

significant and correlated components. Second, the fractal dimension trajectory can be generalized to represent both the spatial and temporal multifractal characteristic of a signal through the Rényi fractal dimension spectrum trajectory [13]. This representation would be valuable for classification, as some signals are not monofractal in a window, rather they are multifractal in both space and time.

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Cognitive Informatics Models of the Brain

Yingxu Wang, *Senior Member, IEEE*, and Ying Wang

Abstract—The human brain is the most complicated organ in the universe and a new frontier yet to be explored by an interdisciplinary approach. This paper attempts to develop logical and cognitive models of the brain by using cognitive informatics and formal methodologies. This paper adopts a memory-based approach to explore the brain and to demonstrate that memory is the foundation for any kind of natural or artificial intelligence. Logical structures of memories are explored, and cognitive models of the brain are proposed. Cognitive mechanisms of the brain, including hypotheses and theories on the thinking engine of the brain, long-term memory establishment, and roles of perceptive eye movement, and sleep in long-term memory development, are investigated. The models and theories can be applied to explain a wide range of fundamental phenomena in psychology, cognitive science, physiology, computing, and neural science.

Index Terms—Cognitive informatics, cognitive models, memory, object-attribute-relation (OAR) model, the brain, thinking engine.

I. INTRODUCTION

The history of human quest to understand the brain is certainly as long as the human history itself. The study of the brain was originally conducted in the domain of philosophy. Plato (428–347 B.C.) observed that the philosophy begins in human wonder, a powerful desire to understand the world, not merely to act in it as animals do. Aristotle (394–322 B.C.) perceived psychology as the study of the soul which differentiates the animate world from the inanimate one. Psychology, as we know it, began with Rene Descartes (1596–1650), who proposed that the brain functions like a machine, in 1649. Descartes also created a framework for thinking about mind and body for philosophers and psychologists. Then, 200 years later, Wilhelm Wundt (1832–1920) founded psychology as a science disciplinary by initiating a link between physiology and philosophy via an experimental approach in 1873 [12].

It is recognized that in computing, software engineering, informatics, and artificial intelligence, almost all hard problems that are yet to be solved, share a common root in the understanding of the mechanisms of the natural intelligence and the cognitive processes of the brain. This leads to an emerging discipline of research known as cognitive informatics [4], [11].

This paper develops the cognitive informatics models of the brain. A main thread adopted in this paper is the memory-based approach that perceives memory as the foundation for any natural and artificial intelligence. Another major thread of this work is the relationship between the inherited and the acquired life functions. Structures of memories are explored in Section II. Cognitive models of the natural intelligence are developed in Section III. Cognitive mechanisms of the brain, including the hypotheses on long-term memory establishment, roles of sleeping in memory, and the cognitive mechanisms of eyes as the perceptual browser of the mind, are investigated in Section IV. On the basis of these analyses, a number of functional and cognitive mechanisms and processes of the brain will be revealed.

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Yingxu Wang is with the Theoretical and Empirical Software Engineering Research Center, University of Calgary, Calgary, AB T2N 1N4, Canada (e-mail: Yingxu@ucalgary.ca).

Ying Wang is with the Fourth City Hospital, Shaanxi 710004, China.
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II. COGNITIVE MODELS OF HUMAN MEMORY

Memory is the foundation for maintaining a stable state of an animate system. Therefore, it plays an important role in natural intelligence. This section explores the taxonomy of human memories and their cognitive models and relationships. It is commonly believed that the elementary function and mechanism of the brain would be quite simple, but the significant aspects of the brain are the magnitude of the neural clusters and their concurrent behaviors [8]–[11]. Comparing the human brain and that of other animals, the magnitude of capacity of the human brain highlights a significant difference. This is one of the evidences that indicates that the capacity of memory is the key to distinguish humans from other animals.

Conventionally, the number of neurons in the brain is perceived as static and fixed in adult brains [1], [2], [6]. This was based on the observation that the capacity of adult brains has already reached a stable state and would not grow continuously. However, latest discoveries in neuroscience and cognitive informatics indicate that the memory is dynamically reconfiguring, particularly at the lower level of the neural clusters [1], [6]. Otherwise, we cannot explain the mechanisms of memory establishment, enhancement, and evolution functioning everyday in the brain.

