Situated Concept Formation from Interactions: An Implementable Constructive Memory Model

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Abstract

This paper presents the foundations and architecture of an implemented cognitive constructive memory model for how situated agents learn concepts from interactions. The cognitive theories underpinning this research are founded on “situatedness” and “constructive memory”. The paper articulates three layers of reasoning in situated concept formation from interactions: reflexive, reactive and reflective. It describes these reasoning processes symbolically and in the form of data flows. The resulting model has been implemented and tested in an interface agent that learns from interactions when optimizing a design.

1. Introduction

This paper presents the foundations and architecture of an implemented cognitive memory model that is based on a constructivist view of cognition. Such a view is in accord with Clancey’s notion of conceptualization as meaning changes where concepts are brought into new relations (Clancey, 2001). The cognitive memories render mental capabilities allowing for learning new experience and making sense of the world (Gero & Peng, 2009). The notion of constructive memories can be traced to Dewey (1896) who articulated “sequences of acts are composed such that subsequent experiences categorize and hence give meaning to what experienced before” (quoted in Clancey, 1997). Memory has a dualist definition in that constructive memory is regarded as both a knowledge construct and a process via which memories (as knowledge structures) are constructed initially from experience in response to demands for a memory of that experience (Bartlett, 1932). The construction of the memory subsequently assimilates and accommodates new situations pertaining at the time of the demand for the memory (Gero, 1999). This dynamic nature of memory construction is referred to by Schacter (2012) as “adaptive constructive processes”, which encompass remembering the past events and more importantly simulating future events. Numerous neuroimaging studies revealed that remembering the past and simulating the future engage many of the same brain regions (Schacter, 2012). Barsalou (2009) has proposed the notion of situated conceptualization where simulations are situated representations of categories in relevant perceptual situations. In this paper, we use a situated agent as an embodiment to present the ideas of a constructive memory model, via which concepts are learned from the agent’s interactions with its environment. A situated agent is a software agent built using the notion of "situatedness" which has its roots in empirical naturalism (Dewey, 1896) and cognitive psychology (Bartlett, 1932). An agent uses a constructive memory model to continuously create and adapt concepts whilst interacting with a dynamic environment (Gero & Peng, 2009). Concepts as bearers of meaning and their formation are essential products that emerge from this cognitive apparatus giving rise to the system's adaptive behaviors, which can be characterized as "reflexive", "reactive" and "reflective" behaviors (Maher & Gero, 2002).

The theoretical grounds for this constructive memory model are briefly presented in Section 2 which revolves around notions of "situatedness" and "constructive memory". Section 3 details the situated concept formation process and relating data flows in the framework of constructive memory. Section 4 concludes the paper with discussions of computational implementation scenarios.

2. Situatedness and Constructive Memory

The theory of "situatedness" claims that human thought and action adapt to their environment. They are situated because of what people perceive, how people conceive of their activity, and what people physically do develop together (Clancey, 1997). It is postulated in situated learning that knowledge should be viewed as a capacity to coordinate and sequence behaviors, to adapt dynamically to changing circumstances (Clancey, 1995). In this vein, "situatedness" entails both the environment and the observer's experiences and the interactions between them. "Situatedness" is paraphrased as "where you are when you do what you do matters" (Gero, 1998), being inseparable from interactions in which knowledge is dynamically constructed. "Situatedness" is related to "Situated Action" (Suchman, 1987), "Situated Cognition" (Clancey, 1997) and "Situated Learning" (Lave and Wenger, 1991). The notion of "situatedness" is considered as a *conditio sine qua non* for any form of "true" intelligence, natural or artificial (Lindblom & Ziemke, 2002). Vygotsky enriched the concept of "situatedness" by introducing activity theory, defining that activities of the mind cannot be separated from overt behavior, or from the social context in which they occur. Social and mental structures interpenetrate each other (Vygotsky, 1978; Clancey, 1995).

Situated cognition describes the way humans construct their internal worlds via their interactions with the external world (Gero, 2003).

