Formal Description of the Cognitive Process of Memorization

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Abstract. Memorization is a key cognitive process of the brain because almost all human intelligence is functioning based on it. This paper presents a neuroinformatics theory of memory and a cognitive process of memorization. Cognitive informatics foundations and functional models of memory and memorization are explored toward a rigorous explanation of memorization. The cognitive process of memorization is studied that reveals how and when memory is created in long-term memory. On the basis of the formal memory and memorization models, the cognitive process of memorization is rigorously described using Real-Time Process Algebra (RTPA). This work is one of the fundamental enquiries on the mechanisms of the brain and natural intelligence according to the Layered Reference Model of the Brain (LRMB) developed in cognitive informatics.

Keywords: Cognitive informatics, cognitive computing, computational intelligence, neural informatics, brain science, memory, memorization, learning, knowledge representation, cognitive processes, memory creation, manipulation, modeling, LRMB, OAR.

1 Introduction

Memory as a faculty of information retention organs in the brain has been intensively studied in neural science, biopsychology, cognitive science, and cognitive informatics [1], [2], [5], [11], [13], [17], [30], [34]. However, memorization as a dynamic cognitive process that manipulates information among memories in the brain, particularly in the long-term memory has not been thoroughly investigated.

Definition 1. *Memory* is the physiological organs or networked neural clusters in the brain for retaining and retrieving information.

William James identified three components in human memory in 1890 known as *the after-image, the primary,* and *the secondary memory* [4]. 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

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replaced by the concept of sensory memory. Contemporary theories on memory classification can be commonly described as the *sensory memory, short-term memory,* and *long-term memory* [1], [2], [8], [12], [13], [14], [15].

Examining the above 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 author and his colleagues introduce a new type of memory called the *action buffer memory* [34] that denotes the memory functions for the output-oriented actions, skills, and behaviors, such as a sequence of movement and a pre-prepared verbal sentence, which are interconnected with the motor servo muscles. Therefore, according to cognitive informatics, the logical architecture of memories in the brain can be classified into the following four categories: (a) the *sensory buffer memory*, (b) the *short-term memory*, (c) the *long-term memory*, and (d) the *action buffer memory*.

The contents of memory, particularly those in long-term memory, are information that may be classified into *knowledge, behavior, experience,* and *skills* [21, 23]. Therefore, the relationship between memory and knowledge is that of storage organs and contents. With the physiological basis of memories, memorization is a process of retention and retrieval about acquired information and past experience [15], [35], [36].

Definition 2. *Memorization* is a cognitive process of the brain at the meta- cognitive layer that establishes (encodes and retains) and reconstructs (retrieves and decodes) information in long-term memory.

This paper presents the cognitive informatics theory of memory and the cognitive process of memorization. Neural informatics foundations of memory and the relational model of memory are explored in Section 2. Logical models of memory, particularly the Object-Attribute-Relation (OAR) model, which form the context of human knowledge and intelligence, are explained in Section 3. The mechanisms of memorization as a cognitive process are investigated in Section 4, which explains how and when memory is created in long-term memory. On the basis of the memory and memorization models, the cognitive process of memorization is formally described using Real-Time Process Algebra (RTPA) in Section 5.

2 The Neural Informatics Foundations of Memory

Neural informatics [22], [34] is an interdisciplinary enquiry of the biological and physiological representation of information and knowledge in the brain at the neuron level and their denotational mathematical models [21], [26]. Neural informatics is a branch of cognitive informatics where memory is recognized as the foundation and platform of any natural or artificial intelligence.

2.1 Taxonomy of Memory

In neural informatics, the taxonomy of memory is categorized into four forms as given in the following cognitive model of memory.

Definition 3. The *Cognitive Model of Memory* (CMM) states that the logical architecture of human memory is parallel configured by the Sensory Buffer Memory (SBM), Short-Term Memory (STM), Conscious-Status Memory (CSM), Long-Term Memory (LTM), and Action-Buffer Memory (ABM), i.e.:

$$\mathrm{CMM}\mathbf{ST} \triangleq \begin{array}{ll} & \mathrm{SBM} \\ \| & \mathrm{STM} \\ \| & \mathrm{CSM} \\ \| & \mathrm{LTM} \\ \| & \mathrm{ABM} \end{array} \tag{1}$$

where || denotes a parallel relations and **ST** represents an abstract system structural model.

