Learning, Concept Formation & Conceptual Change

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ABSTRACT

Learning is a complex process that happens in the brain. This paper attempts to discuss what happening in the brain at the neural level as we learn more about our environments and as we think through concepts. Concepts are mental representations that can be expressed by a single word or a set of ideas described by a few words. Through the use of language individual concepts can then be connected to build more complex concepts. We suggest that a concept in the mind is stored in the form of a neural circuit. Neurons form webs of interconnected neurons. Learning is a mental process that depends how stimuli and new ideas get integrated into the old knowledge database, and on how, through reasoning, a previously acquired mental mechanism, the entire database gets re-organized. Since learning is a continuous process this implies that the brain must also continuously restructure itself. In other words, learning changes the physical structure of the brain, and with it, the functional organization of the brain. This explains why learning always requires a major effort from the side of the student. Students enter the classroom with already formed ideas which implies that neural circuits in the brain are already in place. Alternate conceptions have their origins in a diverse set of personal experiences, the social and religious upbringing by the extended family, language, peer culture, as well as previous teacher’s explanations and instructional materials. We claim that learning is more at ease when specific thinking networks already exist and difficult if new networks have to be created. Changing students’ prior concepts might involve the creation of new neural networks in the students’ brains as well as the rewiring of pre-existing neural circuits. It is suggested that to form new concepts or change old inadequate ones, the student has to be led through several processes. First, he has to consciously “notice” and understand what the problem is; second, he has to “assimilate” more information and try to fit it into already existing neural networks; third, he has to critically think through all the argumentation in his own words and reorganize this thoughts – he has to “accommodate” the knowledge and evaluate against his prior beliefs; and finally, he has to work towards “obtaining fluency” in the newly acquired concept so that this concept itself has then becomes a mere building block for future, more advanced concepts.
1. INTRODUCTION

Our understanding of how people learn has changed radically in the past 20 years. Many advances have been made in the Cognitive Sciences, specifically in Cognitive Neuroscience where laboratory research has been showing how learning changes the physical structure of the brain, and with it the functional organization of the brain. We are now at a time where collaborative studies among cognitive and developmental psychologists and educators are yielding new knowledge about the nature of learning and teaching as it takes place in a variety of settings (see for example the book “How People Learn” published by the National Research Council). It might sound rather superfluous, but the fact is that as we grow up, we learn about the properties and behavior of the world around us, and we all form (sometimes more or less elaborate) concepts of what we observe. These concepts might even become rooted deeply in our psyche, and when quizzed we might then defend these “beliefs”.

Exactly how all thinking happens has been a longstanding philosophical question debated throughout the ages. Descartes’ quote “I think therefore I am” summarizes this quest rather nicely. Although Descartes used this phrase to prove his existence, it can be interpreted in many different fashions, but what is important in this context is that the process of thinking — and its consequence: the process of “learning” — does determine who we are (and who we can become). To what degree this depends on philosophical and biological contributions is still a topic of debate. Generally speaking, the origin of the “process of learning” can be summarized to be a combination of (a) the human evolution and the genetic material (the Darwinist view), (b) on how we observe the world through sensory experiences (the Empiricist view, shared by philosophers like Aristotle, Hume, Locke, Kant), (c) on innate ideas that are developed through the reflection of one’s own thought processes through introspection (the Nativist view, shared by Plato, Descartes, and Chomsky at more recent times), (d) spiritual influences (such as Jung’s ideas on the collective unconsciousness, or Campbell’s mythical connections across cultures), and (e) grounded and ungrounded religious stories and beliefs. Here we discuss mostly (a), (b) and (c) and ask the question of “how” we learn.

2. WHAT IS LEARNING?

Much progress on how people learn has been made at the turn of the last century, starting with the Thorndike’s (1913) “hungry cat experiment” and Piaget’s (1920) “observations” of how children learn about their world. These studies (initially known under the heading of Behavioral Sciences) provided the epistemological foundations of a new field that was emerging in the 1950’s – the “Cognitive Sciences”. Most of Piaget’s theories are still valid today, though neuroscience and brain research has supplemented and refined these theories slightly. Though he contributed substantially to cognitive sciences not all of Piaget’s ideas as still considered valid – for example, Piaget believed that intelligence itself, at least in part, is a biological adaptation, and that innate ideas and personal judgments (that can but do not need to be independent of experiences) contribute to our
process of learning. Today, as more advances especially in the field of neurosciences are made, we have been accumulating more and more evidence for the “biological origins theories” – although the possibilities mentioned in the previous paragraph (mostly the Nativist views and unfortunately ungrounded spiritual arguments) cannot yet be ruled out conclusively.

So then, how do we learn? And what happens as we learn? To answer these questions we first need to define the “process of learning”. For clarity – throughout this paper we will stick to Piaget’s original definition: “Learning is a mental process that depends on perception and awareness, on how additional stimuli and new ideas get integrated into the old knowledge database (a process Piaget called ‘assimilation’), and on how, through reasoning (a previously acquired mental mechanism), the entire database gets re-organized which results in alterations of the mental structures and the creation of new ones (a process called ‘accommodation’ “. With this definition adding new information is only the first part of learning; the whole learning process involves the integration, re-organization and creation of new mental structures.