A. Types of Human Memories

William James identified three components in human memory [2], in 1890, known as the after-image, the primary, and the secondary memory. The after-image memory is considered a relatively narrow concept because there are other sensorial inputs to the memory, such as hearing and touch. Thus, the after-image memory was gradually replaced by the concept of sensory memory. Contemporary theories on memory classification [1], [3] can be commonly described as the sensory memory, short-term memory, and long-term memory.

Examining the above-mentioned types of memory it may be seen that there is a lack of an output-oriented memory, because the sensory memory is only an input-oriented buffer. The authors introduce a new type of memory called the action buffer memory that denotes the memory functions for the output-oriented actions, skills, and behaviors, such as a sequence of movement and a preprepared verbal sentence. Therefore, according to the cognitive informatics, the logical architecture of memories in the brain can be classified into the following four categories: 1) the sensory buffer memory (SBM); 2) the short-term memory (STM); 3) the long-term memory (LTM); and 4) the action buffer memory (ABM).

B. Functional Models of Memories

The SBM is an input-oriented temporary memory corresponding to the five sensors of the brain known as vision, audition, smell, tactility, and taste [10], [11].

Model 1: The functional model of SBM is a set of parallel queues corresponding to each of the sensors of the brain. □

The capacity of SBM is quite small except the visual SBM that is a huge array of vision cells. Some psychological experiments report that the capacity of SBM is about 7 ± 2 digits [5]. However, this type of memory was initially called the STM according to Miller [5]. The basic mechanism of SBM is that the contents stored in it can only last for a short moment until new information arrives to the same sensory buffer. When the new information arrives, the old one in the queue should either be moved into STM or be replaced by the new one. This explains why the SBM seems rather small.

The STM is the working memory of the brain. Information memory duration in STM is about 24 h (some literature considered it as only a few minutes to a few hours [1], [3]). Out of this time span, the information will be either retained into LTM or removed from STM (oblivion).

Model 2: The functional model of STM is a set of temporal and plastic neural clusters that accommodates the thinking threads in the form of relations and links to related objects in other part of STM, as well as LTM, SBM, and ABM. □

The reconfigurable neural clusters of STM cohere and network related objects, such as images, data, and concepts, and their attributes by synapses in order to form contexts and threads of thinking. Therefore, the main function of STM may be analogized to an index memory connecting to other memories, particularly LTM.

The capacity of STM is much smaller than that of LTM, but it is hundred times larger than 7 ± 2 digits, as Miller proposed [5]. Limited by the temporal space of STM, one has to write complicated things on paper or other types of external memories in order to compensate the required working memory space in a thinking process.

The LTM is the permanent memory that human beings rely on for storing acquired information in terms of facts, knowledge, and skills. The LTM is apparently unlimited, because of its enormous number of neurons (at 100×10^9 level) and much more potential synaptic connections (at $10^{8.432}$ level).

Model 3: The functional model of LTM is hierarchical neural clusters with partially connected neurons via synapses. □

The LTM was perceived as static and supposed to not change in an adult's brain [1], [3]. This was based on the observation that the capacity of adult's brain has already reached a stable stage and would not grow further. However, the authors find that LTM is dynamic and lively reconfiguring, particularly at the lower levels or on leaves of the neural clusters. Otherwise, one cannot explain the mechanism of memory establishment and update [11]. Actually, the two perceptions above are not contradictory. The former observes that the macronumber of neurons will not change significantly in an adult brain. The latter reveals that information and knowledge are physically and physiologically retained in LTM via newly created synapses between neurons rather than the neurons themselves.

Supplementing to the input-oriented SBM, the action buffer memory (ABM) is an output-oriented temporary memory.

Model 4: The functional model of ABM is a set of parallel queues, where each of them represents a sequence of actions or a process. □

ABM is first identified by the authors. Detailed mechanism of ABM is explained in Section III, where ABM is put into the context of the dynamic memory model.

C. Object-Attribute-Relation Model of LTM

The capacity of the association cortex, the physiological organ of LTM, had been increased dramatically as humans evolved from animals. This section develops a cognitive model of LTM—the object-attribute-relation (OAR) model which explains how information or knowledge is represented in LTM.