The *external world*, in Figure 1, denotes the world that consists of external events. The *interpreted world* is the world constructed inside the agent. This internal world is composed of sensory, perceptual and conceptual experiences, and created through the work of interpretation. The *expected world* is derived from the interpreted world. Through a process called *focusing*, the agent is able to use some aspects of the interpreted world, for example, concepts, to derive anticipations that predict future states of the external world. The process of *action* affects the external world based on anticipations constructed in the agent's self-organized *focusing* or *refocusing* processes.

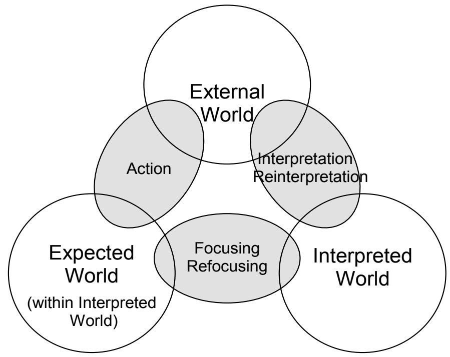

Figure 1. Situatedness as interaction of three worlds (after Figure 2 of Gero and Kannengiesser (2004)).

We hold that “situatedness” not only can be presented as recursive linkages between these three worlds, it is also often accompanied by structural and behavioral adaptation in the internal worlds. An external change may cause changes in the interpreted world. This can be achieved by activating or intentionally reactivating the agent’s experience. With reinterpretations, the agent can further refocus or produce a new concept to affect the external world.

Central to this situated agency is the notion of “constructive memory”. Memory in computational systems often refers to a place that holds data and information called “memories”. It is indexed so as to be queried more efficiently afterwards. We utilize a different notion of memory. Clancey (1991) emphasized that memory is not a place where descriptions of what we have done or said before are stored, but is indistinguishable from our capability to make sense, to learn a new skill, to compose something new. This is the essence of Bartlett’s model of constructive memory (Bartlett, 1932). The theory of constructive memory is supported by cognitive and neuroscience studies (Von Foerster, 1970 reprinted in 2003; Reigler, 2005; Schacter, 2012). The basic functions of a constructive memory are described by Riegler (2005) as:

- the cognitive apparatus creates a structure;
- it interacts with other structures (such as the surrounding environment or the older structure of its apparatus);
- it compares the newly created structures with those encountered in its interactions with other structures; and
- it adapts the structures when needed before returning to the first function.

Reigler's (2005) constructive memory functions emphasize changes of knowledge structures during a construction process. However, the lack of fine-grained descriptions of a cognitive architecture leads to speculations of how the structures are constructed and adapted. A more detailed description of the characteristics of a constructive memory can be found in (Gero, 2006):

- memory is a reasoning process;
- the index need not be explicit, it can be constructed from the query;

- the index can be changed by its use;
- the content can be changed by its use;
- the memory structure can be changed by its use;
- memories can be constructed to fulfil the need to have a memory; and
- memories are a function of the interactions occurring at the time and place of the need to have a memory.

A memory can be regarded as a process of learning or reinforcing a concept. It is a reflection of how the system has adapted to its environment (Gero & Smith, 2006). Such memories are associated with both the previous memories (called "experiences" when used in the current situation), and the current need for a memory (in terms of environment stimuli) (Gero, 2006). A constructive memory system is an unsupervised incremental learning system, where all later memories have the potential to include and affect all earlier memories while earlier memories affect later memories (Gero, 2006). Two operational characteristics of a constructive memory model are constructive learning and experiential grounding mechanisms (Liew & Gero, 2004). Constructive learning is the means by which an agent develops new experiences. It has an effect that potentially brings changes in the structure of the memory system (Alberini, Milekic, et al. 2006; Nader, 2003; Tanabe & Mogi, 2006). Experiential grounding is the mechanism providing meanings to the experiences processed by an agent (Alberini, Milekic, et al. 2006; Liew & Gero, 2004). It is similar to historical grounding (Nehaniv & Dautenhahn, 1998), which accounts for the consequence of the utility of an experience in determining its meaning. According to Liew and Gero (2004), the basic operations for a constructive memory model consist of:

1. cueing: the memory system is initially cued by a demand from the current situation;
2. activation and selection: multiple experiences are activated, with only one being selected;
3. memory construction: memory is constructed based on the selected experience;
4. incorporation: the constructed memory is incorporated into the system; and
5. grounding: providing meanings to the activated experience based on the consequence of its usage.