2.1. Biological Underpinnings

Learning is a complex process and happens in the brain. The first studies on how learning works date back to about fifty years ago – to 1949 when Hebb claimed that cell bodies associated with neurons could be influenced through experience. The current belief is that all mental processes can be linked to networks in the brain, to neurons firing and to the synaptic activity (the fact, that synaptic activity parallels the process of learning was only discovered 30 years ago by Kandel in the1970’s). Today we know that even emotional and intuitive responses can be traced down to physical brain activity. That said if we wish to understand the process of learning, it seems to be of uttermost importance to understand neural and synaptic activity. There are several processes that will be reviewed here starting with the least complicated and most automatic functions to more complex functions of forming concepts to functions that involve deep thinking and reordering of information. However prior to explaining the links between neural and synaptic activity and the process of learning, some of the fundamentals of brain functions will be reviewed in the next few paragraphs. Readers wishing to skip this section can advance directly to section 2.4.

There are two kinds of brain cells: neurons and glial (the Greek for bowstring and glue). Though glial cells have several important functions, the neurons are more relevant to us because of their unique ability to transmit information. Neurons are composed of a cell body with several dendrites (from the Greek for tree) and a thinner extension called axon. The axon may be up to one meter long (only in the spinal cord) and at its end divides itself into branches of two over and over (and as we learn more presumably the branching increases – more later). Information travels in one direction, down the axon, through the synapse to the next dendrite. A single neuron can thus receive signals from thousands of other cells and pass on signals to thousands more. Information is carried inside a neuron by electrical pulses and is transmitted across the synaptic gap by chemicals called neurotransmitters (amino acids, amines, and peptides). Whether or not signals get
forwarded depends on the sum of all synaptic reactions arriving from all dendrites to the cell body, which will then determine whether that cell will fire. Whether the next neuron picks up on that signal (and how fast this happens) depends on the types and concentrations of specific neurotransmitters.

The Brain is a very complex organ, it controls body functions at the conscious and unconscious levels, it allows you to perceive the world outside your body, examine it, think about it, and even come up with abstract theories. It has several different parts, and how we function and think depends on where this happens in the brain, what other processes are happening at the same location, and how the signals are being affected (or even censored) as they travel from one part of the brain with a specific task to another other. The Spinal Cord, although spatially not part of the brain, is (at least structurally) an extension thereof; its chief job is to carry messages between the brain and the body. The Brainstem, located at the base of the brain where the spinal cord begins, is sometimes referred to as the reptilian brain due to its resemblance to the entire brain of reptiles. Thus it is not surprising that its primary function is survival. It is largely in control of the autonomic functions like for example breathing, heartbeat, and basic life support systems. It receives signals from the body and is responsible for adjusting to changing conditions of the environment. It also serves as an effective filter for the thousands of stimuli constantly bombarding the sensory receptors, thus allowing you to focus only on relevant stimuli. The Cerebellum is also somewhat primitive in that it has evolved relatively little throughout human history. It is basically responsible for balance, body posture, and muscle movement and coordination. By the age of two it is fully developed. It is also responsible for learning many bodily tedious skills that became automatic once learned (like for example playing the piano or driving a car). This means that other parts of the brain that do more advanced functions such as thinking need not be used for those functions that have become automatic. The conscious mind is then available for other tasks. The Thalamus is a small plum shaped structure that is often referred to as the “gateway to the cortex” as nearly all input from the sensory organs travel through the thalamus. This is where the signals get “sorted” and then get send on to the receiving areas in the cortex. The Hypothalamus is below the thalamus. It controls functions necessary for homeostasis, the maintaining of the normal state of the body. For example it is responsible to initiating the shivering if it gets cold, thrust if too salty foot is eaten, or an increase in heart rate if a snake is viewed. It also regulates the sex drive, sleep and aggressive behavior. The Amygdala is highly involved with our personal alarm system, the fight-flight response mechanism. It is also the psychological sensory system of the brain that plays a critical role in human emotions.

How do all these parts of the brain work together? Basically all incoming sensory data travel to the thalamus which then relays information to the appropriate sensory processing area in the cortex. At the same time the thalamus sends information to the amygdala for “evaluation”. If the amygdala determines that the stimuli are potentially harmful, it triggers the hypothalamus, which in turn sends hormonal messages to the body altering for example the heart rate. So what is the relevance of all this information to cognitive science, learning and thinking? Any type of thoughts, fantasies or suggestions will be processed and evaluated by the amygdala, which, for example, can
result in knot in the throat when taken on the spot by a teacher. In other words, emotional behavior is basically regulated by the functions of the amygdala. Concerning teaching and learning this has an important function. Let’s say the student gets embarrassed or even humiliated – the amygdala will then signal to the rest of the brain that this is a somewhat life threatening situation, will then send signals to the body to alter the heart rate and induce sweating, and will inhibit any further prefrontal brain activity thus causing a mental block.

