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Brain Activity and Experiential Learning

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> For the things we have to learn before we can do them, we learn by doing them.
>
> —Aristotle, ca. 350 BCE

INTRODUCTION

The chapters in this book deal primarily with students' learning experiences as documented through self-awareness, knowledge acquisition, and behavior. Language makes it possible to communicate these changes to others. This essay, in contrast, will examine learning from the perspective of brain function. The current framework of thinking among neuroscientists, psychologists, and philosophers is that the brain is fully responsible for our minds, and thus studying how the brain functions in molecular, cellular, and systems terms sheds light on all mental processes, including those that are the substrate of learning. A scientific understanding of brain function thus helps to explain the long-term benefits of experiential leaning described by the theorists and practitioners of City as Text™ (CAT).

Learning is the acquisition of knowledge about the world, and in order for that knowledge to be applied to future situations, it has to be stored, recalled, and put to use in a new context. Learning cannot occur without memory, which comprises the multiple processes of information storage and recall.

In recent years, the possible means of exploring brain activity have increased dramatically thanks to advances in molecular biology and in scanning techniques such as functional magnetic resonance imaging (fMRI), which allow the investigator to observe human brain activity in real time while the subject performs some defined task. Additional information comes from a variety of studies that focus on developmental learning in children, defects in memory acquisition and retention resulting from brain injury or disease, and laboratory experiments on animals using techniques that permit the analysis of brain behavior on a single-cell or systems level.

Evolutionary thinking also contributes to the analysis of learning and memory. Early hominids had to develop multiple abilities in order to survive; evolving predictive capabilities about the environment, for example, was essential to avoid being killed. A crucial product of human evolution was aversive and fearful behavior that led the individual to avoid threatening or dangerous situations: a large predator or a dark and unexplored space. Such situations linked emotion to memory, and we know from recent brain studies that emotion heightens memory through indirect brain circuits (LeDoux). Readers will recall from their own experience that emotion heightens memory. Think back to childhood accidents or near accidents: receiving an electric shock from an outlet or almost being hit by a car after not looking in both directions at a crosswalk. Simple examples from everyday experience, when extended and amplified, indicate why evolutionary pressure to link emotion and memory would have survival value for the species. Moreover, not only fearful emotions enhance memory; the nervousness of a first piano recital or the excitement of a first date creates an emotional tone that contributes to the vividness of a given memory years or even decades after the experience.

A VERY BRIEF OUTLINE OF NEUROBIOLOGY

In order to discuss how memories are formed and stored, we need some basic information about the cellular organization of the brain. The human nervous system consists of a central portion (the brain and spinal cord) and a peripheral portion that supplies nerves to the body, e.g., the gut. We are concerned in this essay only with the brain, which contains nerve cells (neurons) and glial cells. Neurons are organized into functional circuits governing every sort of activity from movements to abstract thought, and the glial cells help neurons carry out their tasks in multiple ways but are not directly involved in mental processes. Our brains have about ten billion neurons and perhaps ten times that many glial cells. Like every cell in an organism, neurons have a cell body with a nucleus that contains the cell's genetic material and—in the non-nuclear part of the cell body, called the cytoplasm—the various cellular structures needed to keep the cell alive, that is, to produce energy, synthesize needed materials such as proteins, and destroy unwanted material. Although neurons share many properties with other types of cells in the body, they differ in two fundamental ways: 1) their surface membrane is excitable, meaning that it generates electrical signals, which are the substrate of brain communication, and 2) they have irregular shapes as a consequence of emitting multiple processes. These processes join neurons into functional circuits wherein neurons send and receive messages by electrical and chemical means. Typically, a neuron has a long, slender process called an axon. The axon is capable of discharging and transmitting brief electrical pulses (called spikes or action potentials) that constitute the neuronal signal. At its terminal end, the axon expands into many fine swellings, each of which forms a structural relation called a synapse with a neighboring cell. Other processes, called dendrites, emanate from the neuron's cell body and typically receive synapses. Synapses are the communication points between cells and, as we shall see, are modified by learning experiences. One side of the synapse contains a chemical called a neurotransmitter. Some neurotransmitters excite the target cell, and others inhibit it. Moreover, synapses are polarized: the information flows only in one direction. Typically, the axon terminal controls the release of the transmitter, whereas the dendrites have receptors that respond to the transmitter. Each neuron makes multiple synapses, up to many thousands, with its target cells. The presence of axons and dendrites is common to virtually all neurons, but the particular spatial geometry of each neuron's processes is dictated by the specific communication task the neuron carries out.

