on to answer a question, often known as "cold calling."[27] Besides increasing the student's accountability, students find participatory classrooms more enjoyable than lectures. The initiate-response-evaluate—the I-R-E approach—is a common method of approaching the participatory classroom. The teacher poses a problem, gets a student response (voluntary or cold calling), and then evaluates the response for accuracy. However, this is set up for only one student to participate at a time with the rest of the class passive.

Group discussion centered on problem solving was posed as one solution to the passive classroom. This is a good method for those adept at the technique, as it can be fraught with problems such as getting off point and social loafing.[27] Ways around this are techniques such as graffiti walls,[28] inside-outside circles,[29] think-pair-share,[30] and quick writes.[28] These active-learning techniques are among many others[31] available to supplement the physiological foundation, to develop critical thinking skills for students.

2. The value of spaced learning intervals

If 18-30 hours is required to establish long-term memory protein growth, one cannot hope to "cram" for a test over a six- to eight-hour period and establish the long-term memory needed either for the final exam, or for a profession. The evidence[32] suggests that if only eight hours total are available for study, one should space the learning into two-hour intervals over four days. Such a strategy gives the brain a chance to grow the protein to establish long-term memories, which might only need subsequent refreshment for recall on, for example, the final examination. Of course such spaced study requires significant organization and planning, perhaps aided by mobile devices.

<u>Two Study and Work Skill Recommendations:</u> It is clear that multitasking is much less efficient than single-task performance.[33] More precisely, multitasking is brain "switchtasking," which leads to inefficiencies, so it pays big efficiency dividends to concentrate on a single task. Playing music, or any other diversion while studying, is at best "background tasking"—perilously close to "switchtasking." So try studying without music (or any other diversion) to determine if you concentrate better. Secondly, focus[34] with single-minded, tenacious attention to a study task for about 90 minutes, before taking a brief break, then returning for another 90 minutes to complete one study period.

3. The persistence of the lecture method

The inadequacy of the lecture has been addressed in the pedagogical literature, with compelling evidence.[35] Many believe that the lecture has survived because that is the way faculty learned when they were students, and that many faculty may be unwilling to change.

We do not defend the lecture; such a defense is problematic, with several alternatives in the previous section. Rather neuroscience suggests why the lecture method has persisted since before Thomas Aquinas used slate and chalk at the University of Paris in the 13th century. When a student sees the concepts in a lecture, she uses 30-50% of her neurons in vision; hearing the words of a lecture reinforces vision by activating almost another 20% of her neurons in audition; finally writing down the message activates almost another 20% of neurons through touch. What may explain the lecture's longevity is that many of the brain neurons are reinforcing each other in establishing the patterns discussed in Figure 4. Alternatively, boring lectures may serve to disconnect neural patterns, and encourage forgetting.

This is not to imply that the lecture is better than active-learning techniques, because the data counter that claim. It does suggest however, why lecture has persisted and is likely to persist for millennia[36]; namely, one uses a high percentage of brain neurons in the lecture method if one focuses. In addition, neuroscience implicitly speaks to the memory efficiency of modern educational techniques, such as PowerPoint® and YouTube® via the allocation of neuron subsets. Students generally dislike rapidly transmitted, multiple words (or worse, equations), while they are conditioned by evolution to look at moving pictures for survival.

4. Establishing hierarchical cortical patterns

We frequently consider memories as providing a record of the past, and that is one essential element, but only a part of memory's function. Evidence is clear[37] from functional Magnetic Resonance Imaging spectroscopy that memories enable us to predict the future, using patterns or completing fractions of patterns.

The very young perform multiple repeats of an instance (songs, videos, games, etc., on electronic media) to establish reliable, orderly patterns for the physical world, such as diagrammed in Figure 4. Seen in this light, the establishment and retrieval of memory patterns is one major purpose of higher education. Education enables the partial control of the future so that, for example, posing and solving problems may be reliably based upon past memory patterns.

<u>Example:</u> We give our students meta-guidance like, "Thermodynamics is conceptually challenging. The best way to work a thermo problem is to recognize it as being similar to a thermo problem you've already worked." In such guidance we're encouraging students to establish cortical memory patterns via such things as homework and class examples, and to access such memory patterns for current problems.

Example 3: Expander for natural gas liquids recovery

Consider a turboexpander design in a steady state, natural gas liquids plant. The design results in work produced (W) and outlet temperature (T_2). The objective in decreasing the pressure from P_1 to P_2 from an inlet temperature T_1, is to decrease T_2, so that liquids can be produced from an inlet gas feed, simplified in this example as 90mol% CH_4, 7% C_2H_6, and 3% C_3H_8.

The design requires a thermodynamics student to apply a number of patterns he learned previously, as an illustration of Figure 4.

1. *At the top level are the invariant, general, first, and second laws, which the student will use to obtain W and T_2, respectively. First he might assume adiabatic, isentropic operation to obtain T_2, which he will use to obtain the W, using progressively sophisticated patterns at lower levels.*
2. *At the second level, the student engineer may further simplify to obtain a first approximation, assuming the gas to be pure methane as an ideal process gas, to obtain T_2 via the isentropic assumption, then W from the enthalpy change.*
3. *The third level requires recall of residual (sometimes called departure) functions, to correct the ideal gas assumption at both the expander inlet and discharge.*
4. *The fourth level is still more specific, correcting pure methane to a ternary mixture, perhaps using an equation of state to obtain first T_2 and then W, using the two general thermodynamic laws.*
5. *At the fifth, next-to-bottom level, the student may remove the isentropic assumption, using a field-derived efficiency multiplier (e.g., 72%) to obtain real work, and then repeating steps 1 through 4, to obtain T_2.*
6. *At the bottom level, the student will consider the detail of isothermally flashing the ternary mixture at P_2 and T_2, to determine if any liquids will be produced. If not, the inlet or outlet conditions will be changed and the process repeated. This last step may require a different set of patterns, for example dealing with phase equilibria.*

As the student progresses from the invariant, upper memory patterns, to the lower, case-specific patterns, the upper patterns are reconsolidated as a result of activating the next level.

Further, one might ask questions regarding the establishment of memory patterns:

1. *What patterns already exist in the memory of the learner, perhaps as determined by a pretest?*
2. *What new patterns can be connected to existing patterns the learner already has, so that repetition can be augmented by connections?*
3. *How can the learner's memory be advanced in the hierarchy Haile suggests?[2,3] Too great a challenge might produce anxiety, while too little might produce paralysis in the form of boredom. It seems clear that overcoming slight imbalances, which seems achievable, is key.[38]*

CONCLUSIONS

We have shown some applications of four principles:

1. *Protein growth at the synapse is a key to long-term memory. A physical change in the brain is required; learning is biology. How fast one can learn is determined in part by how fast one can grow protein.*

2. *As a first approximation, the memory process is determined by a dialog between the hippocampus memory index and the neocortex storehouse, using value judgments provided by the prefrontal cortex.*

3. *Based on philosophy and psychology, repetitions and connections were suggested by previous thinkers such as Aristotle and James, to be two keys to establishing memory. The current, harder science of biology allows supplementation of those principles, by more fundamental, but perhaps more difficult, physiology.*

4. *While memory is the basis of learning, pattern recognition and formation are the basis of understanding. The transition from learning to understanding requires more than remembering facts, it requires the scaffolding of organization for retrieval. The professor can aid students by facilitating such transitions. Some example transitions are provided in references 2 and 3, which are recommended reading.*

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