2.2. How neurons communicate

Most neurons communicate with each other by means of both electric and chemical signals. Nerve impulses are basically bioelectrical currents that travel along the axons in the neurons. These impulses are a result of the movement of four common ions: sodium, potassium, calcium, and chloride. Specific channels in the neuron cell membrane allow ions to move from one side of the membrane to the other. The inside of the neuron has a slight excess of negatively charged ions with respect to the outside. In other words, a neuron at rest holds a slight negative charge. When nothing much is happening, a neuron usually sends impulses down the axon at a relatively slow, irregular rate. When a neuron is stimulated (receives excitatory signals from another neuron), however, the sodium channels in the membrane open and the positively charged sodium ions enter the cell. This makes the potential difference temporarily more positive inside than outside. As soon as this occurs, however, positively charged potassium ions leave the cell, changing the voltage to more negative than normal. This brief change in the potential difference usually lasts for about one millisecond and is known as an action potential. The action potential spreads down the axon as the sodium channels open sequentially. This impulse moves only in one direction until it reaches the end of the axon. Though all action potentials have the same intensity, the strength of the message can vary, depending on how frequently the action potential is generated. Some neurons can fire up to 500 action potentials a second. The more normal rates, however, are 30 to 100 potentials a second. The speed of an action potential varies according to the diameter of the axon and whether or not it is insulated with myelin. Some of the neurotransmitters are generated within the cell bodies of neurons, and others are synthesized within the axon terminals. Regardless of their source, all the neurotransmitter molecules are eventually stored in small sacs, or vesicles, in the bulb-like terminals of the axon branches, where they will be ready to go to work when needed. Neurotransmitters are generally either excitatory or inhibitory, meaning that they either increase or decrease the probability that a neuron will fire.

The next step in understanding neural communication is to look at how the electrical and chemical components come together to allow information to be passed from cell to cell within the central nervous system. This action takes place at the junction of the axon terminal of one neuron and a dendrite on the cell body of a second neuron. This junction is known as a synapse. The axon terminal and the membrane of the dendrite are separated by an infinitesimal gap called the synaptic cleft. Most synapses take place on the spines of the dendrites, but 15 to 20 percent of the synapses occur on the cell body itself. When the action potential reaches the terminal of an axon, it stimulates the opening of some of the vesicles and thus triggers the release of one or more
neurotransmitters into the synaptic cleft. The neurotransmitter molecules diffuse across the cleft. The more action potentials that arrive at the terminal, the more molecules are released into the gap. The electrical signal of the action potential has now been converted into a chemical signal, and the synaptic cleft is crossed within thousandths of a second. Once the neurotransmitter molecules reach the other side of the synapse, each molecule makes contact with its target, the postsynaptic or receiving neuron. How is the contact made? On the dendrite of the receiving neuron are special large protein molecules that are called receptors. Each neurotransmitter has a different shape, and the receptors are specifically designed for the shape of the neurotransmitter they are receiving, as precisely as a key is made for a lock. The neurotransmitter molecule fits into the receptor site, opening or closing ion channels on the membrane of the target neuron. Just as a change in the potential difference of the axon membrane generated an action potential, a change in the potential difference in the membrane of the dendrite causes the stimulation of the target neuron. This change then becomes one of the many electrical signals that will be conducted down the dendrites to the cell body of the postsynaptic neuron. The dendrites have now converted the chemical signal back into an electrical signal, thus, in a sense, completing the cycle. Because a neuron can have thousands of dendrites, and the dendrites are covered with tiny spines that effectively increase the surface area, this process is occurring at thousands of sites. As soon as the electrical signals from all the involved dendrites arrive at the cell body, the neuron adds up all inputs to determine whether to generate an action potential. If the net change in voltage is sufficiently large, the ion channels will open near the cell body, the neuron will generate an action potential, and the impulse will begin its travel down the axon. If the voltage isn't high enough, the cell will not generate an electrical impulse, and the neuron will not fire. For more details see the books by Crick (1994), Restak (1994), Thompson (1985), Damasio (2001), and Ledoux (1999, 2003).

What is important for this paper is that electrochemical signals travel from the dendrites (across the synapses) down the axons of the neurons to the next neuron. Neurons form webs of interconnected neurons and signals travel from one neuron to the next depending on whether the combined action potential is large enough for that neuron to fire and send its signal to the next neuron. Learning, then, consists of making the right dendrite connections and tweaking the weights of all signals that add up to firing or not firing, i.e. to passing on the signal after a decision making incident. It is not surprising that the brain is often compared to an advanced computer.

2.3. Placticity & Adaptability

Not very long ago, scientists believed that the structure of the brain remained relatively fixed throughout life. It's true that the basic features of the brain—the wrinkled surface of the cortex, the division into two hemispheres and four main lobes—look basically the same in all humans, and these features don't appear to change much as we get older. But if the structure of the brain remains static, how do we account for the changing abilities of a child or even an adult? Skills and memories must be stored somewhere, which means the brain must change in order to store them.
Experiments with rats have shown that rats in stimulated environments grow thicker brains. In fact what happens is that more dendrites sprout from the neurons. The dendric connections that get used might get myelated (glial cells surround the axons and produce a sheath that conducts the signals more effectively – it can be compared to “oiling the connections”). Unused connections, on the other hand, may get eliminated. In addition, neurons constantly form new synapses, keep some synapses and eliminate others, and change the very nature of information they send at synapses (this is done by tweaking the weights of the action potentials). Some connections between neurons strengthen (they become myelated) and they send information more quickly and efficiently. But a neuron’s dendric branches pick up information from dozens or even hundreds of neurons. In other words the more often connections occur the stronger they become. The main point is that the brain continuously restructures itself as we learn more. In other words, learning changes the physical structure of the brain, and with it, the functional organization of the brain.

