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AN IMPLEMENTATION MODEL OF CONSTRUCTIVE MEMORY FOR A DESIGN AGENT

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Abstract. This paper describes a computational model that implements the operations of a constructive memory system for design. The current model is based on a modified Interactive Activation and Competition (IAC) network with learning capabilities incorporated. Implementations and experiments pertaining to the various features of the constructive memory system are also described.

1. Introduction

Situatedness in designing entails the explicit consideration of the effects of the current external environment, the internal state of a design agent; and the interaction between the environment and the agent, on the behaviour of a design agent in performing a design task. It employs the notions of a design situation (Gero and Fujii 2000) and of constructive memory (Gero 1998b; Gero 1999a; Gero 1999b). The inclusion of the notion of situatedness into the construction of computer aided design system facilitates the creation of computational systems that have the ability to operate in an environment for which they have not been directly programmed.

This paper describes an implementation model of constructive memory for a design agent based on a neural network architecture with learning capabilities added. The system uses the associations it derives between memory traces it processes to construct memory according to when, where and what the memory system is cued.

2. Memory Construction

Memory construction occurs whenever a design agent uses past experiences in the current environment in a situated manner. Memory construction is in contradistinction to memory as a retrieval process, where there is a “memory” stored that can be retrieved directly and the

retrieval has no effect on the “memory”. In a constructive memory system, any information about the current design environment, the internal state of the agent and the interactions between the agent and the environment is used as cues in its memory construction process. Liew and Gero (2002) describes the design of a constructive memory system based on the notion of constructive memory in design (Gero 1998c; Gero 1999a; Gero 1999b). The main components of the memory system consist of a working memory, a short-term memory (STM) and a long-term memory (LTM) system. Several important characteristics of this memory system and their implementations are described here.

2.1. GROUNDING OF EXPERIENCES

Grounding entails the embedment of an artificial agent into its environment such that its behaviour and the mechanisms, representations, etc. underlying this behaviour is intrinsic and meaningful to the agent itself, rather than dependent on an external designer or observer (Ziemke 1999).

Symbolic groundings deal with the provision of *meanings* for symbolic representations. Experiential-based grounding, on the other hand, deals with *applicability* of experiences processed by the artificial agent according to the behavioural interactions between the agent and the environment.

The interaction between the agent and the environment plays an important role in experiential-based grounding and has an effect on preexisting experiences processed by the agent. An agent, with its current experiences creates a particular view of the external world. If this view matches the other view created by agent through its interactions with the external environment, it becomes useful in predicting the effects of a course of actions. The experience underlying this prediction is labeled useful and grounded. This process of grounding models the effect of long-term learning. Grounding can be modeled by increasing the interconnection strengths within a neural network.

2.2. LEVEL OF PROCESSING

Within the memory system, memory traces reside at different level of processing. The level on which the memory of an experience resides is determined by the amount of grounding the experience received. A grounded experience has a higher level of processing and is used more readily in the subsequent operation of the memory system.

3. Representations

The notions of a *design situation* and a *design experience* are based on the work on concept formation by a situated design agent (Gero and Fujii 2000).

A design situation¹ models a particular state of interaction between a design agent and the environment at a particular point in time. It is a snapshot of all the variables that define the internal state of the agent and that part of the external state of the environment that the agent is interacting with. The expectation and interpretation of the agent may or may not be in agreement with each other. A design experience models the transition of state from one design situation to another in which the expectation must match the interpretation after the transition. The set of actions that facilitates this transition is also captured. Symbolically, a design experience, E , is represented by a collection of constituent parts:

$$E = \{V_i, S_i, P, Q_i, H_i, A, H_f, Q_f, V_f, S_f\}$$

where:

A : action on the agent or on the environment;

H_i : initial focused concept;

H_f : final focused concept;

P : percept;

Q_f : final expected percept;

Q_i : initial expected percept;

S_f : final exogenous sensory data;

S_i : initial exogenous sensory data;

V_f : final exogenous variable;

V_i : initial exogenous variable.

An initial exogenous variable, V_i defines that part of the environment that the agent is dealing with. In the case of a design agent, V_i represents the external structure of an design artifact to be manipulated by the agent. A design agent may or may not operate on the entire external structure. What is focused upon is a function of the current focused concept based on the current design requirements (Gero and Fujii 2000). As a requirement for operating in unfamiliar environments, the initial exogenous variables encountered by the design agent will often be different for most of the design sessions.

An action, A , can be an operation performed on the design agent internally to change its state, or an operation the agent performs on the design artifact to be manipulated (the environment). Any mismatch

¹ A design situation is different from a situation in the context of this paper. A situation describes the conditions pertaining to a particular design session where a design agent is performing the act of designing.

between an agent's expectation and interpretation form the basis for actions to be carried out by the agent. An external action defines the operations performed on the artifact that transforms the initial autogenous variable to the final autogenous variable. An internal action defines the change of focused concept to allow proper interpretation of the sensory data. An action is represented by a list of operations that has been performed.

A focused concept (initial, H_i or final, H_f) represents a design prototype (Gero 1990) that the agent is current using. This prototype can either be retrieved from the memory system or derived from existing prototypes according to the current design requirement through external processes such as analogy, combination, mutation and designing from first principles (Rosenman and Gero 1993) and reformulation processes (Gero 1998c) that deal with re-parameterization and parameters expansions. The current focused concept provides the basis to form the expectation of the design agent in the current design session. For any design cycle, the expectation of the agent drives the construction of associated memories to be used for the current unfamiliar environment. All the concepts processed by the agent are captured by the collection of all the focused concepts within the memory system.

A design prototype contains information pertaining to the structure, behaviour and function of a design artifact (Gero et al. 1992). The structural aspects of the prototype forms the expected percepts, Q , used to structure the sensory data to produce percepts, P , which models the interpretation of the artifact as an interpreted structure (Gero and Kannengiesser 2000; Gero and Kannengiesser 2002). The expected percept models the expected structure that the agent expects based on the current focused concept. It also contains information about the relevant feature detectors (Gero 1998a) and structuring procedures required to interpret the sensory data to form percepts.