The major organs that accommodate memories in the brain are the cerebrum or the cerebral cortex. In particular, the association and premotor cortex in the frontal lobe, the temporal lobe, sensory cortex in the frontal lobe, visual cortex in the occipital lobe, primary motor cortex in the frontal lobe, supplementary motor area in the frontal lobe, and procedural memory in cerebellum [36], [34]. The CMM model and the mapping of the four types of human memory onto the physiological organs in the brain reveal a set of fundamental mechanisms of neural informatics.

2.2 The Relational Metaphor of Memory

The conventional model of memory adopted in psychology is the *container* metaphor, which perceives that new information is stored in neurons of the brain. According to the container model, the brain needs an increasing number of neurons in order to store new information and knowledge acquired everyday. However, the observations in neural science and biopsychology indicates that the number of neurons of adult brains is relatively a constant at the level of about 10^{11} neurons [2], [7], [10] that will not increase during the entire life of a person.

Therefore, there is a need to seek a new model rather than the conventional container model to explain how information and knowledge are represented and retained in the brain. For this purpose, a relational model of human memory is developed as described below.

Definition 4. The *relational model of memory* is a logical memory model that states information is represented and retained in the memory by relations, which is embodied by the synaptic connections among neurons.

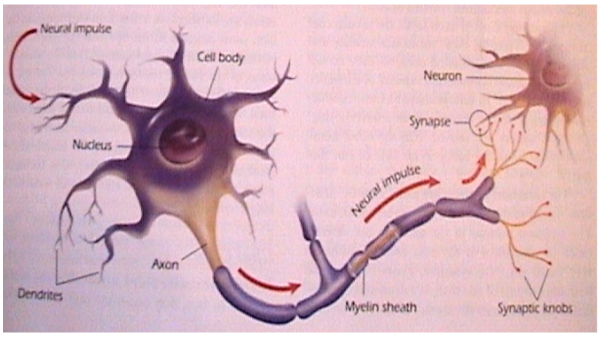

Fig. 1. The micro model of memory (Sternberg, 1998 [15])

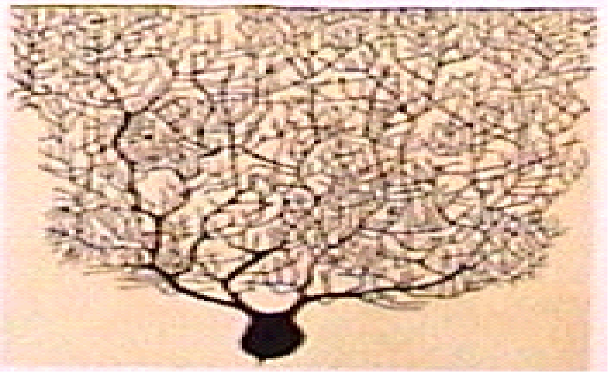

Fig. 2. The macro model of memory (Sternberg, 1998 [15])

The *relational* metaphor indicates that the brain does not create new neurons to represent newly acquired information; instead, it generates new synapses between the existing neurons in order to represent new information.

The *micro* and *macro* models of memory, particularly LTM, can be illustrated in Figs. 1 and 2, respectively, which are supported by observations in neuroscience and neuropsychology [2], [7], [15].

Theorem 1. Properties of LTM are as follows:

- It is dynamic;
- It is directed, i.e. relations $r(\alpha, \beta) \neq r(\beta, \alpha)$ where α and β are two different neurons $\alpha \neq \beta$;
- It is reconfigurable;
- It can be strengthened by frequently accesses;
- It contains loops;
- It can be traversed or searched;
- It cannot be sorted.

2.3 Functional Models of Memory

Corresponding to the CMM model as given in Definition 3, the functional models of the four types of memories can be formally modeled below.

Definition 5. The functional model of *SBM* is a set of *parallel queues* corresponding to each of the sensors of the brain.

Definition 6. 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.

Definition 7. The functional model of *LTM* is *hierarchical neural clusters* with partially connected *neurons* via *synapses*.

Definition 8. The functional model of *ABM* is a set of *parallel queues*, where each of them represents a sequence of actions or a process.

Definition 9. The functional model of *CSM* is a combination of the forms of LTM and STM, where the persistent statuses of the brain and body are maintained in LTM, while the interactive and real-time statuses are retained in STM before they are updated into the LTM form of CSM.