It is found that, at the fundamental level, the brain models two elemental artifacts, the object and the relation [11]:

- 1) *Object:* The abstraction of an external entity and internal concept.
- 2) *Attribute:* A subobject that is used to denote detailed properties and characteristics of an object.
- 3) *Relation:* A connection or interrelationship between a pair of object-object, object-attribute, and/or attribute-attribute.

Based on the above definitions, the OAR model of memory is derived as follows.

Model 5: The OAR model of LTM can be described as a triple, i.e.,

$$\text{OAR} \triangleq (O, A, R) \quad (1)$$

where O is a finite set of objects identified by symbolic names, A is a finite set of attributes for characterizing an object, and R is a finite set of relations between an object and other objects or attributes of them. \square

In the cognitive informatics, relations are identified as information too. The connections between objects can be established via object-object, attribute-object, and/or relation-object. The connections could be highly complicated as analyzed below, while the mechanism is so simple that it can be deducted to the physiological connections of neurons via synapses in LTM. It is noteworthy that although the number of the physical entities of the real world is limited, their possible relations may result in an explosive exponential combination.

As for the human brains [9] as described in Section I, the possible connections of the neural clusters in the brain may reach an order as complex as

$$C_n^s = \frac{n!}{s!(n-s)!} = \frac{10^{11}!}{10^3!(10^{11}-10^3)!} \approx 10^{8,432} \quad (2)$$

where n is the total number of neurons and s is the number of average partial connections between neurons via synapses.

This result is astonishing because it states that the magnitude of complexity of the brain can reach the order of a magnitude we used to find in the universe. However, it interestingly exists indeed in our internal world [9].

Theorem 1: LTM is *dynamic*. Because memory is implemented by synapses, properties of LTM are constrained by the mechanisms of synapses as follows: 1) it is directed; 2) new relations (connections) can be generated; 3) it can be reconfigured; 4) it contains single-directional loops; and 5) it can be traversed or searched. 6) It cannot be sorted. \square

The dynamic manipulation of LTM includes new assignment of spare neurons to represent objects or attributes, and new connections that represent new relations are created and reconfigured in the brain. It is noteworthy that LTM cannot be sorted since it is so complicated and it uses spatial synapse connections to represent information. Therefore, access to information in LTM has to be carried out by content-sensitive and thread-based search. Comparing computer memory and LTM, it can be seen that the former may be fast and randomly accessible by the address-sensitive mechanism, while the latter is far more stable and robust. In addition, for a given object, LTM can be accessed through multiple paths. This is one of the cognitive foundations for reasoning and imagination.

III. COGNITIVE MODELS OF THE BRAIN

This section examines the cognitive models of the brain by studying relationships between the inherited and acquired life functions, and among all types of memory components.

Model 6: The cognitive model of the brain is shown in Fig. 1, where the external world is represented by real entities, and the internal world by virtual entities and objects. The internal world can be divided into two layers: the image layer and the abstract layer. \square

The virtual entities are direct images of the external real entities located at the image layer. The objects are abstract artifacts located at the abstract layer. There are metaobjects and derived objects. The former are objects directly corresponding to the virtual entities; the latter are objects that are derived internally and have no direct connection with the virtual entities or images of the real entities.

The abstract layer of the brain can be further extended into neuron clusters of objects, attributes, and relations, as described in the OAR model [9], [11]. The abstract layer is an advanced property and a unique

power of human beings, because other animals have no such abstract layer in their brains.

Experiment 1: One may communicate with one's cat by a direct real entity such as food and toys. However, if one wants the cat to pay attention to an entity in the distance by pointing his/her finger at it, the cat will never understand the intention but simply look at the finger perplexedly! Thus, animals have no indirect or abstract thinking capability.

The second advantage of human brains, as identified in Section II-B, is the tremendous capacity of LTM in the cerebral cortex [9]. On the basis of these two principal advantages, known as the ability of abstract thinking and the tremendous capacity of memory, we gain the power as human beings.