A percept contains information about the entities extracted from the sensory data (based on the feature detectors and structuring instructions from the expected percept) together with a geometric transformation operator, $_$ that will allow the entities to match the expected percept. Two percepts are considered as belonging to the same class if they contain the same entity irregardless of the specific transformation operators used.

The final exogenous variable, V_f , and sensory data, S_f , models the state of the artifact and its associated data sensed by the agent, after the agent has performed the required action to eliminate the difference between its expectation and interpretation of the environment.

The internal state of the design agent, represented by autogenous variables (Gero and Fujii 2000) and their sensory counterpart are modeled

implicitly by the ever-changing weights and configurations of the neural network implementation of the memory system. The current internal states of the network are captured implicitly in the current configurations or interconnection strengths created by previous memory construction process. During the current memory construction, these states, as part of the sub-structures of the network, are used implicitly to model the current state of the memory system.

A sample design experience is illustrated in Figure 1. The hidden lines in the sensory data ($S_{i_e1_1_d}$ and $S_{f_e1_1_2}$) indicate that only specific parts of the design artifact are focused in this particular design experience. The percept ($P_{e1_1_d}$ and $P_{e1_1_2}$) represents the entity extracted from the sensory data together with a set of geometric transformation operators, $_$ that will allow the percept to match the expected percept ($Q_{i_e1_1_1}$ and $Q_{f_e1_1_1}$) exactly. A set of feature detectors and structuring operations to be used on the sensory data are represented in the expected percepts. The focused concept ($H_{i_e1_1_1}$ and $H_{f_e1_1_1}$) defines the expected percept that contains information about the relevant entity and the various transformations, $_$ that can be used on this entity to match the percept.

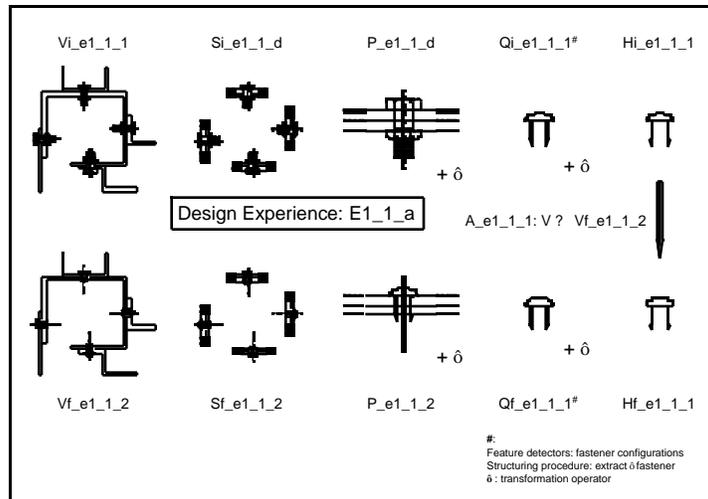


Figure 1. A sample design experience

4. Implementation of a Constructive Memory System

The current implementation of the constructive memory is inspired by a parallel distributed processing model of the medial temporal memory system by McClelland (McClelland 1995). Figure 2 illustrates the overall structure of an implementation model for the constructive memory

system. The Interactive Activation and Competition (IAC) network (McClelland 1981) is used as a foundation upon which the trace synthesis module is implemented.

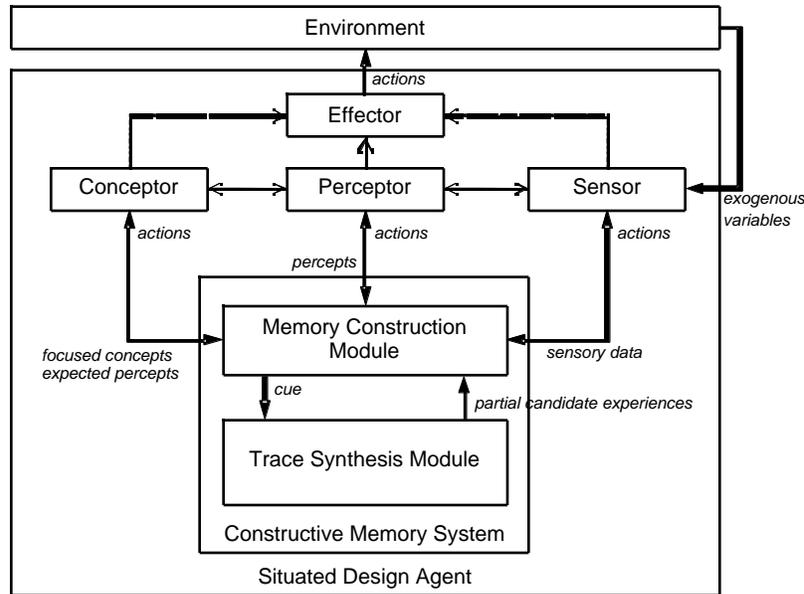


Figure 2. Structure of an implementation model for a constructive memory system (expanded from (Liew and Gero 2002))

An IAC network is a neural network that uses an activation and competition mechanism to operate on a collection of nodes. These nodes are localist representations of concepts. The representations are activated via a spreading activation mechanism where activated exemplars activate a representation of their properties. Mutually exclusive property values compete in such a way that allows properties, which are supported by a large subset of the active instance of the category, to be reinforced and become strongly active while suppressing those that are not. The knowledge of an individual exemplar is captured in a network of nodes. The IAC model defines an instance node for each of the exemplar that it knows and a property node for each of the property (attribute) that these exemplars may have. The property nodes and instance nodes are arranged in groups of mutually exclusive inhibitory connections.

In the current implementation, the system's knowledge of an individual design experience is represented as an instance node linked to a set of property nodes through excitatory connections. The connected

property nodes represent the constituents of a design experience such as: action on the agent or on the environment; initial and final focused concepts; percept; initial and final expected percepts; initial and final exogenous sensory data and initial and final exogenous variables.