The reconfigurable neural clusters of STM cohere and connect 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.

STM is the working memory of the brain. The capacity of STM is much smaller than that of LTM, but it is hundred times greater than 7±2 digits as Miller proposed [9]. 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.

Theorem 2. The *dynamic neural cluster model* states that LTM is dynamic. New neurons (to represent objects or attributes) are assigning, and new connections (to represent relations) are creating and reconfiguring all the time in the brain.

3 The Logical Model of Memory

The neural informatics model of memory has been developed in Section 2. This section describes the logical model of memory by investigating the form of knowledge representation in the brain. Based on the logical models of memory, the capacity of human memory may be formally estimated and mechanisms of the memorization process may be rigorously explained.

3.1 The OAR Model of Memory

To rigorously explain the hierarchical and dynamic neural cluster model of memory at physiological level, a logical model of memory is needed as given below known as the Object-Attribute-Relation (OAR) model.

Definition 10. The *OAR model* of LTM can be described as a triple, i.e.:

$$OAR \triangleq (O, A, R) \tag{2}$$

where O is a finite nonempty set of objects identified by unique symbolic names, i.e.:

$$O = \{o_1, o_2, \ldots, o_i, \ldots, o_n\} \tag{3}$$

For each given $o_i \in O$, $1 \le i \le n$, A_i is a finite nonempty set of attributes for characterizing the object o_i, i.e.:

$$A_i = \{A_{i1}, A_{i2}, \ldots, A_{ij}, \ldots, A_{im}\} \tag{4}$$

where each $o_i \in O$ or $A_{ij} \in A_i$, $1 \le i \le n$, $1 \le j \le m$, is physiologically implemented by a neuron in the brain.

For each given $o_i \in O$, $1 \le i \le n$, R_i is a finite nonempty set of relations between o_i and other objects or attributes of other objects, i.e.:

$$R_i = \{R_{i1}, R_{i2}, \ldots, R_{ik}, \ldots, R_{iq}\} \tag{5}$$

where R_{ik} is a relation between two objects, o_i and $o_{i'}$, and their attributes A_{ij} and $A_{i'j}$, $1 \le i \le n$, $1 \le j \le m$, i.e.:

$$\begin{aligned} R_{ik} = \; & r\,(o_i, o_{i'}) \\ | \; & r\,(o_i, A_{ij}) \\ | \; & r\,(A_{ij}, o_{i'}) \\ & r\,(A_{ij}, A_{i'j}),\ 1 \le k \le q \end{aligned} \tag{6}$$

To a certain extent, the entire knowledge in the brain can be modeled as a global OAR model as given in Fig. 3.

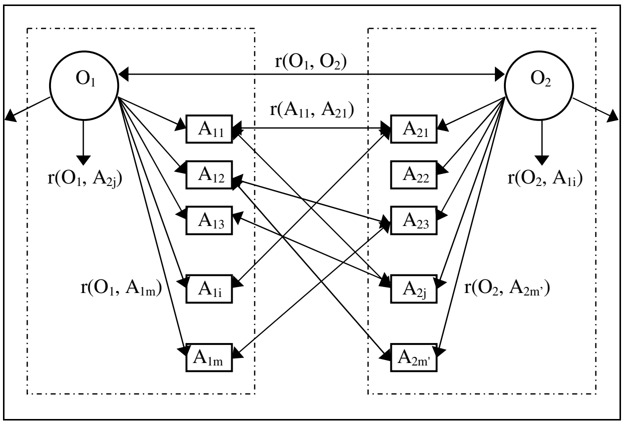

Fig. 3. The OAR model of logical memory architectures

3.2 The Extended OAR Model of Memory

The OAR model developed in the preceding subsection reveals a generic abstract model of LTM and the form of internal representation of learning and other cognitive activities known as knowledge, behavior, experience, and skills. Mapping it onto the cognitive structure of the brain, an extended OAR model of the brain, EOAR, is given in Fig. 4, where the external world is represented by *real entities* (RE), and the internal world by *virtual entities* (VE) and *objects* (O). The internal world can be divided into two layers: the *image* layer and the *abstract* layer.