2.4. The Biology of Learning and Thought Processing

Learning is a process that has been occurring ever since the first formation of the brain cells during the embryonic stage and will continue until death. Information is stored in various locations in the brain which consists of a rather elaborate network of neurons that communicate with each other. This network has been established through prior sensory, emotional, and intellectual experiences, even to the degree that we have learned which stimuli to perceive or ignore. Specific patterns have been established and have even become somewhat hardwired. Whenever we experience something new, the brain searches for an existing network into which to fit that information, and if that network exists, we can process and evaluate the information relatively quickly and at ease. But if we are asked to learn a new skill, additional connections among the neurons have to be made – which almost always takes some time and experience. The same is applicable to the process of thinking where old and new information is combined and evaluated, and if need be new circuits might be established. Thus thinking in ways we have already learned to think will be much easier than being challenged to think in new ways. Since the process of evaluation of signals involves the thalamus, the conclusions we reach will also have an emotional component (e.g. LeDoux 1999). The formation of concepts and belief systems is thus a rather personal and grounded experience. The good news is that new behavior patterns and new concepts CAN be learned, but it does require work (as does creating new networks and changing the hardwiring). In other words, new concepts cannot be “adopted”, they have to be fitted into existing networks and go through all the emotional filtering and evaluation processes first. And even if a newly taught concept might sound logical, it can only be employed after a new network has been established.

Claim: Thinking in a familiar fashion proceeds along already existent networks. When we experience something new the brain “looks” for an existing network into which this information can fit. If the fit is good, what was learned previously is given meaning, if not some confusion may occur. The brain will then search for slightly different avenues to match the old and the new information. Developing new skills and different thinking
patterns requires the formation of additional networks. In other words, learning changes the physical structure of the brain, and with it, the functional organization of the brain.

3. CONCEPT FORMATION

3.1. Defining Concepts

Concepts are like mental representations that, in their simplest form, can be expressed by a single word, such as plant or animal, alive or dead, table or chair, apple or orange (e.g. Carey 2000). Concepts may also represent a set of ideas that can be described by a few words. Through the use of language individual concepts can be connected to build more complex representational structures, like for example “babies crawl” or “birds fly”. At other times two concepts can be combined to form a third representational structure. An example of the latter could be “density”, which is the “matter” per “volume”, i.e., a concept that stands in itself but is a product of two other concepts. Through the use of language, we can thus create new concepts that can stand by themselves. More complex concepts can describe a whole idea, like for example “the theory of natural selection”. Similarly, though the use of math, we can build somewhat more abstract theories that in the end up representing one idea, like for example “the big bang model of the universe”. In other words, within a particular representational structure, concepts help us make deductions and explain even more complex ideas. Concept can thus act like building blocks of more complex or even abstract representations.

3.2. Constructing Concepts

So then what is thinking and understanding? In the cognitive sciences the term “deep understanding” generally refers to how concepts are “represented” in the student’s mind, and most importantly how they are “connected” with each other (Grotzer 1999). Representations are generally made in the form of images in simple cases, and in the forms of models in more abstract situations. Deep understanding then means that the concepts are well represented and well connected. At the neural level it implies that concepts consist of webs of interconnected neurons that then get connected to even larger systems in the case of models or in more abstract situations.

An expert in a particular field does not just have more knowledge, but the knowledge he has is connected in a “logical and meaningful” manner. This is important because when individual facts are recalled it is as if a whole set of interconnected further concepts are accessed at the same time and whole sets of neural networks become activated. As such deep understanding of a subject involves the ability to recall many connected concepts at once, where every single concept has a deep meaning in itself. Deep thinking then involves being able to make further connections between the webs of concepts – and neurons. Deep thinking involves the construction of new concepts and is almost always based on what the student already knows. When a learner “makes sense” of new material he is able to make the connections between different concepts.
3.3. Concept Map of Concept Formation

It is generally accepted that students do not enter the classroom (as what Pinker 2003 called) a “blank slate”. Students come to class with already formed ideas on many topics, including on how they view and interpret the world around themselves (e.g. Novak 1987, Helm & Novak 1983, Smith DiSessa & Rochelle 1994) and have their own individual present knowledge, beliefs, and ways of thinking. After all the webs of neurons are connected already in a certain fashion and are formed by prior experiences.

Sometimes these views may be rather strange, even elaborate, but regardless of their content, these views tend to be highly resistant to change. The views can change but what has to happen at the neural level is to establish new dendric connections, eliminate others and tweak the weights of the signals that determine weather or not particular neurons will fire. While “learning the unfamiliar” and “conceptually understanding” the subject-matter already provides a large challenge and involves much neural activity, unlearning misconceptions is significantly more difficult.

Throughout the student’s lives ideas have been forming. In other words, the student has become what he is based on a variety of factors. First, he has inherited specific genes from his parents that determine to some degree who he is and who he can become. To which degree his genetic makeup is important still is open to debate (see for example Ridley 2003), but it seems that generally it is on the order of about 50% (e.g. Pinker 2003). Other biological factors that influence his persona are the chemicals in his brain, specifically certain types of neurotransmitters; these can also strongly affect his mood and thus change his personality. Other environmental factors that determine who the student has become are his socio-emotional learning and upbringing. The language and culture certainly affects his characteristics, personal habits, and preset ways of thinking. The parents, specific mentors, relatives and peer opinions and interactions also affect his character and might influence personal his beliefs. Other factors include incidents and special events that seem to have affected our lives and opinions – these might be specific events that have shaped our lives. In other words, our genetic predisposition coupled with a variety of socio-emotional factors, special events and prior experience have shaped our personality and are responsible for who we have become.