A crucial point is that the organization of the adult brain is not completely governed by genetic processes or pre-wired. It is true that in the early stages of brain development, genetic programming dictates the generation of neuronal cell bodies and the growth of their axons toward their targets, but the specific patterns of synaptic connectivity that define neuronal circuits are strongly shaped by experience, by learning and repeated use. As young humans interact with the world, their brains establish connections through sensory experience—looking, touching, smelling, hearing—and by motor movements. A newborn's first movements are awkward and reflexive but become refined by repetition. Similarly, language acquisition happens through the repetition of significant sounds from the caregiver and then by the infant. Many studies show that for the developing brain, repetition strengthens synaptic connections, whereas disuse causes connections to be pruned (Kandel, Dudai, and Mayford). Moreover, human brain development is not confined to early childhood: it continues into the adult state. The ability of neural circuits to enhance some connections and to eliminate others is called *plasticity*, and it underlies all learning and memory.

Of course, the brain is more than a random collection of interconnected neurons. On the contrary, neurons assemble into functional regions devoted to the processing of sensory information, the execution of motor tasks, the control of language comprehension and production, and all higher operations, including cognition. Brain imaging has enabled investigators to identify which brain region or regions are activated when the subject performs a given task, and a general conclusion is that for most tasks, brain information flows widely, with the result that multiple brain areas are activated.

EXPERIENTIAL LEARNING

Before expanding on these details of brain structure and function, I think it will be useful to consider the learning paradigms for which brain circuits are the substrate. If learning can be parsed into identifiable components, for example, memory formation and attention, studying their neurobiological correlates becomes easier. Given the bias of this book, here we focus on experiential learning, for which a well-accepted theory was developed by David A. Kolb.

In Kolb's schematic, one begins with a concrete experience such as learning to ride a bicycle. The physical experience of mounting, pedaling, and steering the bike leads to reflective observation about what went right or wrong in a first attempt at biking. Observation, in turn, leads to abstract conceptualization of what needs improvement and how to go about it. Conceptualization gives rise to active experimentation in which the novice biker tries again by incorporating behavioral modifications derived from past learning. In neurobiological terms, this set of linked processes begins with sensory experience of the hands gripping the handlebars and the feet feeling contact with the pedals, coupled with the emotional twinges the rider experiences as the bike wobbles and perhaps falls. There are, as well, the motor (muscle movement) responses: steering the bike, pushing the pedals, and so forth. Visual and tactile sensations flow from the peripheral receptors in the hands and eyes into their corresponding primary regions in the brain's cerebral cortex, the convoluted surface area of the brain.

The brain is divided into four lobes: occipital, parietal, temporal, and frontal. Vision begins to be processed through the back end of the cortex in the occipital lobe, whereas touch is initially processed in the parietal lobe. Sensory inflow guides the production of the motor responses that move the bike. At the same time, memories are being formed that include motor performance, the environment in which it occurs, e.g., a city street or a park, and the emotional flavor of the event. These memories are stored and inform the reflective observations of what went right or wrong. Memories are channeled to cognitive portions of the brain in the frontal lobe, where notions of how and what to improve are generated, and these newly created ideas inform the biker's future attempts. As most of us recall, repeated iterations of this cycle occur before one rides a bike with ease and confidence.

Kolb emphasizes that in order to profit from the series of steps in the cycle, the learner must

a. be willing to be actively involved,

b. be able to reflect on experience,

c. possess and use analytical skills to conceptualize, and

d. employ decision-making and problem-solving skills.

When these four processes are correctly applied (and reapplied), users acquire long-term memories of experiences, techniques, and information that increase their cognitive abilities to cope successfully with novel situations that extend beyond the initial experience. Not every human will react identically to the same challenge. Some are natural athletes who easily learn to ride a bike, whereas others have lesser athletic gifts but might be good at grasping mathematical concepts. One learning mold does not fit all, but the concept of actively participating in these four steps is generally valid and necessary.