To construct a memory for the current design session, an incomplete design experience is first created in the network based on available information. The network is then cycled to allow other constituents of preexisting design experiences to blend into the incomplete experience through the network's activation and competition mechanism. This mechanism provides some of the constituents for the memory construction process according to the knowledge an agent processed about past design experiences. The blending process together with the subsequent sensation and perception process, allow a new representation of a design experience (the completed partial memory trace not stored explicitly within the system initially) to be constructed according to what the agent knows at the current point in time and its interaction with the environment.

4.1. DEMARCATION OF LONG-TERM AND SHORT-TERM MEMORY

The STM and LTM are modeled as a multi-layered IAC network, Figure 3. The separation of instance nodes (together with their associated property nodes), modeling design experiences as memory traces within the system, into different layers are based on their level-of-processing. The interconnection strength between the instance node and its corresponding property nodes provide the basis for these levels.

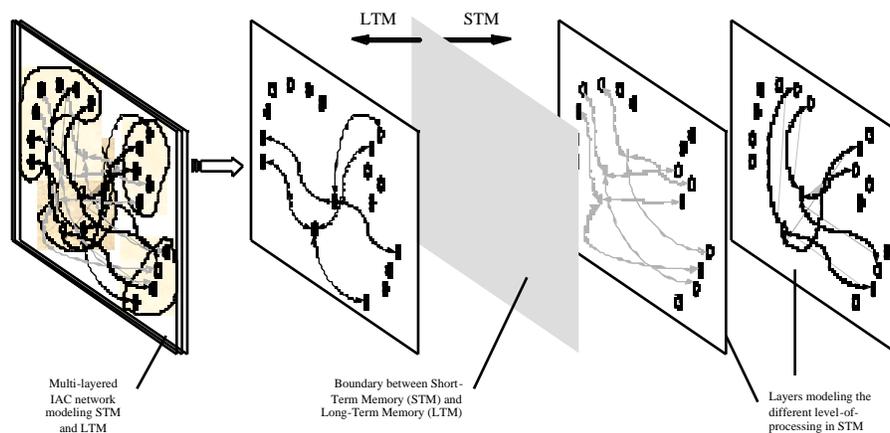


Figure 3. Demarcation of STM and LTM

In Figure 3, memory traces with high interconnection strengths are placed close to the left to indicate that the respective nodes are more durable within the memory system, while instances with low interconnection strength are suppressed towards the right. As the grounded usage of an experience increases, it is repeatedly presented to the system to emphasize the relevant memory traces through the strengthening of the interconnections between the relevant nodes.

A threshold value for the interconnection strength is set up to delineate LTM and STM. This threshold can be visualized as a cutting plane that separates LTM from STM among the different layers in the modified IAC network. When memory traces are to be removed from the system (by a forgetting process to increase computational performance), the traces sitting at the lowest level (to the right of Figure 3) within the STM are purged from the system first.

Newly created memories start off in the STM (right side of Figure 3). As their usage gets grounded, they move towards the LTM (left side of Figure 3). This gradual incorporation of new experiences is to avoid catastrophic interference.

All memory traces in LTM and STM are subjected to a decay process. If the subsequent memory construction process does not reinforce these memory traces, their interconnection strengths will decay and they will move towards the STM region.

4.2. LEARNING MECHANISM

The original IAC network (McClelland 1981) does not provide any learning mechanism. Learning can occur through:

- grounding via adjusting the weights between existing nodes;
- constructive learning via adding new memories in terms of new nodes;
- constructive learning via reconfiguring existing nodes to represent new memories.

These learning processes occur in light of the newly acquired experiences by the situated design agent.

4.2.1. Learning via Weight Modifications

Learning via the changing of weights (long-term learning/grounding) makes memory traces more readily available for the subsequent memory construction process. Only the strengths of excitatory links are allowed to change in the implementation. Negative are not changed locally as their global settings are used to control blending.

The learning mechanism is formulated as (Medler 1998):

$$\Delta w_{ij} = -\{(w_{max} - w_{ij})a_i a_j - w_{ij}\}$$

where:

Δw_{ij} : amount by which to change the link between node i and node j

η : learning rate

λ : weight decay factor

w_{max} : maximum weight value

This formulation of learning is similar to the one for computing activation values of nodes. The learning process occurs as a separate process only after memory construction has taken place.

The learning processes based on weight adjustments is implemented by presenting the memory system with the memory traces representing a design experience that the design agent found to be useful. This emphasis of particular memory traces strengthens the interconnections between the nodes involved.

4.2.2. Constructive Learning

Constructive learning (Mandic and Chambers 2001) occurs through the change in the architecture or interconnections within the network. This occurs with the addition of new instance nodes into the original IAC network, Figure 4. The idea behind these learning mechanisms is similar to the concepts of ontogenic networks (Fiesler and Beale 1997) where the topology of the network changes over time.

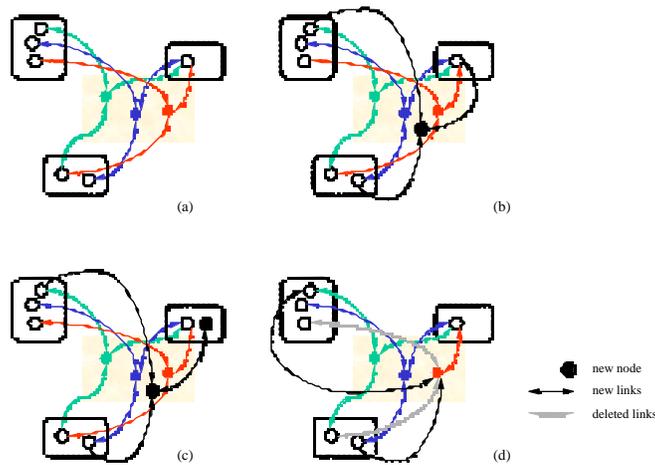


Figure 4. Comparison of the original network before learning (a) and after: (b) learning via adding new instance node, (c) learning via adding new instance through new property node, (d) learning via reconfiguring existing nodes

Constructive learning via network growth can occur with the addition of new instance nodes created via either reconfiguring existing property

nodes or adding new property nodes within the IAC network. New property nodes are created as a result of external designing reasoning processes such as analogy, combination, mutation and designing from first principles (Rosenman and Gero 1993) and reformulation processes (Gero 1998c) that deal with re-parameterization and parameters expansions. The creation of these new property nodes will result in new instance nodes being created to integrate the new nodes into the system as new memories. New instance nodes are also created when new configurations of existing property nodes are highlighted in the memory construction process. This is a result of the implicit relationships (associations) between nodes captured within the network. One implication of this is that the memory construction process can produce different design experiences for the same cue at different stages of the agent's lifetime. What is constructed is a function of both what was originally experienced and what the agent has learnt since it gained that experience.