All this is responsible for creating the person with a hardwired network of neurons, i.e. the biological brain, and with a “way of thinking”, and “feeling”, i.e., what most people refer to as the mind. This all creates the persona as a whole – the beige oval. The person has a certain database of knowledge that he has acquired over the years (how much of this material is really accessible or there on recall is another issue). The person has a set of intellectual abilities and has developed specific ways of thinking and of surviving in general. The person has learned a variety of skills during his lifetime, including how to speak and how to read.

So why is all this important – the main point is that our background, the genetic predisposition, our socio-emotional upbringing and training and learning has determined how our brain has become hardwired. We will have developed specific personality traits
and skills and we will have learned specific ways of thinking. We will have developed special talents and ways of thinking with which we are more at ease than with others. In other words, our experiences have determined how our brain got hardwired, what types of specific skills and intelligences we possess and how we think in general.

Now, everybody’s brain has a unique history of way hardwired and behavior and way of thinking. The point is that we cannot predict how this material will be organized and processed in the students’ brain – it depends on who the student is and how his brain has become hardwired. If we wish to teach new material we also have to teach in a fashion that is compatible with the student’s way of being hardwired. If pre-existing networks of how to think already exist, it will be relatively easy for the student to employ these and think in a familiar way, but if these networks do not already exist they have to be created first. The whole point it that the individual will have pre-set ideas of thinking and operating in general. But that is not all, being an emotional human being, the individual will also have developed mechanisms of responding directly to stimuli. For example, when intimidated the individual’s heart rate might increase irrespective of how much control the individual has over that specific function. This will affect how well the individual is going to be able to think and to what degree this thinking might be inhibited.

So, if we teach new materials in a yet foreign fashion we have to consider having to reconfigure or even create some of the thinking networks and thus the hardwiring. If new information is fed into the student’s brain and a thinking network already exists, the student will feel more at ease and will more readily be able to follow certain arguments. This is more difficult if the student is challenged to think in an unfamiliar fashion. This then requires changing the original hardwiring. But with a lot of training, and a lot of effort from the students side this can be done – but the point is the student has to do all the thinking, i.e., construct knowledge.

Claim: Alternate Conceptions have their origins in a diverse set of personal experiences (including direct observations, varying levels of perceptions, the neurological development of the brain, and personal preferences and training); the social and religious upbringing by the extended family; Language; Peer Culture; as well as previous teachers explanations and instructional materials. When teaching all of these networks have to be considered. Learning is more at ease when specific thinking networks already exist and difficult if new networks have to be created. The process of learning involves the rewiring, and to some degree the creation, of new neural networks. Thinking, that is organizing, analyzing and evaluating all the thoughts, is a major effort.

4. PROMOTING CONCEPTUAL CHANGE

If we wish the student to go beyond conceptual change then we are requiring the student not only to willingly change his opinion, but also to integrate the newly acquired knowledge into his neural thinking network to the degree that it can readily be used to construct further concepts upon that whole knowledge. Here we describe some of the processes that are going on in the students mind during the process of conceptual change.
But that is not all, we will also claim that conceptual change has to change some of the fundamental rewiring of the neural network for it to be truly effective.

Diagram 2 (the red oval) illustrates some of the steps involved that might lead to the formation of a concept to conceptual change to the ultimate discovery of new ideas. It incorporates all the steps involved in the conceptual change model, tries to integrate that into each individual student’s neural network and personal character, shows how and under which conditions a concept forms or is being altered, and how this information might lead to the formation of other new concepts, ideas, and even to new discoveries.

4.1. Processes in the student’s Mind

*Step 1: Acknowledging the New Information*

In 1920, Piaget already claimed that a stimulus is not a stimulus until some “mental structure” has been acquired through the assimilation of experiences. The proof was only provided in 1984, when von Foster performed his first brain scans (on a cat!). The cat got her food only when a sound was produced. Initially the electrodes indicated no neural activity, but this changed as the cat learned to press the lever when hearing the sound. In other words, as Piaget suggested, a stimulus is not a stimulus until the corresponding mental structure exists.

Even if the so-called blank slate with no prior knowledge would exist we would have an initial problem. It depends on what stimulus or thought process the student perceives at the conscious level. We consciously perceive many stimuli, but only a select few, those on which we consciously chose to focus on, will be detected. So first question in the equation is “which thought process will the student consciously chose to grab on?” Or simply, what will the student notice? This might depend on a series of parameters, for example it has that is somewhat unusual or somewhat interesting enough to stand out. In other words for some reason the mind must first “consciously notice” a particular thought process and then find it special enough to “hook” onto it. Once the student is aware of that thought process, the mind will inevitably try to come up with various associations – this is when the pre-established hardwiring of the brain is being activated.

Within this pre-established network of neurons this thought process might then activate other networks, and once activated information will be passes along. The information that becomes activated can be thought of as prior ideas or in short – memory.

What is important at this stage is what types of associations the students will make between those prior ideas and that particular thought process that triggered those memories. How will this information then be merged and what other associations will then come up? At this stage several neural pathways might be activated and provide additional information. Somehow that student has then got to decide how to proceed, which thoughts to filter out and which to keep. In part this will depend on the original hardwiring already present and on which mental skills the student possesses. It depends on which type of thinking the student is more at ease than with others, i.e. it depends on
how the neurons which neurons are connected and on which pathways are myelated to what degree. Although it appears that the student might have a choice on how to think, or at least which strategy to apply, it really depends on which pathways become activated to facilitate this process.