In the next section, we present a detailed schema of a constructive memory model and how concepts are constructed.

3. Situated Concept Formation in a Constructive Memory Architecture

Concept formation has been regarded as a process of incremental unsupervised acquisition of categories and their intentional descriptions (Fisher & Pizzani, 1991). Based on this view, a broad spectrum of computational models has been developed, including inductive learning methods, explanation-based learning approaches and connectionist algorithms. Theories of concept formation reduced to categorization are not able to address the complexity of the world (Bisbey & Trajkovski, 2005). A concept lacking an understanding of why the object, entity or event has its particular properties is called a proto-concept instead (Vygotsky, 1986; Bisbey & Trajkovski, 2005). Learning a concept inherently entails understanding its influence on its environment. It is postulated that concepts that incrementally capture the knowledge of a dynamic process are formed as a consequence of "situatedness" (Gero & Fujii, 2000; Peng & Gero, 2006a; Smith & Gero, 2005).

3.1 Information Processing of Sense-data, Percepts

The basic data structures that are used in concept formation are sense-data, sensory data, percept and memory cue. Sense-data are environment variables and their states that are captured by sensors. The sense-data are generated by sensors through "push" and "pull" processes. A push process is a data-driven process in which changes from the external world trigger changes in the agent's internal world, for example, the agent's experience. A pull process is an expectation-driven process in which the agent changes the internal world based on the expectation-biased external changes (Gero & Fujii, 2000; Gero & Kannengiesser, 2006). The push and pull processes can occur during processes of sensation, perception and conception. The pushed sense-data are also called exogenous sense-data (S_e). They are triggered by external environmental changes, for example, mouse clicks performed by designers in using the computer-aided design tool. The pulled sense-data are intentionally collected during the agent's expectation-driven process. In the pull process, sensors are triggered from the agent's higher level processes (that is, perception, conception) and use environmental changes to change their sense-data.

Sensory data consist of two types of variables: the exogenous sense-data (S_e) and the autogenous sensory experience (S_a). S_a is created from activating the agent's memory structures using the exogenous sense-data (S_e). Sensory data, also called sensory-experience data, (S_{e+a}) are a combination of the agent's exogenous sense-data (S_e) and the related autogenous information (S_a).

Percepts are intermediate data structures that are generated from mapping sensory data into categories. A memory cue refers to a stimulus that can be used to activate the agent's memories. A cue is subsequently assigned with an activation value to trigger responses from the agent's memory structures.

3.2 Proto-concepts and Concepts

A concept is a result of an interaction process in which meanings are attached to environmental stimuli. The term "proto-concept" is used to describe the intermediate state of a concept. A proto-concept is a memory structure that depicts the agent's interpretations and anticipations about its external and internal environment at a particular time. A concept is defined as the grounded invariants over the agent's experience. They are abstractions of experience of memories which were utilized that confer a predictive ability for new situations (Rosenstein & Cohen, 1998; Smith & Gero, 2000). On the other hand, a concept contains context-dependent specifications for an abstraction which are encapsulated in anticipations. An agent focuses on parts of its experience to produce a proto-concept, depicting its interpretation and expectation for the related environmental changes (also called stimuli). The concept formation process involves a process of validation for the constructed proto-concepts. An ill-formed proto-concept triggers a process (later referred as 'Reflection') in which the agent reasons and refocuses on a new proto-concept. A validated proto-concept forms a concept.