Constructive learning via network pruning occurs through the forgetting process based on the grounding of memory traces.

5. Behaviour of the Constructive Memory System

Memories are constructed from existing experiences and earlier memories of these experiences. This construction process is affected by the amount of learning that has taken place since the system has last obtained that experience or since it had constructed memories of that experience. These experiences and memories form part of the situation and affect the kinds of memories that are constructed subsequently (Gero 1999a).

To start off the memory construction process, a probe is created and presented to the extended IAC network as a cue for memory construction. The content of this probe is essentially a collection of available information about the current state of the external environment, the internal state of the agent and the interactions between the agent and the environment. The probe to the memory system is modeled as a partial design experience to be partially completed via cycling the network.

Once the probe has been set, the network is cycled and allowed to settle into an equilibrium state. The resulting property nodes that are highlighted provide the constituents for memory construction. The configuration of these nodes may form a new instance node or highlight a pre-existing instance node.

Several scenarios are possible in the memory construction process. These are:

- an existing memory (instance node) that matches the probe exactly is constructed;
- a new memory is formed through the generation of new instance node by the network reconfiguring its topology; or
- a new memory is formed through the addition of new property nodes to the network, via some other external processes, to form a new instance node.

Each of these is elaborated in the following sections with respect to the behaviour of the memory system as outlined in (Gero 1999a). In the figures that correspond to these sections, the circle represents instance nodes within the extended IAC network. These nodes represent either the original experiences or memories of these experiences.

5.1. MEMORY CONSTRUCTION AND GROUNDING OF EXPERIENCES

When the cue to the memory system matches a pre-existing experience exactly, that experience is constructed, Figure 5. After the construction process, that memory is grounded so that it will be used more readily in the subsequent memory construction process. If similar probe is sent into the system again, the same experience will be highlighted again and its grounding will increase, Figure 6.

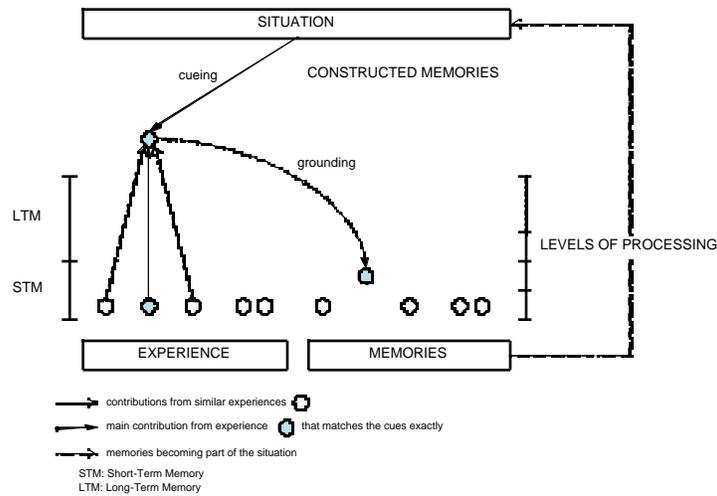


Figure 5. Memories constructed from experience that matches the cue from the situation exactly (modified from (Gero 1999a))

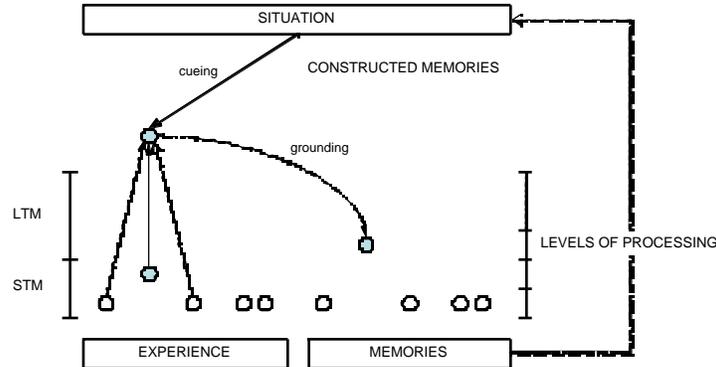


Figure 6. Subsequent grounding of the same experience that matches the cue

This form of learning is affected through the adjustment of weights between the instance node and its related property nodes. After the instance node is found to be useful, it is sent back into the system as a positive experience to be grounded. The interconnection strengths between the nodes modeling this experience are increased to reflect this emphasis.

5.2. CONSTRUCTION AND GROUNDING OF NEW MEMORIES

New memories are constructed when the property nodes in the probe create a new configuration of interconnection within the network. There are two possible cause of this reconfiguration: either new property nodes have been added to the system via another external process or the network reconfigures its pre-existing configuration by highlighting a new combination of property nodes that forms the new instance node, Figure 7.

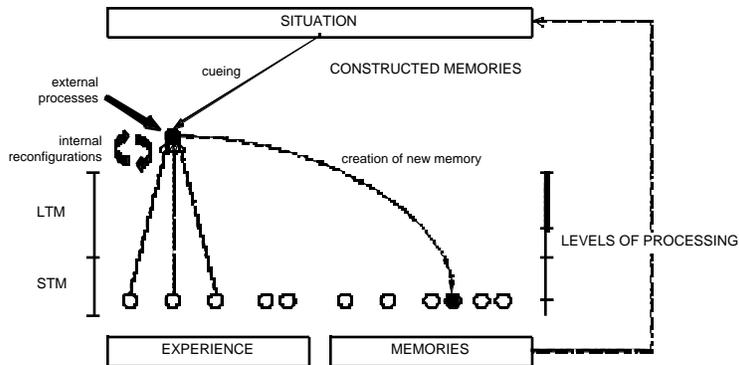


Figure 7. New memories constructed from a series of similar experiences

These two forms of learning are constructive in nature as compare to learning via adjusting the weights among the interconnections between nodes. If the subsequent memory construction process highlights the new instance again, it is also grounded, Figure 8.