The characteristics of the types of associations that will be made, or other simultaneous and additional stimuli that are perceived are also of importance and the mind will evaluate or senor any of those thoughts or associations. For example if a disturbing smell is registered it is possible that that particular thought process will get diverted by signals coming from the amygdala and the hippocampus. And when fight-flight responses in the amygdala get triggered this may manifest itself in the form of an emotional response to a particular signal. So then what is a concept in this context? A prior concept then is some type of neural circuitry that already exists and that is retrieved through various associations from the memory – and it may or may not be emotionally loaded depending of whether the circuitry in the amygdala is also involved.

Let’s assume new material is presented. What will register with the student? If the student has an already existing network he might pick up on a certain thought pattern, similarly to how, for example, we might pick up on a certain sound we might like to hear. If the “sound” is somewhat unusual, chances are that we will notice it. If the sound is familiar we will only notice it if we pay particular attentions to it, otherwise it might be heard with the unconscious and might not get officially registered. This same is true with particular ideas that the student might encounter – if the idea does not stand out on its own, it might go by undetected, i.e., be unintelligible.

*Step 2: Filing and Assimilating the New Information*

What happens next depends on the student’s personal character and pre-existing neural hardwiring and on the associations that this student will make with the new thought or information. The student, in his mind, will look for pre-existing or even somewhat familiar networks, and if none exist something has to be created. However, the creation of new networks will involve real thinking and is hard work. Before the student willingly embarks on that task, he has to do something with the newly presented information. Even if it is not exactly the appropriate place, the student will have to file the information somewhere into his short term memory before it gets lost. What the student will most likely do is to search for some associations that will be more or less meaningful. In other words, his mind will search for and file the new information in an already existing neural network that might appear more or less reasonable. Information that is totally foreign to the student might get lost unless the student can relate the new material to something else he has in store.

The student must also retain this thought for long enough to reflect on it and find some associations that will be somewhat meaningful. The new information must have some meaning for the student, or at least enough meaning for the student to want to know more. Again, what happens next depends on the student’s already existing neural network and preset ways of thinking and his already integrated other beliefs. What other
stored information will the student recall from memory? What additional associations will the student make and then how will the student combine the new and old information? What methods of thinking will the student employ to bring meaning to the problem at hand? And if the student already has an opinion about the subject to be discussed, how deeply is that integrated into his own belief system? In other words, how easily can the hardwiring of the brain be changed if the information cannot be integrated easily into a pre-existing network?

This is the point where the student will have to do some real thinking. Clearly, this depends also on how the student has previously learned to think through problems. What he has to do in his brain is to make some minor adjustments to the already existing networks and try to fit in the new information. At this stage the student is still assimilating the knowledge.

*Step 3: Evaluating and Accommodating the New Information*

It is natural to try to fit the new knowledge into pre-existing networks, or if needed tweaking those networks slightly so that it does fit. At this stage the student is still trying to hold on to his prior beliefs. There is nothing wrong with that – it is natural to search for already familiar fashions of thinking through the problem.

What is so nice about alternate conceptions (as opposed to just forming new concepts) is that there is something not quite correct – this implies that it just is no longer possible to integrate the new knowledge into the old networks – it does not fit, so-to-say. This then means that the student is being confronted with his prior theory (this corresponds to the first step in Posner et al’s (1982) conceptual change theory, the student now has to become dissatisfied with his prior belief), for now comes the hardest part of real radical thinking. First, the student has to let go of his prior belief and second, he will have to create a new network into which to fit the new information. And, creating new networks or radically rewiring old networks takes the largest amount of work and involves profound thinking and rethinking. At the neural level we suggest that it actively involves creating new dendritic connections and radically tweaking the action potentials.

At this stage the student has to critically think through the problem at hand and combine and evaluate prior beliefs and even reject some of them if they are incorrect. Now rejecting existing beliefs is something very personal in the sense that the individual’s networks that he created over the years (and that culture, his parents, and prior teaching has affected). And if some of the networks that are activated throughout this process also involve the hippocampus, it might feel rather “emotional” to the student, and the student might then, more or less instinctively, show a stronger resistance to the problem.

At this stage the student will be challenged profoundly. How, will he defend his beliefs? How strongly rooted are those beliefs? How many networks are activated while the student thinks through the problem? What methods does the student use to argue his way though the problems – this too requires the usage of already existing networks of “how” the student thinks, so it is both, his previous knowledge and his methods of thinking that
are being challenged. Ultimately, what will have to happen is that the old and the new information have to be combined and critically evaluated. The new information has to be logically integrated into student’s prior knowledge database. During this process new neural circuits are being created and old circuits have to be rewired – after all, the prior beliefs do no longer fit together into the newly created networks. This might be a little different to forming new concepts – they involve the creating of new network, and perhaps tweaking the existing ones, conceptual change, however, involves all, creating new networks, tweaking existing ones, and disconnecting and disposing of no longer correct information and methods of thinking. In other words, to some degree, it involves almost complete rewiring and reorganizing thoughts and the neural networks.

Step 4: Enhancing the Fluency

But the work of the student does not finish here. Thinking through a problem “once” hardly creates a new and robust neural network. The newly formed network might still be rather fragile and might easily become disintegrated. How often does it happen that we think we understood something to then find out that we are still confused and probably did not understand the problem at a “deeper” level. Most people would probably agree that understanding at a deeper level means being able to apply the concept to other situations. Here we will argue that “fruitfully applying” the material to other situations (as Posner et al 1982 claimed to be in their last step) is in itself not quite sufficient.