3.3 Situated Concept Formation in Interactions

Interactions are fundamental bases for the concept formation process in a situated agent. This paper draws ideas from the concept formation framework of Gero and Fujii (2000). Interactions are modelled at two levels. Macro-level interaction is the means via which data can be transferred between the agent and its environment. Micro-level interaction details the coordination of the agent's internal processes. The macro-level interactions provide a set of resources for the agent to use in learning and constructing situational memory. The macro-level interactions and the agent's micro-level interactions form a coupled interaction mechanism that gives rise to the system's adaptive behaviors, which are defined as "reflexive", "reactive" and "reflective" behaviors (Maher & Gero, 2002).

3.4 Constructive Memory Architecture for Situated Agents

A situated agent contains sensors, effectors, grounded memory structures and concept formation related processes consisting of paralleled sensation, perception, conception, hypothesizing, expectation, validation, consolidation and action processes, shown in Figure 2.

The sensor is the instrument by which the agent receives and gathers stimuli from the environment. The agent gains access to the environment through the sensors and affects the environment through its effectors. An effector is the instrument by which the agent changes the environment through its actions.

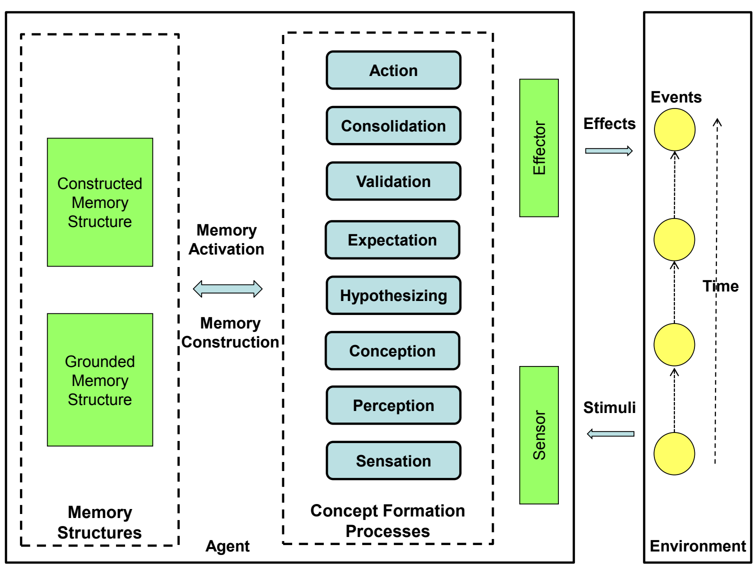

Figure 2. The constructive memory model for a situated agent.

Sensation is the process of transforming sense-data into expected sensory experience data, called S_{e+a} in 3.1. Perception is the process of generating percepts from sequencing and coupling sensory data. Perception maps sensory data to predefined category descriptions, and can generate new information from the transformation of stimuli sensed (Clancey, 1997). Perception also structures these sensory data into a sequence or simultaneous chunks (percepts) based on past sequences, coupled categorizations (perceptual experiences) and activated abstractions of percepts (proto-concepts). Perception is a "data-driven" and "expectation-driven" process in which percepts are constructed from the synthesizing of expected percepts with current percepts caused by environmental changes. Once environmental changes are sensed and structured into sensory data, they are processed by expectation and grouped into current percepts.

Conception is the process of categorizing perceptual sequences and chunks in order to form proto-concepts. Conception is implemented by three basic functions: conceptual labelling (C_1), constructive learning (C_2) and induction (C_3). The conceptual labelling function selects existing proto-concepts based on memory responses to an environment cue. This includes deriving expectations from the responses and identifying the target (focusing). Constructive learning allows the agent to accumulate environment data. Induction generalizes patterns from the captured data and is responsible for generating conceptual knowledge structures.

Expectation produces the agent's predictions about environment events. Expectation reflects on the agent's view about possible consequences from certain actions. When unexpected events are recognized, the agent engages in reinterpretation (Gero & Fujii, 2000; Kelly & Gero, 2014). Reinterpretation is implemented in the hypothesizing process, in which focused concepts are selected for expectation and the causalities of failures are activated. The hypothesizing process generates a hypothesis from current learned proto-concepts, allowing the agent to learn in a "trial and error" manner. An agent needs to refocus on or construct a new proto-concept to produce a new hypothesis.