MEMORY

Given that memory is central to learning, we need to consider in greater detail how memories are formed and stored. A crucial phase of memory research revolves around a man known during his lifetime as H. M., but since his passing in 2008, we know his name: Henry Molaison. Molaison suffered from intractable epilepsy, and in 1953, at the age of 27, he underwent surgery that removed, bilaterally, a portion of his medial temporal lobe that included most of a structure called the hippocampus, so named because of its resemblance to a seahorse. Many brain structures, including the hippocampus, are paired, with one on each side of the brain, so H. M.'s surgery was bilateral, removing both hippocampi. Molaison recovered from the surgery. The frequency of his epileptic seizures was greatly reduced, but the law of unanticipated consequences manifested itself in a surprising way: he could no longer retain memories of recent events. Beginning in 1957 and until his death, Molaison was studied intensively (Milner, Corkin, and Teuber; Corkin). Over the hundreds of times Milner met with Molaison, she had to introduce herself each time because he retained no memory of their prior encounters. On the other hand, he retained memories of events in his childhood. Milner tested him on memory acquisition and retention tasks, and the results revealed the complicated and multistage nature of memory formation and storage. The fact that he remembered well distant events from his early childhood indicated clearly that long-term memory storage was not situated in the medial temporal lobe, the part of his brain removed by the operation, yet he did suffer memory loss of past events in a graded way. Events that occurred just before the surgery were lost completely, and there was partial loss of other memories in inverse proportion to their temporal distance from the surgery, up to about ten years. We learn from this finding that memory storage is a progressive process. (*N.B.* In a 2016 *New York Times Magazine* article, Luke Dittrich referenced research indicating that the surgery also slightly damaged H. M.'s frontal lobe; the possible significance of this finding for conclusions about memory formation is as yet undetermined.)

Another crucial finding was that Molaison did not lose all memory function. He could learn motor tasks and benefit from prior experience on repeated trials of a task even though he did not specifically remember having practiced the task earlier, leading researchers to make a distinction between *explicit*, or declarative, memory and *implicit* memory. Explicit memory is the sort concerned with objects, facts, places, and persons, in short, all the details that underlie our knowledge base: the *where*, *what*, *who*, and *when* of an experience. In humans, declarative memory requires conscious awareness. Implicit memory refers to motor skills that we have acquired through practice (riding a bike, playing the piano, drawing) and that come into play automatically when we perform a given activity. Implicit memory does not require conscious awareness and is not routed through the hippocampus but does depend upon the cerebellum, among other brain structures. Molaison's brain was removed post-mortem, processed for microscopic study, and is still being studied today. The brain sections show that, in addition to the hippocampus, he lost the amygdala (almond-shaped structure), which is a crucial component of the brain circuitry processing emotions. He also lost entorhinal cortex, which is implicated in memory storage. These three structures—hippocampus, amygdala and entorhinal cortex—are located in adjacent brain areas that are intimately involved in memory, including its emotional component.

Molaison was also able to remember number sequences for a brief time, especially if he aided himself by repeating the numbers frequently. Additionally, his intelligence was found to be above normal; he had no known memory deficits prior to surgery; he retained language skills and personality; and he expressed an interest in helping scientists gain insight into the biological basis of memory. What the Molaison case revealed indisputably was that memory formation, consolidation, and storage are a complex set of processes involving multiple brain regions.

Early studies on memory formation employed simple systems such as classical conditioning, a kind of learning also called Pavlovian. Pavlov trained dogs to expect food after the ringing of a bell. The bell is the "conditioned stimulus," so-called because by itself it is neutral, but it acquires significance in the learning paradigm. The food is the "unconditioned stimulus" because no prior training is required to give it significance. After a small number of pairings (the sound of the bell followed by the presentation of food), the dog learns to associate the two and salivates (the conditioned response) to the sound of a bell. This paradigm is an example of implicit memory formation in that the salivation response occurs reflexively.