Definition 11. The *extended OAR model* of the brain, *EOAR*, states that 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 known as the *image layer* and the *abstract layer.*

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. The abstract layer is an advanced property of human brains. It is noteworthy that animal species have no such abstract layer in their brains in order to support *abstract* or *indirect* thinking and reasoning [34]. In other words, high-level abstract thinking is a unique power of the human brain known as the *qualitative* advantage of human brains. The other advantage of the human brain is the tremendous capacity of LTM in the cerebral cortex known as the *quantitative* advantages. On the basis of these two principal advantages, mankind gains the power as human beings.

There are *meta-objects* (O) and *derived objects* (O') at the abstract layer. The former are concrete objects directly corresponding to the virtual entities and then to the external world. The latter are abstracted objects that are derived internally and have no direct connection with the virtual entities or images of the real-entities such as abstract concepts, notions, numbers, and artifacts. The objects on the brain's abstract layer can be further extended into a network of objects, attributes, and relations according to the EOAR model as shown in Fig. 4. The connections between objects/attributes (O/A) via relations are *partially* connected rather than fully connected. In other words, it is not necessary to find a relation among all pairs of objects or attributes.

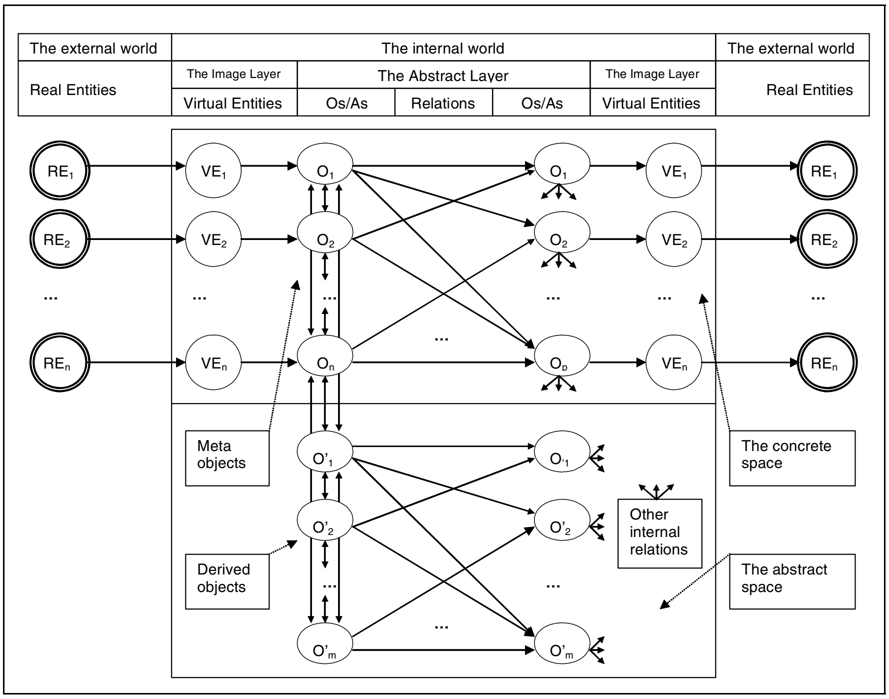

Fig. 4. The EOAR model of the brain

It is noteworthy that the higher level cognitive processes and consciousness, such as willingness, emotions, desires, and attributes are results of both such internal states in the brain and current external stimuli. Detailed discussions may be referred to the LRMB model [35]. It is also noteworthy that the cognitive model of the brain is looped. This means that an internal virtual entity is not only abstracted from the real-entity as shown on the left-hand side in Fig. 4, but also eventually connected to the entities on the right-hand side. This is the foundation of thinking, reasoning, learning, and other high-level cognitive processes, in which internal information has to be related to the real-world entities, in order to enable the mental processes meaningfully embodied to real-world semantics.

3.3 The Capacity of Human Memory

It is observed that the total neurons in the brain is about $n = 10^{11}$ and their *average* synaptic connections is $s = 10^3$ [2], [7], [10]. According to the relational model of memory, the fundamental question on the capacity of human memory derived in cognitive science and neuropsychology can be reduced to a classical combinatorial problem [33].