Action is the process in which the activated memories are experimented on within the current environment to achieve goals. The feedback from the environment can serve as cues for adjustment of the agent's behaviors.

Validation is the process in which the agent verifies proto-concepts and hypotheses. It examines the deviation of the concepts and expectation with environment changes. A valid concept will be reinforced in consolidation, in which the memory structures of valid concepts are strengthened in that the likelihood of the consolidated memories being activated in similar circumstances is enhanced.

3.5 Micro-level Interaction

Central to a situated agent is the micro-level interaction schema, which denotes how an agent's internal processes coordinate with one another in attaching meanings to low-level sense-data, and, as a consequence, contributes to the agent's behaviors. Table 1 indicates data flows that will be further illustrated in this section.

S_e is captured by sensors as a sequence of unlabelled raw stimuli and is sent to Sensation (label 1 in Table 1 and Figure 3).

Table 1. Data flows notation for a situated agent. Numbered data flows are referred to in Figures 3 to 8.

1	sending sense-data (Environment variables) from sensor to Sensation	12	sending command to activate Sensation
2	sending sense-data, current percept and concept to Expectation which will further activate memory structures to generate an expected sensory data, percepts and concepts	13	Sending current percept to Conception
3	activating memory structures to create a response	14	creating constructed memory from current proto-concept at runtime
4	sending activated memory to Action	15	sending constructed memory to Action
5	sending sensory data to Perception to generate percepts	16	sending constructed memory to Validation
6	sending action plans to drive Effector to change the environment	17	pulling current proto-concept to Hypothesizing
7	pulling current sensory data from Sensation	18	pulling current percept to Conception
8	pulling current sense-data from Sensor	19	pulling grounded memory to Hypothesizing or activating grounded memory from Hypothesizing
9	sending expected percept, pulled sense-data and sensory data to Validation	20	sending hypothesis to Conception
10	sending validation result to Consolidation	21	activating Conception to perform inductive learning function
11	sending command to strengthen the validated memory structures		

An environmental stimulus is captured by a sensor which is transformed into sense-data. This denotes the effect of a push process in Figure 3.

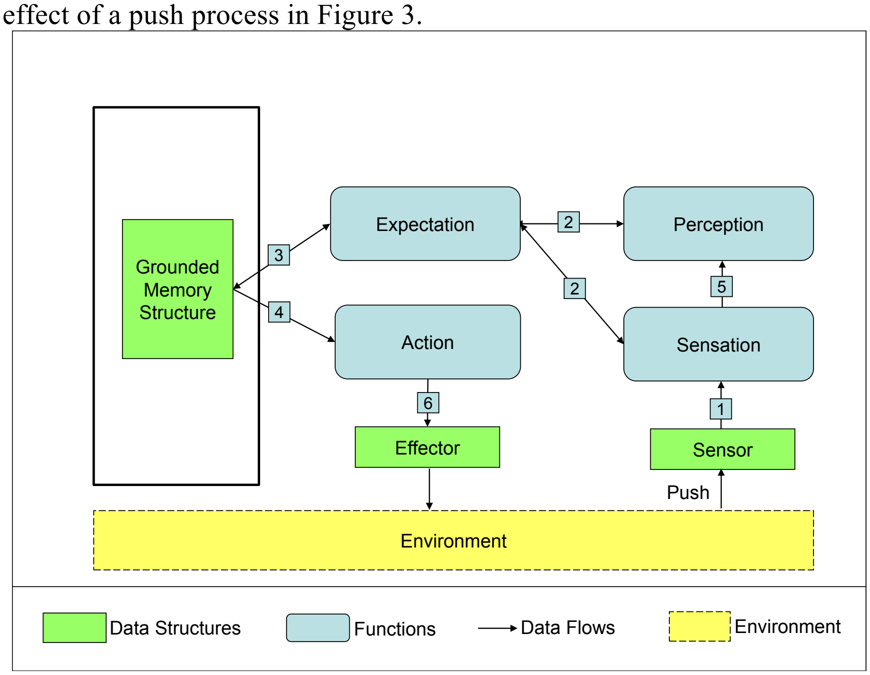

Figure 3. Interactions that drive the reflexive behavior (numbers refer to Table 1).