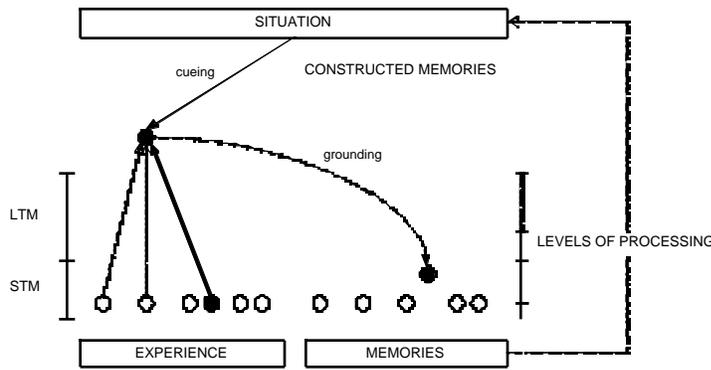


Figure 8. Subsequent grounding of newly created memory through its matching with the cue to the system

All the memory constructed so far are available for use in the subsequent memory construction as pre-existing experiences, Figure 9.

6. Experiments

The following sections describe two experiments that demonstrate memory construction and learning via weights modifications. To demonstrate the ability of the system to extract similar memory traces, a series of similar design experiences, Figure 10 are embedded within the memory system together with other unrelated memory traces and a probe that triggers their construction are used to cue the system.

6.1. MEMORY CONSTRUCTION

A design cycle starts off with a focused concept that is retrieved from the memory system or derived from existing focused concepts (Gero and Fujii 2000). A partial design experience, modeling the current design session, $E1$ is created as a collection of this focused concept (represented by a preexisting initial and final focused concept, $Hi_{e1_1_1}$ and $Hf_{e1_1_1}$) and an initial exogenous variable, Vi that represents the initial artifact to be manipulated by the agent. Symbolically, $E1$ is represented by: $E1 = \{Vi, Hi_{e1_1_1}, Hf_{e1_1_1}\}$.

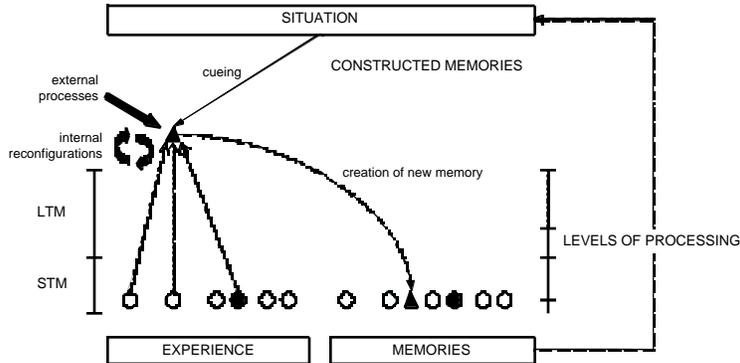


Figure 9. Further new memories constructed from a series of similar experiences

The network is clamped by setting external input to these property nodes and then cycled. The associations between memory traces captured implicitly within the network are used to highlight candidate constituents to be used for completing the partial experience; E1, TABLE 1.

<p>VL_{e1,1,1} SL_{e1,1,d} P_{e1,1,d} QL_{e1,1,1*} HL_{e1,1,1}</p> <p>Design Experience: E1_1_a</p> <p>A_{e1,1,1:V?} VL_{e1,1,2}</p> <p>VL_{e1,1,2} SL_{e1,1,2} P_{e1,1,2} QL_{e1,1,1*} HL_{e1,1,1}</p>	<p>VL_{e1,1,1} SL_{e1,1,d} P_{e1,1,d} QL_{e1,1,21*} HL_{e1,1,21}</p> <p>Design Experience: E1_1_k</p> <p>A_{e1,1,5:V?} VL_{e1,1,a}</p> <p>VL_{e1,1,a} SL_{e1,1,a} P_{e1,1,a} QL_{e1,1,21*} HL_{e1,1,21}</p>
<p>VL_{e1,1,2} SL_{e1,1,2} P_{e1,1,2} QL_{e1,1,21*} HL_{e1,1,21}</p> <p>Design Experience: E1_1_n</p> <p>A_{e1,1,x:V?} VL_{e1,1,a}</p> <p>VL_{e1,1,a} SL_{e1,1,a} P_{e1,1,a} QL_{e1,1,21*} HL_{e1,1,21}</p>	<p>VL_{e1a,2,3} SL_{e1a,2,3} P_{e1,1,d} QL_{e1,1,1*} HL_{e1,1,1}</p> <p>Design Experience: E1a_2_c</p> <p>A_{e1a,1,5:V?} VL_{e1a,2,2}</p> <p>VL_{e1a,2,2} SL_{e1a,2,2} P_{e1,1,2} QL_{e1,1,1*} HL_{e1,1,1}</p>
<p>VL_{e1a,2,3} SL_{e1a,2,3} P_{e1,1,d} QL_{e1,1,21*} HL_{e1,1,21}</p> <p>Design Experience: E1a_2_b</p> <p>A_{e1a,1,4:V?} VL_{e1a,1,3}</p> <p>VL_{e1a,1,3} SL_{e1a,1,3} P_{e1,1,a} QL_{e1,1,21*} HL_{e1,1,21}</p>	<p>VL_{e1a,2,2} SL_{e1a,2,2} P_{e1,1,2} QL_{e1,1,21*} HL_{e1,1,21}</p> <p>Design Experience: E1a_2_a</p> <p>A_{e1a,1,2:V?} VL_{e1a,1,3}</p> <p>VL_{e1a,1,3} SL_{e1a,1,3} P_{e1,1,a} QL_{e1,1,21*} HL_{e1,1,21}</p>