The student now will have to strengthen (myelate) his newly created networks mostly through exercise and practice. The student will have to iterate through this process until the new way of thinking appears to be natural and at ease. What happens at the neural level at this stage is that the axons become myelated, which corresponds to oiling the newly established network so that it may function more efficiently.

Ultimately, the new knowledge needs to be integrated into the belief systems and into the methods of thinking in such a manner that it is no longer a new circuit, but that this circuit has become a building block for the creation of additional circuits. At this stage, the newly established circuits will be ready to be used by the student at ease and without much effort – in other works the new knowledge and newly acquired way of thinking has become part of the students’ foundation of robustly wired circuits. In fact, this circuit now has become a building block for further concepts.

4.2. Guided Help during the Process of Conceptual Change

While the rewiring occurs in the brain of the student, the student does all the hard work of thinking through a problem and disposing of his prior beliefs. The student is doing all the work – he himself is doing the wiring and rewiring. This is something nobody can do for the student, however there are certainly some methods that can be employed to help or guide the student in his process of learning. How to teach in a classroom setting to initiate conceptual change will be discussed extensively in Paper III. Here we mention how a good teacher help “facilitate” the process through all of the above four steps.
Step 1: Hooking the student (Acknowledging Information)

From an educational perspective, it is the task of the educator to assure that the particular idea does get noticed efficiently. In terms of teaching this might mean that if a new idea is presented the student might need to be told explicitly to pay attention, or is somehow forced into consciously noticing the particular idea that is being presented. Presenting any topic that the student can somehow relate to might help. In other words, the new idea has to be dressed up enough so that it gets noticed and preferably also so that the student is initially intrigued by it enough to want to know more.

The problem needs to be stated clearly in a language that the student will understand. [Telling is not enough. Establishing the intelligibility of a concept or word is a more common way of staring instruction – ‘what does the word force mean to you?’] Furthermore the problem will need to be stated in an interesting way so that the student, even if he in not intrigued by the problem itself, is at least willing to try to solve it for some meaningful reason (though one would wish that the reason is more than merely getting a better grade).

Step 2: Suggesting Bridges (Assimilating Information)

Again, this might be the place where a good educator can help the student. Although the student himself has to do the job of assimilating the new knowledge, a good educator might help with meaningful analogies that the student is already familiar with. This might help the student organize his ideas and help activate (hopefully) those networks that will be used later to help solve the problem. Meaningful associations are particularly useful, because they might also help the student file the new information in the appropriate place in the brain.

If there are no meaningful analogies the material must be presented in such a simplified fashion that the student can follow every part of the arguments clearly. The student should at least have the feeling that something makes sense. But the new information still needs to be stored in the most appropriate place in the brain, or remain in short term memory for long enough to be able to continue the thinking. Suggesting to the student how to chunk the information might be another way a good instructor might be able to help. Throughout this process, a good instructor can try to keep the student interested in the problem at hand. If the interest fades, the student’s willingness to continue to think through the problem might also fade.

But a good instructor also has to go a little beyond the mere problem at hand by putting it into the right context or by stating how the particular example is either different or unique from other cases. The teacher can thus aid the student filing the information into the appropriate places.

Step 3: Querying and Confronting the Student (Accommodating Information)
The step of thinking through the problem, understanding it, and more importantly evaluating it, is the hardest part for the student. It requires the reorganization of knowledge, the creating of new neural circuits, and the rewiring of old ones. This is something a teacher cannot do for the student, and his help can only be relatively limited. The student is on his own. A good teacher can help him with two things, first he can guide him through the new explanations so that they really do make sense, and second he can help him reject prior beliefs by having the student explain to him why they no longer work. Finding out exactly where the prior theory is defect might help the student – but unfortunately only if the student really is also willing to let go of his prior beliefs. Furthermore, what a good instructor can do at this stage is to continually challenge the student – provided the student is willing to be challenged.

What is important here is that the student thinks aloud and articulates the problem in his own words – regurgitating the information provided by the instructor might be easiest for the student, but this does not mean that the student is really understanding the problem. The student will have to phrase the problem in his own words, and provide an answer; also in his own words. The instructor can guide the student by challenging the student with the right questions, but without putting the words into his mouth.

This stage might also be rather challenging for the instructor. Guiding and at the same time challenging the student, without guiding and challenging too much or too little, is a real art. The instructor must be very tightly in touch with how the student thinks through the problem, not with how he thinks through the problem himself – the teacher will have to be able to read the student’s mind in some sense. Yet, the teacher must listen very carefully to how the student describes the problem and thinks through the answer.

Also, a good teacher can help with the right type of encouragement at the right time. This is the hardest phase that the student goes through and words of encouragement, even compliments when the student is on the right track, are definitely appropriate. After all the student is confronted with his alternate concepts, which might in some cases be so deeply rooted that those prior concept might even feel “emotional”. So treating the student with respect for his emotions is definitely appropriate. It shows understanding from the instructor’s side and it will ease the process that the student has to work though.