Theorem 3. The capacity of human memory C_m is determined by the total potential relational combinations, C_n^s, among all neurons $n = 10^{11}$ and their *average* synaptic connections $s = 10^3$ to various related subset of entire neurons, i.e.:

$$\begin{aligned} C_m &\triangleq \mathrm{C}_{\mathrm{n}}^{s} \\ &= \frac{10^{11}!}{10^3!(10^{11}-10^3)!} \\ &= 10^{8,432} \quad [bit] \end{aligned} \tag{7}$$

Theorem 3 provides a mathematical explanation of the upper limit of the potential number of connections among neurons in the brain. Using approximation theory and a computational algorithm, the solution to Eq. 7 had been successfully obtained [33] as given above.

The finding on the magnitude of the human memory capacity on the order as high as $10^{8,432}$ bits reveals an interesting mechanism of the brain. That is, the brain does not create new neurons to represent new information, instead it generates new synapses between the existing neurons in order to represent new information. The observations in neurophysiology that the number of neurons is kept stable rather than continuous increasing in adult brains [7], [10], [12] provided evidences for the relational cognitive model of information representation in human memory.

LTM was conventionally perceived as static and supposed to no change in an adult's brain [1], [4], [12], [13], [15]. 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 relational model of memory as given in Theorems 2 and 3 states 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 [12], [14], [34].

Actually, the two perceptions above are not contradictory. The former observes that the macro-number 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.

4 Mechanisms of Memorization

On the basis of formal models of memory at the physiological and logical levels as developed in Sections 2 and 3, this section attempts to rigorously explores the mechanisms of memorization and its cognitive process.

4.1 Memorization as a Cognitive Process

According to Definition 2, the process of memorization encompasses *encoding* (knowledge representation), *retention* (store in LTM), *retrieve* (LTM search), and *decoding* (knowledge reformation) as shown in Fig. 5. The sign of a successful memorization process in cognitive informatics is that the same information can be correctly recalled or retrieved. Therefore, memorization may need to be repeated or rehearsed for a number of cycles before it is completed.

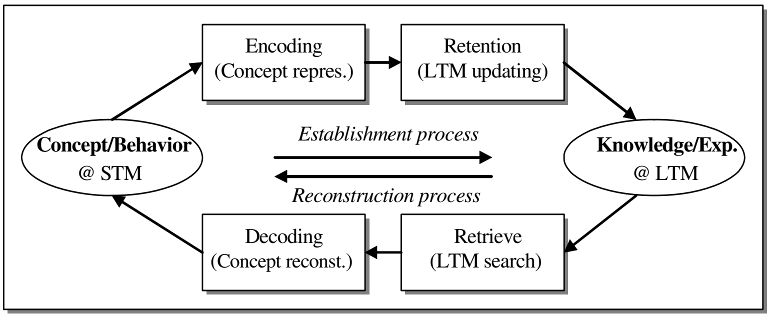

Fig. 5. The process of memorization

It is noteworthy that the memorization process is a closed-loop between STM and LTM, where it may be divided into the establishment and reconstruction phases.

Definition 12. The *establishment phase* of memorization is a memory creation process that represents a certain information in the form of a sub-OAR in STM via encoding, and then creates relations with the entire OAR in LTM via retention.

Definition 13. The *reconstruction phase* of memorization is a retrieval process that searches the entire OAR in LTM via content patterns or keywords, and then reconfigures the information in STM via decoding.

It is recognized that computers store data in a direct and unconsumed manner; while the brain stores information by relational neural clusters. The former can be accessed directly by explicit addresses and can be sorted; while the latter may only be retrieved by content-sensitive search and matching among neuron clusters where spatial connections and configurations themselves represent information. The tremendous difference of memory magnitudes between human beings and computers demonstrates the efficiency of information representation, storage, and processing in human brains.

4.2 How Memory Is Created?

As learning is aimed at acquiring new knowledge based on comprehension [32], memorization is required to create or update LTM by searching and analyzing the contents of STM and selecting useful (i.e. most frequently used) information into LTM.

According to the *OAR* model, the result of knowledge acquisition or learning can be embodied by the updating of the existing *OAR* in the brain.

Theorem 4. The entire knowledge model maintained in the brain states that the internal memory or the representation of learning results in the form of the OAR structure, which can be updated by concept compositions $\uplus$ between the existing OAR and the newly created sub-OAR (sOAR), i.e.:

$$\begin{aligned} OAR'\mathbf{ST} &\triangleq OAR\mathbf{ST} \uplus \mathrm{s}OAR\,\mathbf{ST} \\ &= OAR\mathbf{ST} \uplus (O_s, A_s, R_s) \end{aligned} \tag{8}$$

where $\mathbf{ST}$ is a type suffix of system structure as defined in *Real-Time Process Algebra* (RTPA) [18], [21], [24], [29], and $\uplus$ denotes the concept composition operation in *Concept Algebra* [27].