Take for example the visual, somatic and olfactory stimuli for an orange:

- $S_e(t)$ = {…… "stimuli of round yellow object", "rough skin surface", "specific smell"……}.

Based on the memory of sensory modality information of "orange", the agent creates an autogenous variable with its initial label for the S_e from its expectation: (Sensation → "2" → Expectation → "3" → Grounded Memory Structure (Sensory Modalities) → "3" → Expectation → "2" in Figure 3):

- $S_a(t)$ = {"Assignment of Modalities to stimuli"}.

Thus, sensory data S_{e+a} takes the form in Sensation as:

- $S_{e+a}(t)$ = {…… ["vision of round yellow object", "touch of rough skin", "smell like orange"]……}

The sensory data S_{e+a} can be further categorized to create initial percept P_i based on its grounded memories relating to categories (Perception → "2" → Expectation → Grounded Memory (Categories) → Expectation → "2" in Figure 3). The initial percept can be structured as a triplet "P (Perceptual Category, Sensory Modalities, Sensory Stimuli)". It is expressed as:

- $P_i(t)$ = { Orange, Orange Modality, "vision of orange"- "touch of orange"-"smell of orange"}

Reflexive behavior is produced when the experiential response to current sensed data is sufficiently strong to reach a reflexive threshold. A memory response to a perceptual category can affect action directly ("4"). In this circumstance, the agent reflexes to environment stimuli based solely on its experience. This is generated from data flows which are illustrated in Figure 3. The agent uses the activated memories to organize acts to bring changes to the environment ("6" → "Effector" → "Environment"). At the same time, Perception initiates the "pull" process ("7" in Figure 4) to validate the current formed percept that contains the agent's expectation of environmental changes.

The agent pulls data from its external macro-interactions and alters its interactions, Figure 4. "Push" processes which are driven from "data-driven" commands run parallel with the expectation-driven "pull" process, so that the agent's internal processes can access real time data.

A validation function uses the expected percept that was derived from the activated memories (in Figure 3) to activate "Perception" to pull data from its lower level process (("7" in Figure 4).

A new version of percept is created based on the pulled sense-data ("Perception" ← "Pull" + "7" ← "Sensation" ← "Pull" + "8" ← "Sensor"). The validation function measures the discrepancy between the agent's predictions and the environment changes by comparing this pulled percept with the expected percept created at a previous time.

A consolidation function strengthens the valid experience through a flow – "Validation" → "10" → "Consolidation" → "11" → "Grounded Memory Structure". An invalid expectation causes the agent to shift its behavior to stand-by and to capture additional data from the environment ("Consolidation" → "12" → "Sensation").

When the agent's experiential response to the current sensed and perceived data is not strong enough to reach the reflexive threshold, the agent moves into the reactive behavior mode. This behavior is produced by micro-level interactions that are described in Figure 5. A percept at

runtime can act as a memory cue that activates the agent's grounded memory structures ("2" → "Expectation" → "Grounded Memory Structure"). Based on the experiential response, the agent generates an expectation for the current percept and creates a proto-concept ("13" → "Conception" → "2" → "Expectation" → "3" → "Grounded Memory Structure" → "Expectation" → "Conception"). The agent uses the proto-concept to construct a memory, representing a response to current situation ("Conception" → "14" → "Constructed Memory Structure"). The constructed memory structure is transferred to an action function and produces an effect on the environment (via "15" → "Action" → "6" → "Effector" → "Environment").
The agent subsequently examines the constructed memory in its macroscopic interactions with the environment.