It is noteworthy that the cognitive model of the brain is looped. That is, an internal virtual entity is not only abstracted from the real-entity as shown on the left-hand side in Fig. 1, but also eventually connected to the entities on the right-hand side. This is the foundation of thinking, reasoning, and other high-level cognitive processes in which internal information has to be related to the real-world entities in order to get its semantics embodied.

IV. COGNITIVE MECHANISMS OF THE BRAIN

On the basis of the functional and cognitive models of the brain developed in Sections II and III, the cognitive mechanisms of the brain can be systematically examined and analyzed. This section demonstrates that by using the cognitive models of the brain and memories a wide range of natural intelligent phenomena and the mechanisms behind them may be explained.

A. When Is Memory Created in LTM?

The cognitive model of the brain classifies life functions into two categories known as the conscious and subconscious ones. The latter are inherited subconscious processes, while the former are acquired and can be programmed consciously based on desires and goals. It is noteworthy that the subconscious life functions play an important role in parallel with the conscious counterparts. That is, the higher layer cognitive processes are implemented based on the support of the underlying subconscious ones at the lower layers [11]. Therefore, a study on the subconscious behaviors of the brain and their mechanisms may be the key to understand how the brain works.

We start the investigation by examining the following questions.

Question 1: Why do all mammals need sleep? What is the cognitive mechanism of sleeping?

Sleep as an important physiological and psychological phenomenon was perceived as innate, and few hypotheses and theories have been developed to explain the reason. The following discussions explore the role of sleep in LTM establishment.

Question 2: When is the memory process completed in LTM?

Hypothesis 1: The LTM is established during sleeping. \square

This hypothesis logically explains the following common phenomena: 1) All mammals, including human beings, need to sleep. 2) When sleeping, the blood supply to the brain reaches the peak at about 1/3 of the total consumption of the entire body. However, during daytime the brain just consumes 1/5 of the total blood supply in the body [4], [7]. 3) According to the *NI-Sys* model, human beings are naturally an intelligent real-time information processing system. Since the brain is busy during day-time, it is logical to schedule the functions of LTM establishment at night, when more processing time is available and less interruptions occur due to external events.

Hypothesis 1 is supported by the following observations and experiments.