At the time Pavlov's investigations were underway, neuroscience was in its infancy. Explaining how a Pavlovian reflex operated on a cellular level took another five decades or so. Although reflex responses were known in mammals, for example, the eye-blink that results from touching the eyeball, the mammalian brain appeared too formidable an experimental subject. Eric R. Kandel opted to study reflexive behavior in a marine mollusk, Aplysia, whose simple nervous system of fewer and larger cells facilitated experimentation. A single shock to the tail of Aplysia was followed by gill withdrawal. Kandel, Dudai, and Mayford analyzed the withdrawal reflex at the cellular level and showed that the synaptic connections between the sensory input (the shock) and the motor response (the withdrawal) were strengthened by repetition, providing a clear example of synaptic plasticity. Moreover, Kandel was able to identify some of the neurochemicals participating in reflex modification. In spite of the great evolutionary distance between a mollusk and a human, the same neurochemicals are found in the human brain and often have similar functional roles. In Aplysia the relevant cellular components of the reflex circuit could be removed from the animal and studied in a culture. In this reduced system, the neurochemical serotonin could be applied in place of the tail shock: it had the same facilitating result. One application of serotonin resulted in a short-term increase in synaptic strength, whereas systematically spaced application of serotonin led to long-term changes, which depended on gene activation and protein synthesis. These results became a model for how memories are formed and stored in the human brain (Kandel).

Before the experimental tools for exploring mammalian brain function on a cellular or systems level were available, D. O. Hebb postulated that repeated activity led to stable changes in synaptic circuitry:

> Let us assume that the persistence or repetition of a reverberatory activity tends to induce lasting cellular changes that add to its stability. . . . When an axon of cell A is near enough to excite cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased. (62)

His mechanism was stated more succinctly by Löwel and Singer: "neurons wire together if they fire together" (211). This insight has proven correct. Recent investigations of the hippocampus, which as we learned from the analysis of how H. M.'s amnesia is implicated in short-term memory formation, show that stimulation of nerve fibers entering the hippocampus increase synaptic transmission in hippocampal cells, a phenomenon called "long-term potentiation." Investigators have shown that hippocampal synapses increase their efficiency through repeated stimulation and that the effect can be short term or long term depending on the timing and duration of the stimuli. Short-term enhancement does not require gene activation or protein synthesis, but long-term stimulation does, exactly analogous to what was found in Aplysia.

Moreover, with regard to learning and memory, much more information has been gleaned from hippocampal studies. Unlike simple reflexes, hippocampal cells are activated by complex stimuli. One of the striking features of the hippocampus is that it is a brain center concerned with the location of the body in space. A simple experiment in mice or rats indicates how this works. If a rodent is placed in a water tank containing a small platform, it will ultimately locate the platform and rest there. If the water is now made murky so that the platform is invisible, the rodent will nevertheless head straight for it. Further work shows that hippocampal cells are "place" cells that chart the environment, i.e., each neuron fires when the rodent passes through the limited environmental space coded by that cell. Coding of space extends to a neighboring region, the entorhinal cortex, which contains so-called "grid" cells that provide the hippocampus with information about position, direction, and distance. Both of these brain regions are intimately involved in memory formation. Moreover, the hippocampus-dependent memory for space and the subsequent retrieval of the memory are optimized by attention. This relationship was studied by associating the exploration of space with a defined task such as searching for food. Finally, when mice were genetically modified to prevent long-term potentiation in the hippocampus, the animals showed deficits in hippocampus-dependent learning paradigms (Kandel, Dudai, and Mayford).

Although these studies were performed on rodents, they are presumed to apply also to humans. Evidence comes from drivers of black cab taxis in London who acquire a very detailed knowledge of the city's geography. A magnetic resonance imaging study of their brains identified an increase in posterior hippocampus volume relative to that of untrained control subjects (Maguire et al.)

To summarize where our discussion has taken us: short-term memories of specific events are first formed in the hippocampus, and explicit learning by repetition results in synaptic strengthening in certain hippocampal synapses, leading to the formation of stable brain circuits that underlie future performance. Other related studies have shown that for long-term memories to be established, new protein synthesis is required. Long-term memories are distributed widely in the brain, and somehow, in ways that are still not well understood, adding an emotional component and a time/place component to the memory event increases the probability of its retention in the brain. Long-term memory formation is not a one-time event; instead, the memory is renewed each time it is recalled, at times resulting in alteration of that memory.