Step 4: Practicing and Constructing (Familiarizing Information)

The work of the teacher certainly does not finish with helping the student understand why his prior theory is not appropriate and why the new theory is so much better. Maybe the student even ends up agreeing and accepts the conceptual change, but this still does not mean that the student can readily apply his newly acquired skills. The student needs to practice, and this is a point where the teacher definitely can help again. He needs to provide the student with meaningful examples and other problems that involve the newly acquired concept. The idea is to make the student feel at easy with the new concept. In fact further challenges might be appropriate here – examples that go beyond just regurgitating the problem, examples that go beyond, examples that involve applying the new knowledge and testing it.
At the neural level, what the teacher ought to be trying to do is to help the student “oil” his newly established networks as well as his old rewired networks. The idea is to ground those networks in such a fashion that thinking in this new way becomes second nature. In other words, a good instructor might be able to supply the appropriate examples that will employ the new knowledge as if it were yet another conceptual building block that is part of the student’s entire neural network.

Clearly, the very last step, of making original discoveries, and using the newly acquired and now integrated information, is in the hands of the student himself. No instructor will be able to help with that – but maybe he might be able to challenge the student – if this turns out to be appropriate and is invited by the student.

5. SUMMARY

Learning is a complex process that happens in the brain. This paper attempts to discuss what happening in the brain at the neural level as we learn more about our environments and as we think through concepts. Concepts are mental representations that can be expressed by a single word or a set of ideas described by a few words. Through the use of language individual concepts can then be connected to build more complex concepts. Identifying the origin and the nature of concepts is rather tricky and no clear theories of how this happens in the student’s mind are available. Though this is a natural process, the construction of concepts requires a complex mixing and repeated evaluation of old and new observations, facts and thoughts. This is a natural process of learning and we do it every day.

We suggest that these concepts are represented in the brain through how the neurons are connected with each other. Electrochemical signals travel from the dendrites, across the synapses, down the axons to the next neuron. Neurons form webs of interconnected neurons. A concept in the mind is then represented in the form of a neural circuit. Students enter the classroom with already formed ideas which implies that neural circuits in the brain are already in place. Learning, then, is a mental process that depends how additional stimuli and new ideas get integrated into the old knowledge database (a process Piaget called ‘assimilation’), and on how, through reasoning (a previously acquired mental mechanism), the entire database gets re-organized which results in alterations of the mental structures and the creation of new ones (a process called ‘accommodation’). Since learning is a continuous process this implies that the brain must also continuously restructure itself. In other words, learning changes the physical structure of the brain, and with it, the functional organization of the brain. Learning is more at ease when specific thinking networks already exist and difficult if new networks have to be created. The process of learning involves the rewiring, and to some degree the creation, of new neural networks. This explains why learning always requires a major effort from the side of the student.

We conclude that initiating conceptual change is a difficult job, perhaps because concepts
become deeply rooted in the students’ minds and because their formation and change requires several personal learning experiences. Since concepts cannot be changed easily, we claim that the formation of concepts and the later constructions of more elaborate concepts is a fundamental and deeply rooted process that might be somewhat inscribed into our neural networks. In fact, we even claim that a certain part of our knowledge database and our automatic ways of thinking become somewhat “hardwired”. We further suggest that this happens at the neural level and involves neural plasticity and selective reinforcements or rewiring of dendrite connections. Thus, changing this hardwiring requires a major effort (of thinking and re-thinking, or of creating new neural networks and re-wiring old ones) and a strong willingness from the part of the student.

Furthermore, whether or not a student is going to undergo a conceptual change depends not only on the complexity of the concept itself, but also on the character and upbringing of the student – i.e., it involves his entire personality, his general cultural and personal belief systems, his acquired and inherited intellect, his ability to follow and think though arguments, and his personal attitude towards undergoing conceptual change. All of these attributes contribute towards each of the four (or five) distinct or continuous stages of the conceptual change model. Initially the student has to become “dissatisfied” with his own prior theory that will involve letting go of his precious prior beliefs which might be rather “personal”. He has to be able to logically follow and understand the new theory and find that it does a better job than his prior theory in explaining the situation (in the words of Posner et al, he needs to find the new theory “intelligible” and “plausible”). But that is not all, the student will need to find the new theory fruitful in the sense that he can apply it to other situation and solve new problems.

It is suggested that to form new concepts or change old inadequate ones the student has to be led through several processes. First, he has to consciously notice and understand what the problem is; second, he has to assimilate more information and try to fit it into already existing neural networks; third, he has to critically think through all the argumentation in his own words and reorganize this thoughts – he has to accommodate the knowledge and evaluate against his prior beliefs; and finally, he has to work towards obtaining fluency in the newly acquired and understood concept so that this concept itself has then becomes a mere building block for future, more advanced concepts. The claim here is that during the process of conceptual change what happens in the student’s mind is a reorganization of his thoughts, the creation of new neural networks, and the rewiring of old ones. This process is difficult to provoke and requires the student to work hard at this.

It is suggested that a good instructor can help with the process of conceptual change. But his task goes beyond clearly explaining the new theory – ideally he plays the role of a “facilitator”. He might confront the student with the problem (so that the student becomes dissatisfied with his prior belief), prompt the student to not only to regurgitate the new theory, but also explain it in his own words, and provide further examples of where to apply the new theory. Throughout this process, a good instructor would also be understanding and supportive to the student and challenge the student at the right moment.
This paper also tried to draw some parallels between education and neuroscience and made suggestions of how conceptual change might proceed at the neural level – in terms of affecting the formation and rewiring of neural networks in the brain. These are only claims and cannot be proven nor disproven with the current technology and our current understanding of what happens at the neural level in the students brain as he thinks. Nevertheless, the analogies are worthwhile making and might provide incentive for further studies.
References

von Foster 1984
Diagram 1