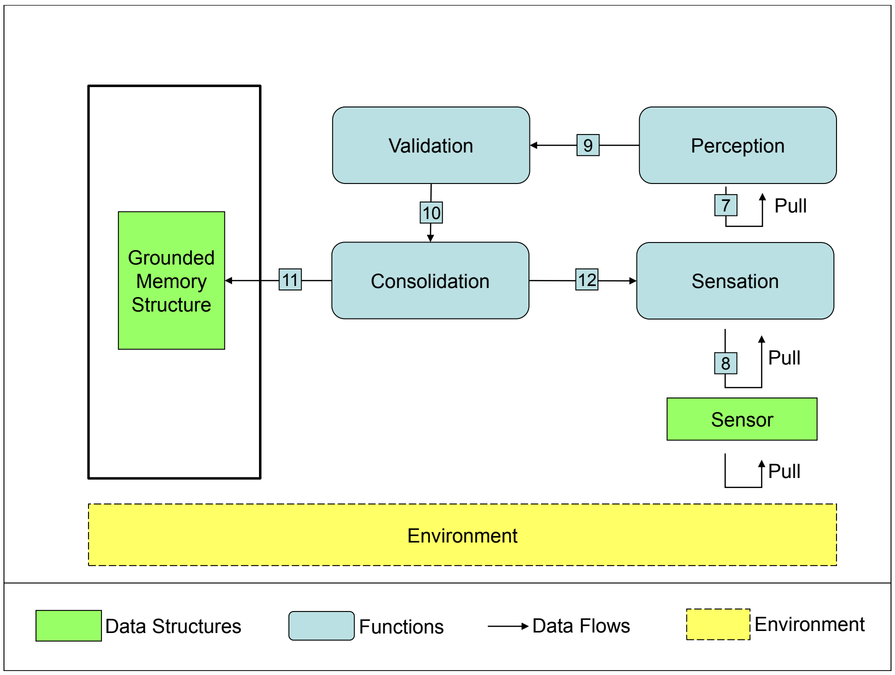

Figure 4. The agent's micro-interaction pulls data from macro-interactions and alters the interactions which further alters the agent's behavior.

The agent matches this memory with the current pulled percept[1] ("16" + "9" → "Validation"), Figure 6. Based on the validity of that memory, it either consolidates that memory into experience (via "11" → "Grounded Memory Structure") or initiates a reflective behavior ("12" → "Sensation").

Reflective behavior is activated by discrepancies between the constructed memory and the current environmental changes – the failure of the system's reactive behavior. In its reflective

[1] The pull process is activated by the validation function to draw environment changes and the interpreted perceptual categories of these changes.

behavior, the agent coordinates all its internal processes in two forms of interactions (Reflections I and II) to reinterpret environmental changes. The "Reflection I" is triggered by circumstances when the agent's constructed proto-concepts fail in the validation function. The agent reactivates its memories at a later time when a memory cue is able to be identified in the environment. This uses similar data flows depicted in Figure 5. The agent then validates its reactivated memories which represent the agent's re-interpretation and re-expectation. If the agent fails to validate the constructed proto-concepts, it activates "Reflection II" interactions, Figure 7.