ATTENTION

Attention refers to the behavioral and cognitive process of selectively concentrating on a discrete aspect of information while ignoring other available information. The relevant information could come from the environment (some interesting sight) or be internally generated by cognitive processes (what do I do next?).

As noted above, hippocampal studies brought out a salient feature for learning theorists: the stability of location mapping by hippocampal neurons was increased when the animal had a task to perform compared to animals with no such task. Tasks included foraging for food or remembering the spatial relationships of the environment in order to turn off disagreeable stimuli such as loud sounds or light (Kentros et al.). These concerns may seem modern, but only the ability to study them in biological terms is modern. The Spanish philosopher Juan Luis Vives (1492–1540), in his 1538 multi-volume study *De Anima et Vita*, concluded that the more closely one attends to stimuli, the better they will be retained. The modern notion that we humans can multitask—e.g., look at our computer while listening to a lecture or talk on a cell phone while driving—is true only to a limited degree since performance in one or both tasks is reduced. In the first example, retention of the lecture material is reduced, and in the second example, driving deteriorates, leading to more accidents. For maximum benefit, attention should be focused on a single task.

The human brain has multiple specific centers involved in focusing attention on the task at hand. We can begin by considering external stimuli of interest that come to the individual through one or more sensory pathways (e.g., vision, audition). All sensory pathways in the brain consist of a series of stages beginning with the sensory organ (the eye, the ear) and processing through various brain centers, culminating in multiple cortical areas. In vision, for example, the lower stages of processing characterize the visual stimulus in terms of its shape, size, color, contrast, and movement. Each processing neuron is concerned only with a small piece of the visual world. For this visual stimulus to have behavioral relevance, however, it has to be identified, meaning that some relevance is assigned to it by reference to whatever related material is in the viewer's memory. Higher visual processing areas in the brain are concerned with more global properties of the stimulus. Neurons in the parietal cortex direct the viewer's gaze toward the direction of movement, and cells in the inferotemporal cortex identify faces. Some humans lack the ability to recognize face definition, a condition called prosopagnosia, which is associated with damage to the inferotemporal cortex.

Attention centers in the brain receive input from multiple sensory pathways. Imagine an early human on a hunt for deer suddenly encountering a large and aggressive bear. The size and face identification neurons would play a role in identifying the animal, and its sounds and body attitude might well indicate aggression. Finally, its direction of motion would obviously be important in determining the hunter's course of action. For these external stimuli, attention centers in the parietal and temporal cortex come into play. For internal concerns like task performance that demand the actor's close attention, the frontal cortex and basal ganglia are implicated.

In general terms, attention focuses the mind away from extraneous stimuli—the background noise with which our everyday waking lives are filled—onto the relevant stimuli for ordered activity. Many psychological studies show that lack of attention or dispersed attention is inimical to learning. Attention-deficit hyperactivity syndrome is a case in point, and many mental illnesses, such as bipolar syndrome or schizophrenia, have analogous learning difficulties. On a less pathological level, boredom and apathy diminish learning because they get in the way of focused attention. It follows that a good learning strategy is one that increases attention and dispels boredom.

DEVELOPMENT

Newborn humans are relatively helpless beings, but as recent studies have shown, they are far from lacking the ability to observe and react to their surroundings (Gopnik). The newborn brain is not a blank slate; it has built-in preferences that help channel activities. One example is a preference for hands and faces. In the first few years of life, brain circuits are wiring up through axon growth and synapse formation. Acquisition of the ability to identify visual, auditory, and other sensory stimuli is associated with the enhancement of some synapses and the elimination of others. We can relate this process to the way babies learn, which is primarily by observation of others and attempting to copy their actions.

In that regard, a fascinating and relatively new neurobiological finding is "mirror neurons." The phrase refers to neurons that become active both while an individual executes some action *and* while the person sees or hears another individual performing a similar action (Del Guidice, Manera, and Keysers). Such mirror neurons have been identified in primate brains, including in humans. A working postulate is that mirror neurons help to form functional brain circuits by focusing the infant's activities on certain movements and perceptions, thereby utilizing a Hebbian learning mechanism that reinforces certain synapses and builds functional circuits. Some researchers have implicated mirror neurons in the process of socialization. The question is still open whether mirror neurons are built into the brain's genetic information or are formed through activity; this is still an active area of research from which we can expect important insights about learning in the near future.