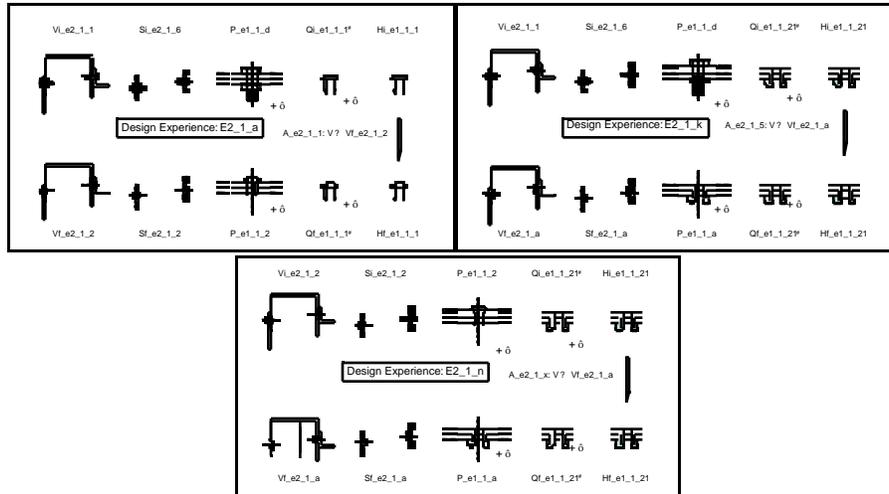


Figure 10. A series of similar design experiences

TABLE 1. Constituents of memory traces highlighted for a partial design experience. (*italic* text indicate constituents of experiences constructed in by the memory system based on what it knows and numbers in brackets indicate the activation values of the respective nodes)

Design Experience	Initial Exogenous Variables	Initial Exogenous Sensory Data	Percepts	Initial Expected Percepts	Initial Focused Concepts	Actions	Final Focused Concepts	Final Expected Percepts	Final Exogenous Variables	Final Exogenous Sensory Data
E2_1_k (0.832)	Vi (0.792)	Si_e1_1_d (0.539)	P_e1_1_d (0.810)	Qi_e1_1_2 (0.812)	Hi_e1_1_1 (0.893)	A_e1_1_5 (0.283)	Of_e1_1_2 (0.812)	Hf_e1_1_1 (0.893)	Vf_e1_1_a (0.537)	Sf_e1_1_a (0.537)
E1a_2 (0.832)	Vi_e1_1_1 (0.527)	Si_e2_1_6 (0.539)	P_e1_1_2 (0.663)	Qi_e1_1_1 (0.808)	Hi_e1_1_2 (0.812)	A_e2_1_5 (0.283)	Of_e1_1_2 (0.808)	Hf_e1_1_2 (0.812)	Vf_e2_1_a (0.537)	Sf_e2_1_a (0.537)
E1_1_k (0.832)	Vi_e2_1_1 (0.527)	Si_e1a_2_1 (0.539)	P_e1a_1_2 (0.301)			A_e1a_1_4 (0.283)			Vf_e1a_1_1 (0.537)	Sf_e1a_1_1 (0.537)
E1_1_a (0.822)	Vi_e1a_2_3 (0.527)	Si_e2_1_2 (0.275)	P_e1a_1_3 (0.301)			A_e1_1_1 (0.278)			Vf_e1_1_2 (0.280)	Sf_e1_1_2 (0.280)
E2_1_a (0.822)	Vi_e2_1_2 (0.245)	Si_e1_1_2 (0.275)	P_e1a_1_4 (0.301)			A_e2_1_1 (0.278)			Vf_e2_1_2 (0.280)	Sf_e2_1_2 (0.280)
E1a_2_c (0.822)	Vi_e1a_2_2 (0.245)	Si_e1a_2_2 (0.275)				A_e1a_1_5 (0.278)			Vf_e1a_2_1 (0.280)	Sf_e1a_2_1 (0.280)
E2_1_n (0.811)	Vi_e1_1_2 (0.245)	Si_e1a_1_1 (0.259)				A_e1_1_x (0.272)			Vf_e1_1_2 (0.259)	Sf_e1_1_2 (0.259)
E1a_2_c (0.811)	Vi_e1a_1_2 (0.228)	Si_e1a_1_1 (0.259)				A_e2_1_x (0.272)			Vf_e1_1_2 (0.259)	Sf_e1_1_2 (0.259)
E1_1_n (0.811)	Vi_e1a_1_3 (0.228)	Si_e1a_1_4 (0.259)				A_e1a_1_2 (0.272)			Vf_e1_1_2 (0.259)	Sf_e1_1_2 (0.259)
E1a_1_a (0.780)	Vi_e1a_1_4 (0.228)					A_e1a_1_a (0.256)				
E1a_1_b (0.780)						A_e1a_1_b (0.256)				
E1a_1_c (0.780)						A_e1a_1_c (0.256)				

There are various ways to complete E1 since there are several options for filling each of the slots for the percept, initial expected percepts, initial focused concept, action, final focused concept and final expected percept. All the (5_2_2_12_2_2=960) possible combinations can be enumerated by considering the cartesian product of the various possibilities for the above slots. However, most of these combinations are

not applicable due to the inter-relations between the constituents of a design experience. For example, a focused concept is always associated with a particular expected percept if the former represents a design prototype and the latter represents an expected structure. Some of these heuristics are captured by the existing design experiences (modeled as instance nodes) that are also highlighted during the memory construction process, TABLE 2. A pragmatic way to get the valid combinations is to consider the highlighted instance nodes and extract the valid combinations based on their configurations.

TABLE 3 illustrates the partial candidate experiences constructed by the memory system based on the information from the previous two tables. All the initial and final exogenous variables in the previous design experiences are replaced by vi and vf respectively since they are representing the current and new artifact respectively. The other exogenous variables that are highlighted represent other artifacts encountered by the agent in previous design sessions that are associated with the current focused concept according to its specific design requirements.