According to cognitive informatics [17], [19], [20], [21], [22], [25], [29], [30], [31], sleeping plays an important role in the implementation of memorization. Sleeping is a subconscious process of the brain that its cognitive and psychological purpose is to update LTM in the form of OAR as shown in Fig. 6.

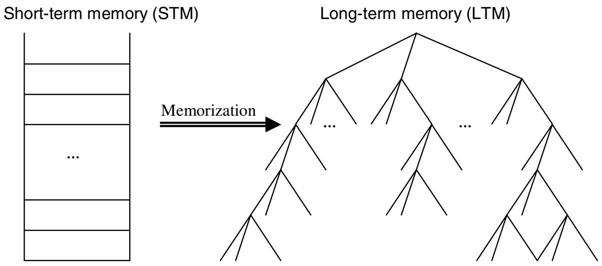

Fig. 6. Memorization as information transforming from STM to LTM

Theorem 5. The *mechanisms of memorization* characterized by OAR updating in LTM is based on the following selective criteria:

- A sub-OAR in STM was frequently or repetitively used in the previous 24 hours;
- A sub-OAR was related to the entire OAR in LTM at a higher level of the neural cluster hierarchy;
- A sub-OAR was given special attention or a higher retention weight.

Corollary 1. The *algorithm of memorization* can be described by the following steps:

- To identify association to existing knowledge structure in the LTM clusters in the form of OAR;

- To generate physiological neural links between new and existing objects by synapses, if there are existing or related knowledge clusters in LTM;
- To create a new sub-OAR cluster, if there is no existing or related knowledge cluster in LTM.

It can be seen that the third step stated in Corollary 1 is the hardest case in memorization. Based on the memorization algorithm, the relationship between learning and memorization becomes apparent. The former is a front-end process to acquire and represent knowledge in the form of sub-OARs; while the latter is a back-end process to create or update the OAR model of entire knowledge in LTM by knowledge composition as defined in Eq. 8.

Typical *memory devices* identified are categorization, organization, clustering, acronym/acrostics, interactive imagery, visualization, highlight keywords, rehearsal, and elaboration [3], [11]. It may be observed that *rehearsal* and *repetitive processing* of the same information play a crucial role in memorization.

Corollary 2. The longer the time spent on memorization and learning, the better the effect of memorization.

Corollary 2 indicates that time of concentration is the only magic in learning, memorization, and knowledge creation. Therefore, the fundamental approach to improve memorization and creative research is both concentration and sufficient time investment.

4.3 When Memory Is Created?

The cognitive model of the brain [34] classifies life functions of the brain into two categories known as the conscious and subconscious ones. The latter are inherited subconscious processes and cannot be intentionally changed; while the former are acquired and can be programmed consciously by certain motivations 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 according to the LRMB model [35]. Therefore, a study on the subconscious behaviors of the brain and their mechanisms may be the key to understand how the brain works.

The investigation on the subconscious aspect of memorization may be focused on the following questions: a) When is the memorization process completed in LTM? b) Why do all mammals need sleep? and c) What is the cognitive mechanism of sleep?

Sleep as an important physiological and psychological phenomenon was perceived as innate, and few hypotheses and theories have been developed to explain the reason [6], [16]. The following theories explain the roles of sleep in LTM establishment.

Lemma 1. The memory in LTM is established during sleeping.

Lemma 1 is supported by the following observations and experiments. A group of UK scientists observed that stewardesses serving long-haul flights had bad memory in common [21]. An explanation about the reason of this phenomenon was that the stewardesses have been crossing time zones too frequently! However, according to Lemma 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.

Lemma 1 logically explains the following common phenomena: (a) All mammals, including human beings, need to sleep; (b) 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 [6], [15], [36]; and (c) According to the cognitive model of the brain [34], 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 fewer inference or interruptions occur due to external events.

Based on Lemma 1, the following cognitive informatics *theory of sleeping* can be derived.