As the child matures and acquires language, much new learning is done through play. Alison Gopnik has noted that children left to their own devices with toys and puzzles are quite good at developing hypotheses about how things work. In fact, they behave like young scientists, testing first one possible mechanism and then another until they arrive at a solution. Young children do also pay attention to what a parent says, but as Gopnik points out, if the parents play teacher by saying "this is how x works," then children tend to adopt that solution rather than coming up with one of their own (4).

SUMMARY

In this brief survey, we have examined experiential learning from two perspectives: from the standpoint of brain function and as a theoretical framework for examining the psychology of learning (Kolb). To these we can add the knowledge acquired by teachers and educators as they search for the best methods to convey information and stimulate interest about the world in their children and students. In particular, we want to make reference to the conclusions reached by those participating in the City as Text programs documented elsewhere in this book. The challenge is to find unifying hypotheses that will identify putative specific brain mechanisms associated with learning that can be examined experimentally.

Some principles have emerged. One is that the newborn brain is not a tabula rasa. Infants are born with certain genetically dictated predilections, and these guide the ways they acquire and store information. Understanding these mechanisms obviously will have relevance for teaching strategies. One principle derived from observing young children (two to five years old) is that leaving them to sort out problems is a good strategy when coupled with the presence of an adult who listens and comments on what a child has learned. This mode of acquiring knowledge fits well within the framework of experiential learning.

Some factors that emerge from brain science in relation to individual learning seem clearly to favor the acquisition and retention of new information. One of these is attention, which involves not only exclusion of random stimuli but also a conscious focus on a subset of information that is considered relevant. In that context it is worth focusing on sensory input.

Humans utilize multiple avenues of sensory input—vision, audition, taste, smell, and touch—but of these vision is the most important. Our language reflects this in, for example, the sayings "I see what you mean" or "it's in my mind's eye"; vision clearly is a metaphor for comprehension. Audition comes in a close second. Both vision and hearing function at a distance, whereas taste and touch require contact with the stimulus. Odor does function at a distance for animals such as dogs that are well endowed with odor sensitivity, but humans are not particularly sensitive or discriminative for odors, so for early man evolution favored the development of vision, and a large fraction of our brain is devoted to visual information processing.

As described above, the brain manifests multiple centers for focusing attention, each associated with one or another modality of sensory input. We see a parallel here between brain organization and Kolb's scheme. He places great significance on the willingness of the subject to participate in the learning experience, i.e., to pay attention to the task at hand. In City as Text exercises, the student's first task is to take in the new surroundings, and that happens via sensory input, particularly visual input. As Bernice Braid puts it, "Developing the eyes, ears, noses, and tastebuds that serve as collecting tools for systematic observation is central to integrative fieldwork in City as Text™" (20).

A second factor that favors short-term memory formation is emotion, in all its varieties from fear to exhilaration. Emotion also is an inevitable accompaniment of City as Text exercises. Any new situation tends to elicit a little anxiety simply because the learning situation is unpredictable and open-ended, and this emotional color also favors short-term memory, as documented by animal experiments and psychological examination of human memory storage.

A third factor common to neuroscience investigation and City as Text exercises is the importance of place. Evolutionary pressures have resulted in the wiring of neuronal circuits specifically for place recognition, both in the hippocampus and the adjacent entorhinal cortex. Although this work has been carried out primarily on rodents, evidence suggests that "place-coding" neurons also exist in the human brain. We can imagine that early humans would benefit from circuits that recognized familiar elements in the environment, such as places of shelter or sources where food and water could be found. Thus, the emphasis on "place" in City as Text fits in well with what we know of mammalian brain organization.

This brief review has suggested some evident parallels between the ways in which our brains are organized for knowledge acquisition, for memory formation and storage, and for learning strategies that emerge from direct experience. Many other factors, including those involving higher-order functions such as language and cognition, enter into the educational experience, but while brain scientists posit that language and cognition also are subserved by neural circuits, a neural description of their workings awaits much further experimentation and may further deepen our understanding of why experiential leaning has such a powerful impact on its practitioners. Meanwhile, recognizing that cognitive science provides grounding for the value of such learning affirms the validity of participants' subjective perception that City as Text is a transformative practice.

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