TABLE 2. Configurations of various existing design experiences that are highlighted in the memory construction process

Design Experiences	Initial Exogenous Variables	Initial Sensory Data	Percepts	Initial Expected Percepts	Initial Focused Concepts	Actions	Final Focused Concepts	Final Expected Percepts	Final Exogenous Variables	Final Sensory Data
E2_1_k	Vi_e2_1_1	Si_e2_1_6	P_e1_1_d	Qi_e1_1_2	Hi_e1_1_2	A_e2_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf_e2_1_a	Sf_e2_1_a
E1a_2_b	Vi_e1a_2_1	Si_e1a_2_3	P_e1_1_d	Qi_e1_1_2	Hi_e1_1_2	A_e1a_1_4	Hf_e1_1_2	Qf_e1_1_2	Vf_e1a_1_3	Sf_e1a_1_3
E1_1_k	Vi_e1_1_1	Si_e1_1_d	P_e1_1_d	Qi_e1_1_2	Hi_e1_1_2	A_e1_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf_e1_1_a	Sf_e1_1_a
E1_1_a	Vi_e1_1_1	Si_e1_1_d	P_e1_1_d	Qi_e1_1_1	Hi_e1_1_1	A_e1_1_3	Hf_e1_1_1	Qf_e1_1_1	Vf_e1_1_2	Sf_e1_1_2
E2_1_a	Vi_e2_1_1	Si_e2_1_6	P_e1_1_d	Qi_e1_1_1	Hi_e1_1_1	A_e2_1_3	Hf_e1_1_1	Qf_e1_1_1	Vf_e2_1_2	Sf_e2_1_2
E1a_2_c	Vi_e1a_2_1	Si_e1a_2_3	P_e1_1_d	Qi_e1_1_1	Hi_e1_1_1	A_e1a_1_3	Hf_e1_1_1	Qf_e1_1_1	Vf_e1a_2_4	Sf_e1a_2_4
E2_1_n	Vi_e2_1_2	Si_e2_1_2	P_e1_1_2	Qi_e1_1_2	Hi_e1_1_2	A_e2_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf_e2_1_a	Sf_e2_1_a
E1a_2_a	Vi_e1a_2_1	Si_e1a_2_3	P_e1_1_2	Qi_e1_1_2	Hi_e1_1_2	A_e1a_1_3	Hf_e1_1_2	Qf_e1_1_2	Vf_e1a_1_3	Sf_e1a_1_3
E1_1_n	Vi_e1_1_2	Si_e1_1_2	P_e1_1_2	Qi_e1_1_2	Hi_e1_1_2	A_e1_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf_e1_1_a	Sf_e1_1_a
E1a_1_a	Vi_e1a_1_1	Si_e1a_1_2	P_e1a_1_2	Qi_e1_1_1	Hi_e1_1_1	A_e1a_1_3	Hf_e1_1_1	Qf_e1_1_1	Vf_e1_1_2	Sf_e1_1_2a

TABLE 3. Partial candidate design experiences

Design Experiences	Initial Exogenous Variables	Initial Sensory Data	Percepts	Initial Expected Percepts	Initial Focused Concepts	Actions	Final Focused Concepts	Final Expected Percepts	Final Exogenous Variables	Final Sensory Data
E1_1	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e2_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_2	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e1a_1_4	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_3	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e1_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_4	Vi	Sensation	Perception	Qi_e1_1_1	Hi_e1_1_1	A_e1_1_3	Hf_e1_1_1	Qf_e1_1_1	Vf	Sensation
E1_5	Vi	Sensation	Perception	Qi_e1_1_1	Hi_e1_1_1	A_e2_1_3	Hf_e1_1_1	Qf_e1_1_1	Vf	Sensation
E1_6	Vi	Sensation	Perception	Qi_e1_1_1	Hi_e1_1_1	A_e1a_1_3	Hf_e1_1_1	Qf_e1_1_1	Vf	Sensation
E1_7	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e2_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_8	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e1_1_5	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_9	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e1_1_x	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_10	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e1a_1_2	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_11	Vi	Sensation	Perception	Qi_e1_1_2	Hi_e1_1_2	A_e1_1_x	Hf_e1_1_2	Qf_e1_1_2	Vf	Sensation
E1_12	Vi	Sensation	Perception	Qi_e1_1_1	Hi_e1_1_1	A_e1a_1_a	Hf_e1_1_1	Qf_e1_1_1	Vf	Sensation
E1_13	Vi	Sensation	Perception	Qi_e1_1_1	Hi_e1_1_1	A_e1a_1_b	Hf_e1_1_1	Qf_e1_1_1	Vf	Sensation
E1_14	Vi	Sensation	Perception	Qi_e1_1_1	Hi_e1_1_1	A_e1a_1_c	Hf_e1_1_1	Qf_e1_1_1	Vf	Sensation

The memory construction process provides information (based on past experiences) for the following:

- alternative focused concepts that are associated with the current focused concept;
- alternative expected percepts based on the focused concepts together with their associated feature detectors and structuring procedures to manipulate sensory data during sensation; and
- alternative actions to operate on the design artifact to fulfill the design requirements so that the agent's expectation and interpretation can be matched.

The sensation and perception processes are required to extract the sensory data and percepts from the environment to from a complete design experience.

An important behaviour of the constructive memory system is the triggering of associated concepts ($Hi_e1_1_21$ in this case). The original focused concept, $Hi_e1_1_1$, triggers the activation of other focused concepts and effectively forms a cluster of associated concepts. The same phenomenon is observed in the list of exogenous variables that are highlighted. The list of external structures ($Vi_e1_1_1$, $Vi_e2_1_1$, $Vi_e1a_2_3$, $Vi_e2_1_2$, $Vi_e1a_2_2$, $Vi_e1_1_2$, $Vi_e1a_1_2$, $Vi_e1a_1_3$ and $Vi_e1a_1_4$) that are activated forms another cluster of similar artifacts based on the current focused concept and its associated design requirements. This is the differentiating factor that sets the memory system apart from a pure database retrieval system: memories are constructed according to the cue sent into the system *and* its associations with the contents of the memory system. Clusters of memory constituents are formed on the fly as a result of the cue into the system. These results of the memory construction process cannot be obtained from a simple query into a SQL database based on set theory.

