A Formal Model for Emulating the Generation of Human Knowledge in Semantic Memory[*]

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Abstract. This presentation focuses on the transfer of information processed by human beings from their short-term memory (STM) to their semantic memory (SM) to create two kinds of knowledge: a semantic network of associations and a structured set of rules to govern human deliberate behaviour under explicit attention. Human memory storage and processing is modeled using the Real-time Maude rewrite language. Maude's capability of specifying complex data structures as many sorted algebras and the time features of Real-Time Maude are exploited for (1) providing a means for formalising alternative memory models, (2) modeling insilico experiments to compare and validate such models, and (3) using such models in the analysis of interactive systems. We then plan to use Maude's model-checking features for the formal verification of interactive system as well as for a sort of 'formal validation' of memory models against real datasets.

Keywords: Cognitive Science · Human Memory Models · Formal Methods · Rewriting logic · Real-Time Maude.

1 Introduction

Human *semantic memory (SM)* is a core aspect of declarative long-term memory (LTM), comprised of propositional information, specifically word meanings and facts. An example of SM being the fact that a penguin is a bird. Clearly, such information must be acquired from the environment, such as reading, or formal education.

In terms of information flow within the human memory system, sensations of the environment (e.g., sounds heard) are first processed by modality-specific sensory stores, which we globally call *sensory memory*. Items attended in those sensory stores persist for very short time periods and are then passed to a temporary *short-term memory (STM)* limited capacity store (about 7 items for healthy adults), with rapid access and rapid decay. From STM information passes to LTM, which has a virtually unlimited capacity and where information is organised in structured ways, with slow access but little or no decay. Finally, within
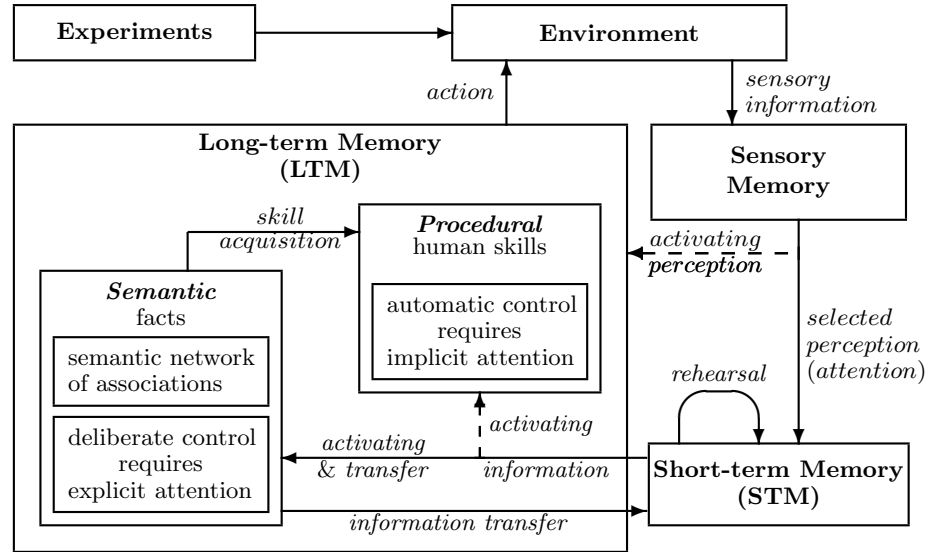
Fig. 1. Human Memory Architecture

LTM, information repeatedly used in practice activities may move from SM to *procedural memory (PM)*, thus determining skill acquisition. In fact, the transfer from SM to PM refers to our skills and consists of rules and procedures that we unconsciously use to carry out tasks, particularly at the motor level.

This structure of human memory is depicted in Fig. 1, where continuous arrows show transfer of information between memory components while dashed arrows denote information stored in the source component that activate memory processing in the target component.

2   Cognitive Models for Information Transfer

The sequential processing from STM to LTM is captured by several cognitive models, most commonly, the Multistore Model [1] and Working Memory [3], however, both are equivalent in proposing structural distinctions between phonologically-coded STM storage for verbal content and a separate LTM. The STM and LTM distinction is known partially through cognitive neuroscience, as it is observed that brain lesions can selectively impair either phonological STM capacity or LTM contents (either semantic or episodic). Furthermore, severe reductions in STM capacity caused by brain lesions, such as the inability to hold more than two items in phonological STM simultaneously, also prevent the acquisition of new SM entries in LTM [4]. Thus, indicating that items for storage in SM must first be processed within phonological STM.

The mechanism by which information transfers from STM to SM is *elaborative rehearsal* [2]. This involves using the items within STM to access existing entries within SM. This deep processing, based on semantics, increases the chance that the items will become stored in LTM, probably by strengthening their appropriate connection within the nexus of semantic entries. This elaborative rehearsal within STM, which induces transfer to LTM, can be contrasted with *maintenance rehearsal*. This latter form of processing can be seen as phonological looping of the items to renew their representations within STM, thereby delaying signal decay.

As shown in Fig. 1, among the sensory information briefly stored in sensory memory, attention selects some and transfers it to STM. Information in STM can then be used

- to activate the deliberate control in semantic memory or the automatic control in procedural memory, or
- after elaborative rehearsal, to create associations as well as deliberate control rules in SM.

Moreover, information can be retrieved from SM and transferred to STM. Furthermore, the repeated use of rules for automatic control in SM produces skill acquisition and the resultant creation of rules for automatic control in PM. In previous work we have formally modeled human behaviour under deliberate and automatic control [6] as well as information retrieval from SM [5].

3   Real-time Maude Model

In this presentation we focus on creation of associations in SM. We use Real-time Maude to formally model

1. the planned insilico experiments;
2. the sensory information available in the environment;
3. the perceptions stored in sensory memory;
4. the information stored in STM;
5. the semantic network and deliberate control rules in SM.

For example

1. `exp(((a "dog" can "bark") for 10000) in 60000)`
   is a statement that in one minute (60000ms) will be shown on a screen for 10s (10000ms);
2. `(a "dog" can "bark") for 10000`
   is the actual statement appearing on the screen for 10s;
3. `perc((a "dog" can "bark") for 10000)`
   is the perception of the statement by the human subject;
4. `(a "dog" can "bark") <decay 20000>`
   is the information stored in STM, which is going to decay (unless rehearsed) in 20s;

5. `"dogs" : "dog" |- 3 ->| can "bark"`
   models that the fact is stored in the SM under the "dogs" knowledge domain
   and can be retrieve in 3ms.

The model includes simple rewrite rules for converting planned experiments into sensory information, sensory information into perceptions, select perceptions and transfer them to STM. Moreover, rewrite rules that involve the usage of information in STM to activate SM processing set the decay time of all used pieces of information to the specific decay time that depends on the level of their connection within the nexus of semantic entries and decrease, according to the elapsed time, the decay time of all other pieces of information in STM. This implements elaborative rehearsal.

4 Analysis

Our approach supports two kinds of analysis.

- the comparison of alternative memory models and their validation against real datasets;
- the formal verification of interactive systems.

Insilico experiments can be used to compare a number of alternative memory models. Their results are then compared with real datasets to evince which model best mimics reality. In addition to a manual comparison, we aim at the generalisation of an approach from our previous work [7] in which 'formal validation' is achieved by converting a dataset into a formal representation that can be composed in parallel with the system model. In the context of this paper, the system model is actually the human memory model. Model-checking is then used to verify properties that may only hold when the dataset matches the insilico experiment.

Finally, the human memory model of a user can be combined with the model of the used computer system and such an overall model can be formally verified using Real-time Maude model-checking features.

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