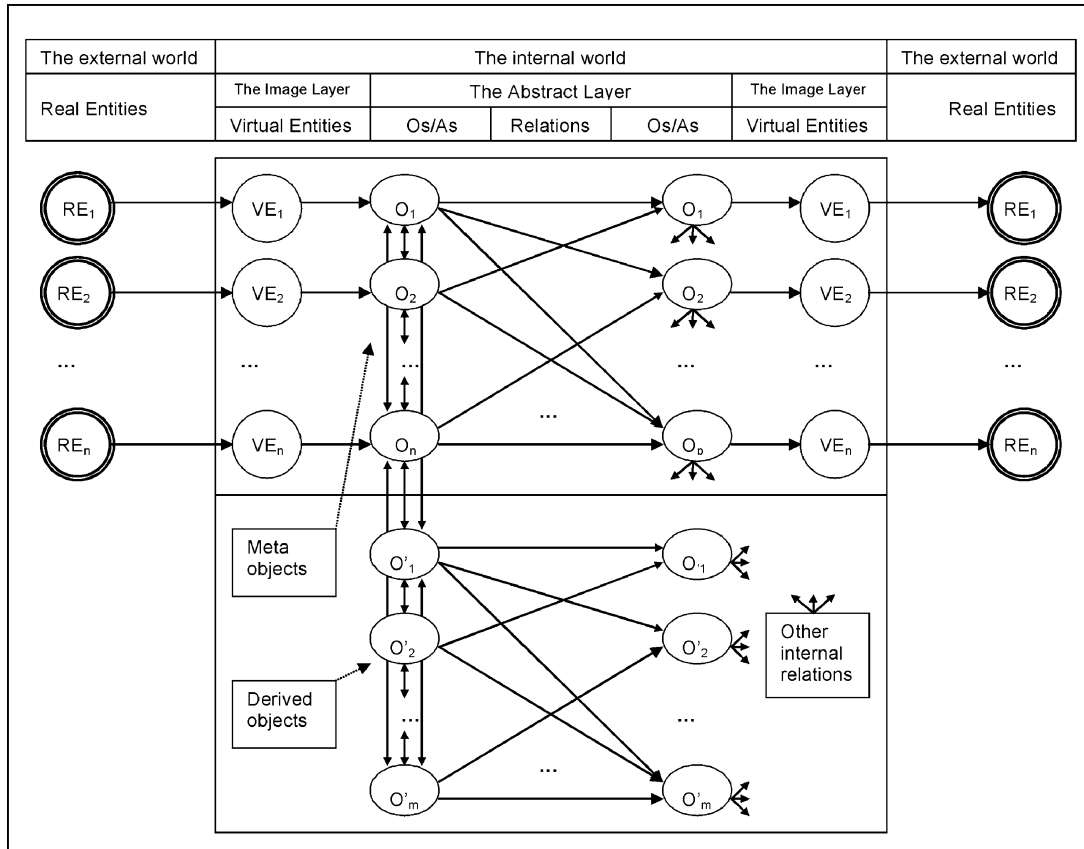


Fig. 1. Cognitive informatics model of the brain.

Experiment 2: A group of UK scientists observed that stewardesses serving long-haul flights had bad memory in common [8]. An initial explanation about the cause of this phenomenon was that the stewardesses have been crossing time zones too frequently! The authors think this might be a partially correct explanation. According to Hypothesis 1, the memory problems of stewardesses were caused by the lack of quality sleep during night flights. As a consequence, the LTM could not be properly built.

Based on Hypothesis 1, we can derive the cognitive informatics theory of sleeping as follows.

Theorem 2: LTM establishment is a subconscious process. The major mechanism for LTM establishment is by sleeping, i.e.,

$$\text{Cognitive purpose of sleep} = \text{LTM establishment.} \quad (3)$$

Theorem 2 describes an important finding on one of the fundamental mechanisms of the brain and the cognitive informatics meaning of sleep. Of course, there are obvious physiological purposes of sleep as well, such as resting the body and saving energy.

Corollary 1: Lack of sleep results in bad memory, because the memory in LTM cannot be properly established. □

Corollary 2: The subconscious cognitive processes of the brain, NI-OS, do not sleep throughout the human life. □

It was commonly believed that the heart is the only organ in the human body that never takes a rest during the entire life. Corollary 2 reveals that so does the brain. The nonresting brain is even more important than the heart because the latter is subconsciously controlled and maintained by the former.

Corollary 3: The general establishment cycle of LTM is equal to or longer than 24 h, i.e., LTM establishment cycle ≥ 24 [h] (4) where the 24-h cycle includes any kind of combinations of awake, asleep, and siesta. □

B. How Is Memory Created in LTM?

Sleep is recognized as subconscious process in cognitive informatics. Its cognitive and psychological purpose is to build and update the LTM. LTM is updated by searching and analyzing the contents of STM and selecting useful (i.e., the most frequently used) information.

Theorem 3: The mechanism of LTM establishment is to update the entire memory of information represented as an OAR model in the brain based on the following selective criteria: 1) the new subOAR was more frequently used in the previous 24 h; 2) the new subOAR was related to the existing OAR in LTM at a higher level of the neural cluster hierarchy; and 3) the new subOAR was given special attention so that it obtained a higher retention weight. □

It can be seen that the third case mentioned above is the most difficult situation in learning and memory where a set of totally new knowledge has to be memorized.

On the basis of Theorem 3, the relationship between memory (especially LTM) and learning becomes apparent. That is, learning is to gain knowledge or acquire skills, where the results of learning are retained in LTM or ABM, respectively.

C. How Is the Mind's Thinking Engine Works?

The brain possesses both external and internal senses. The former are vision (70% of sensory information entered the brain), auditory,

smell, tactility, and taste [10], [11]. The latter are the perceptivity of the brain, which encompasses consciousness, memory searching, motivation, willingness, goal setting, emotion, sense of spatiality, sense of motion, and equilibrium [11].

There are four types of eye movements known as saccades, smooth pursuit, vergence, and internal browsing [10]. The first three types of eye movements are needed to conduct external sensorial life functions and have been identified in classical psychology literature. The fourth type of eye movement, internal browsing, is discovered by the authors [10]. The observations of eye movement during the rapid eye movement (REM) sleep support the existence of the fourth type of eye movement.