Theorem 6. *Long-term memory establishment* is a subconscious process that its major mechanism is by sleeping, i.e.:

$$\text{Cognitive purpose of sleep} = \text{LTM establishment} \tag{9}$$

Theorem 6 describes an important finding on one of the fundamental mechanisms of the brain and the cognitive informatics meaning of sleep, although there are other physiological purposes of sleep as well, such as resting the body, avoid dangers, and saving energy.

Corollary 3. Lack of sleep results in bad memory, because the memory in LTM cannot be properly established.

Corollary 4. The subconscious cognitive processes of the brain do not sleep throughout the entire human life.

It was commonly believed that heart is the only organ in human body that never takes rest during the entire life. However, Corollary 4 reveals that so does the brain. The non-resting brain is even more important than heart because the latter is subconsciously controlled and maintained by the former.

Based on Lemma 1 and Theorem 5, the following principle on memorization can be established.

Theorem 7. The *24-hour law of memorization* states that the general establishment cycle of LTM is equal to or longer than 24 hours, i.e.:

$$LTM\ establishment\ cycle \geq 24\ \text{[hrs]} \tag{10}$$

where the 24-hour cycle includes any kind of combinations of awake, asleep, and siesta.

5 Formal Description of the Memorization Process

The physiological and neural informatics foundation of memorization is the dynamic updating of the LTM in the logic form of the OAR model. This section presents a formal treatment of memorization as a cognitive process. Based on the cognitive process perception, a formal algorithm and a rigorous RTPA model for explaining the memorization process are developed.

5.1 The Memorization Process and Algorithm

As illustrated in Fig. 5, memorization as a cognitive process can be described by two-phases: the establishment phase and the reconstruction phase. The former represents the target information in the form of OAR and creates the memory in LTM. The letter retrieves the memorized information and reconstructs it in the form of a concept in STM. Memorization can also be perceived as the transformation of information and knowledge between STM and LTM, where the forward transformation from STM to LTM is for memory establishment, and the backward transformation from LTM to STM is for memory reconstruction.

The logical model of the memorization process can be described as shown in Fig. 7. Based on Fig. 7, a memorization algorithm is elaborated as follows.

Algorithm 1. The cognitive process of memorization can be carried out by the following steps:

(0) *Begin*
(1) *Encoding*: This step generates a representation of a given concept by transferring it into a sub-OAR model;
(2) *Retention*: This step updates the entire OAR in LTM with the sub-OAR for memorization by creating new synaptic connections between the sub-OAR and the entire OAR;
(3) *Rehearsal test:* This step checks if the memorization result in LTM needs to be rehearsed. If yes, it continues to practice Steps (4) and (5); otherwise, it jumps to Step (7);
(4) *Retrieval:* This step retrieves the memorized object in the form of sub-OAR by searching the entire OAR with clues of the initial concept;
(5) *Decoding:* This step transfers the retrieved sub-OAR from LTM into a concept and represents it in STM;
(6) *Repetitive memory test:* This step tests if the memorization process was succeeded or not by comparing the recovered concept with the original concept. If need, repetitive memorization will be called.
(7) *End.*

It is noteworthy that the input of memorization is a structured concept formulated by learning.

5.2 Formal Description of the Memorization Process

The cognitive process of memorization described in Algorithm 1 and Fig. 7 can be formally modeled using RTPA [18], [21], [28] as given in Fig. 8. According to the LRMB model [Wang et al., 2006] and the OAR model [23] of internal knowledge representation in the brain, the input of the memorization process is a structured concept $c(O\mathbf{S}, A\mathbf{S}, R\mathbf{S})\mathbf{ST}$, which will be transformed to update the entire OAR model of knowledge in LTM in order to create a permanent memory. Therefore, the output of memorization is the updated $OAR'\mathbf{ST}$ in LTM.