6.1.1. Interpretation of results

If the variables are instantiated as follows, Figure 10:

- Vi is taken as a variable representing the external structure of an artifact that the agent had never encountered before, say a mechanical assembly;
- $Hi_e1_1_1$ is a design prototype of a "snap fit" used for ease of fastening in the assembly operation of the artifact;
- $Qi_e1_1_1$ is the expected structure of the snap fit;
- $A_e1_1_1$ is the action to replace all fasteners in the assembly with the snap fit;
- $Hi_e1_1_21$ represents another design prototype associated with a snap fit. An example of this would be an integrated snap fit feature integrated into the original items to be fastened;
- $Qi_e1_1_21$ is the expected structure of an integrated snap fit;
- $A_e2_1_5$ is the action to replace all fasteners in the assembly with an integrated snap fit;

Essentially what is constructed by the memory system is a collection of candidate (partial) design experiences for the current situation based on the information the agent has. The constructed experiences provide alternative information for what to do in terms of how the sensory data of the artifact is to be structured and what action is to be performed on the artifact based on the requirements of the selected design prototype or related design prototype highlighted by the memory system. These memory traces are still subjected to verification by the agent through its interaction with the environment before they are incorporated into the memory system as new experiences.

This process of memory construction is a form of constructive learning via reconfiguring the topology of the network with network pruning. The partial design experience, E1 is reconfigured to create a new memory trace by rewiring the existing interconnection of the network and it is removed from the system once the completed new memory has been verified.

6.2. EFFECTS OF LEARNING

The constructed memories define memories of various design experiences associated with the cue provided by the initial partial experience. Each of these candidate memory traces has about the same emphasis (based on the activation of the instance nodes) since there was no learning/grounding before memory construction.

In the last experiment, TABLE 1, the first three memory traces (E2_1_k, E1a_2_b and E1_1_k) that were constructed have equal emphasis. To show the grounding effect, a particular memory trace, E1_1_k, is grounded five times to simulate its usefulness in five consecutive design sessions. The network is cycles again to show the extra emphasis on E1_1_k, via higher activation values of the related instance and property nodes, TABLE 4. This higher activation value highlights the higher applicability of the relevant memory traces E1₁ in TABLE 3 after learning has occurred.

TABLE 4. Memories constructed after grounding instance E1_1_k five consecutive times

Design Experience	Initial Exogenous Variables	Initial Exogenous Sensory Data	Percepts	Initial Expected Percepts	Initial Focused Concepts	Actions	Final Focused Concepts	Final Expected Percepts	Final Exogenous Variables	Final Exogenous Sensory Data
E1_1_k (0.852)	Vi (0.791)	Si_e1_1_d (0.560)	P_e1_1_d (0.814)	Qi_e1_1_2 (0.815)	Hi_e1_1_1 (0.893)	A_e1_1_5 (0.333)	QF_e1_1_2 (0.816)	HF_e1_1_1 (0.893)	Vf_e1_1_a (0.558)	Sf_e1_1_a (0.558)
E2_1_k (0.832)	Vi_e1_1_1 (0.550)	Si_e2_1_6 (0.539)	P_e1_1_2 (0.663)	Qi_e1_1_1 (0.808)	Hi_e1_1_2 (0.815)	A_e1a_1_4 (0.281)	QF_e1_1_2 (0.808)	HF_e1_1_2 (0.815)	Vf_e2_1_a (0.536)	Sf_e2_1_a (0.536)
E1a_2_b (0.832)	Vi_e2_1_1 (0.527)	Si_e1a_2_3 (0.539)	P_e1a_1_2 (0.300)			A_e2_1_5 (0.281)			Vf_e1a_1_3 (0.536)	Sf_e1a_1_3 (0.536)
E1_1_a (0.823)	Vi_e1a_2_3 (0.527)	Si_e1_1_2 (0.275)	P_e1a_1_3 (0.300)			A_e1_1_1 (0.277)			Vf_e1_1_2 (0.280)	Sf_e1_1_2 (0.280)
E2_1_a (0.822)	Vi_e1_1_2 (0.245)	Si_e2_1_2 (0.274)	P_e1a_1_4 (0.300)			A_e2_1_1 (0.276)			Vf_e1a_2_3 (0.280)	Sf_e1a_2_2 (0.279)
E1a_2_c	Vi_e1a_2_2	Si_e1a_2_2				A_e1a_1_5			Vf_e2_1_2	Sf_e2_1_2

(0.822)	(0.244)	(0.274)				(0.276)			(0.280)	(0.279)
E1_i_n (0.813)	Vi_e2_i_2 (0.244)	Si_e1a_i_2 (0.258)				A_e1_i_x (0.272)			Vf_e1_i_2a (0.258)	Sf_e1_i_2a (0.258)
E2_i_n (0.811)	Vi_e1a_i_3 (0.226)	Si_e1a_i_3 (0.258)				A_e2_i_x (0.271)			Vf_e1_i_2b (0.258)	Sf_e1_i_2b (0.258)
E1a_2_a (0.811)	Vi_e1a_i_4 (0.226)	Si_e1a_i_4 (0.258)				A_e1a_i_2 (0.271)			Vf_e1_i_2c (0.258)	Sf_e1_i_2c (0.258)
E1a_1_a (0.780)	Vi_e1a_i_1 (0.226)					A_e1a_i_a (0.254)				
E1a_1_b (0.780)						A_e1a_i_b (0.254)				
E1a_1_c (0.780)						A_e1a_i_c (0.254)				

7. Discussions

This paper has described implementation of the major functionality and behaviour of a constructive memory system for a situated design agent. The learning mechanisms provide a means to construct memories of experiences processed by the agent in a situated. Memories that are constructed by the system may or may not match the original experiences exactly as they were first experienced, but changes according to when, where and what the memory system is cued with.

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