On the basis of the above definitions and observations on eye movements, a key hypothesis on the cognitive mechanisms of eyes may be introduced as follows.

Hypothesis 2: The cognitive mechanisms of eye movement are both the sensor of the brain and the browser of the mind. In other words, the eyes are the driver of the *perceptive thinking engine* of the brain. □

Hypothesis 2 indicates that the eyes work as a bifunctional organ—the visual sensor (photoreceptor) and the perceptual browser of the mind. The latter plays a very important role in perceptive thinking.

Corollary 4: Conscious and subconscious thinking is driven by the internal browsing-type eye movements. □

The following experiment supports Corollary 4.

Experiment 3: Subconscious eye movement during thinking: During thinking, eyeballs move rapidly. Even when eyes are closed, eyeballs are still moving as usual in order to conduct memory browsing and access in a subconscious manner.

Corollary 5: No thinking may be conducted properly without eye movement, particularly the internal browsing-type movement. □

The following experiment supports Corollary 5.

Experiment 4: Forcible stopping of eye movement during thinking: If eyeballs are forced not to move, one cannot read and think, because the memory access and browsing functions are interfered or interrupted.

Corollary 6: The phenomenon of *eye blinking* reveals the cognitive mechanism of time-sharing multiplex of the bifunctional eyes. When eyes are open, they function as the visual sensor consciously and subconsciously; when they are closed, they function as the browsing engine on memory in the brain subconsciously via the thalamus. □

The following experiment supports Corollary 6.

Experiment 5: The mechanism of eye blinking: During thinking or conversation, the more complicated is the problem or topic, the more frequent is the blink of the thinker's or speaker's eyes. The blink frequency, or the ratio of closed eye browsing, indicates the intensiveness of thinking. In an extreme case, when in deep thinking, e.g., during an examination, one's eyes may need to be closed from time to time.

According to Hypothesis 2 and Corollary 4, an age-long question on why eyes move unconsciously during sleep can be explained by Corollary 7.

Corollary 7: Eye movement during REM sleep is required for LTM establishment. □

The following experiment supports Corollary 7.

Experiment 6: Eye movement during REM sleep is a general phenomenon of human beings [4], [7]. REM sleep is characterized by the following three phenomena: 1) rapid eye movements; 2) muscle atonia; and 3) electroencephalograph (EEG) desynchronization.

REM is the indicator of dreaming no matter being observed consciously or not, because REM is associated with the visual imagery and other information of dreams.

On the basis of Corollary 7 and Experiment 6, the following corollary can be derived.

Corollary 8: Dream as an indicator of LTM establishment is always ongoing during REM sleep. An observed dream is only an exceptional

case when the dream is interrupted by external events and then consciously captured by the dreamer. □

This section explored the cognitive mechanisms of the eyes—the visual sensor of the brain and the perceptual browser of the mind. The revelation of the internal perceptual mechanism of the eyes is not only theoretically significant to identify the physiological organ that drives the thinking engine of the brain, but also practically useful to explain a wide range of cognitive mechanisms of the brain and mind. It also explains how consciousness can be the product of physiological and mental processes of the brain on the basis of the cognitive informatics model and perceptual senses.

V. CONCLUSION

The human brain and its information processing mechanisms are at the center of cognitive informatics theories. Investigation into the brain is a unique problem that requires recursive and introspective mental power to explore the brain by the brain.

This paper has explained some fundamental cognitive mechanisms of the brain, such as the architecture of the thinking engine, knowledge representation and establishment in LTM, and roles of the perceptual eyes and sleep in LTM development. This paper has demonstrated that memory is the foundation for any natural intelligence. Structures of memories have been investigated and modeled. Logical and cognitive models of the brain and natural intelligence have been developed. Because computation is also memory-based, computing itself has been perceived as the machine implementation of intelligence. An interdisciplinary approach has been adopted in exploring the architectures, models, and mechanisms of the brain. This paper has attempted to introduce formalism in forms of mathematics, logic, and formal methods into the study of cognitive and neural psychology. Potential solutions have been explored for next generation computing, software engineering, cognitive psychology, neural science, and natural philosophy.

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