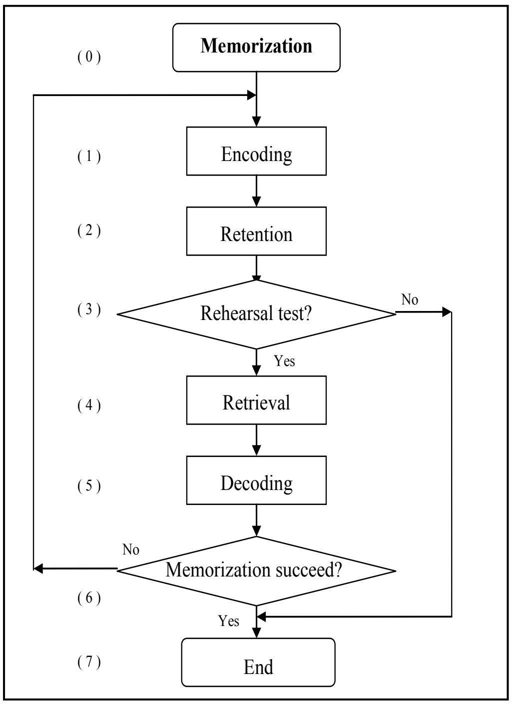

Fig. 7. The cognitive process of memorization

In the formal memorization process as shown in Fig. 8, the *encoding* subprocess is modeled as a function that maps the given concept *c***ST** into a *sOAR***ST**. The *retention* subprocess composes the *sOAR***ST** with the entire *OAR***ST** in LTM that maintains the whole knowledge of an individual. In order to check the memorization quality, rehearsals may usually be needed. In a rehearsal, the *retrieval* subproecss searches a related *sOAR***ST** in LTM by giving clues of previously memorized objects and attributes in *c***ST**. Then, the *decoding* subprocess transfers the *sOAR***ST** into a recovered concept *c*'**ST**. In the repetitive memory test subprocess, the reconstructed *c*'**ST** will be compared with the original input of *c***ST** in order to determine if further memorization is recursively needed.

According to the 24-hour law of memorization as stated in Theorem 7, the memorization process may be completed with a period longer than 24 hours by several cycles of repetitions. Although, almost all steps in the process as shown in Fig. 7 are conscious, the key step of *retention* is subconscious or non intentionally controllable. The rules of thumb of high quality retention have been described in Theorem 5.

Based on the LRMB model [35], the memorization process is closely related to learning [24]. In other words, memorization is a back-end process of learning, which retains learning results in LTM and retrieves them when rehearsals are needed. The retrieve process is search-based by concept or sOAR matching.

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The Memorization Process

Memorization (I:: c(OS, AS, RS)ST; O:: OAR'ST) ≙
{I. Encoding
c(OS, AS, RS)ST → sOAR ST
// Concept representation

II. Retention
→ OAR'ST := OARST ⊎ sOARST
// Update OARST in LTM

III. Rehearsal
→ � Rehearsal BL = T
    (IV. Retrieval
     ↣ Search (I:: OARST;
                  O:: sOARST | (OS, AS, RS)ST ⊑ OARST))
     // Retrieval sOARST in LTM

     V. Decoding
     → (sOARST →  c'(OS, AS, RS)ST)
     // Concept reconstruction
    )
VI. Repeat
→ � (c'(OS, AS, RS)ST) ~ c(OS, AS, RS)ST)
       → ⊗  // Memorization succeed
  | � ~
       → Memorization (I:: c(OS, AS, RS)ST; O:: OAR'ST)
       // Retry
}
```

Fig. 8. Formal description of the memorization process in RTPA

It is noteworthy that the memorization process is a fully creative process, which generates new sub-OARs and establishes physiological representations of them with the existing OAR in LTM by new synaptic connections. Therefore, in some extent, memorization is a subconscious physiological process where new synapses have to be grown inside the brain over time in order to transfer learnt information or knowledge into permanent memory.

6 Conclusions

This paper has presented a theory of memory and the cognitive process of memorization. Memorization has been identified as a key cognitive process of the brain because almost all human intelligence is functioning based on it. Neural informatics foundations and function models of memory and memorization have been explored in this paper. Logical models of memory, particularly the Object-Attribute-Relation (OAR) model have been developed, which form the context of human knowledge and intelligence.

Some enlightening findings on memory and memorization in cognitive informatics are as follows:

- LTM establishment is a subconscious process;
- The LTM is established during sleep;
- The major mechanism for LTM establishment is by sleeping;
- The general acquisition cycle of LTM equals to or is longer than 24 hours;
- The mechanism of LTM establishment is to update the entire memory of information represented as an OAR model in the brain;
- Eye movement and dreams play an important role as the observable indicator in LTM creation.

The mechanisms of memorization have been rigorously explored as a cognitive process, and the fundamental queries on how and when memory is created in long-term memory have been logically explained.

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