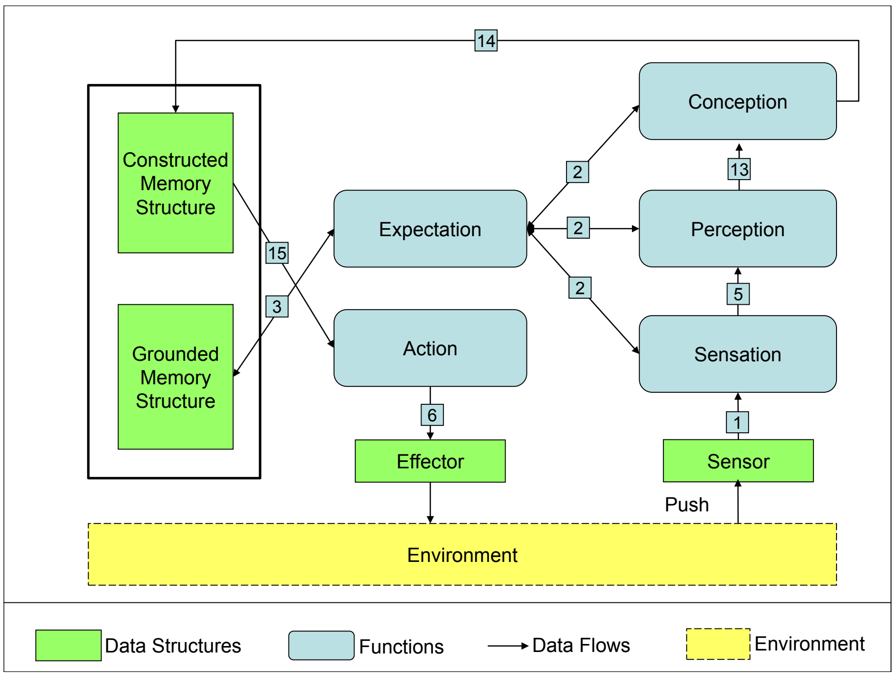

Figure 5. Micro-interactions that drive reactive behavior.

"Reflection II" involves the agent's conceptual level experience (in the grounded memory structure) and hypothesizing process to deduce explanations (hypothesis) for the current circumstances and construct a new proto-concept. A hypothesizing process draws data from a lower level conception process, which in turn pulls data from perception and sensation (via "Hypothesizing" ← "Pull" + "17" ← "Conception" + "Pull" ← …… ← "Environment"). It also takes conceptual knowledge in the grounded memory structure as inputs ("19").

The generated hypotheses represent the agent's reinterpretation about environment changes. In the meantime, the agent uses its hypotheses to refocus on a memory structure (through "Hypothesizing" → 19 → "Grounded Memory Structure" → "3" → "Expectation" → "Conception"). In this way, the hypotheses can be used by "Conception" to form new proto-concepts, via which new memories are formed.

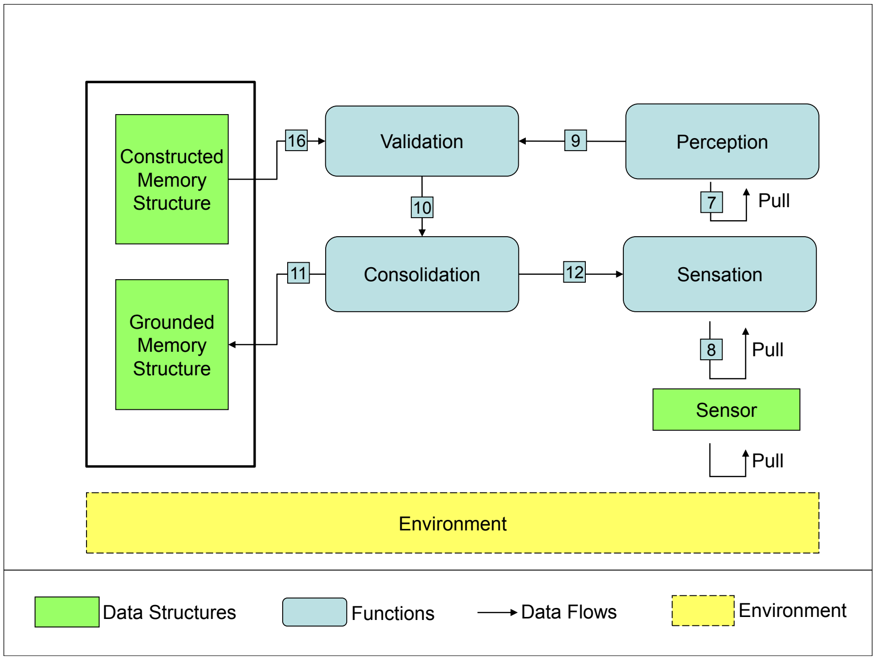

Figure 6. Pulling data from macro-interaction and validating the constructed concept in reactive behavior.

Receiving positive feedback from the macro-level interaction of the system, the agent consolidates the proto-concept into grounded memory structures ("11" in Figure 8). An unsupported proto-concept triggers a constructive learning process, in which the agent develops a new grounded memory structure (via "21" → "Conception" → "14" → "Constructed Memory Structure" → "11" → "Ground Memory Structure" in Figure 8).

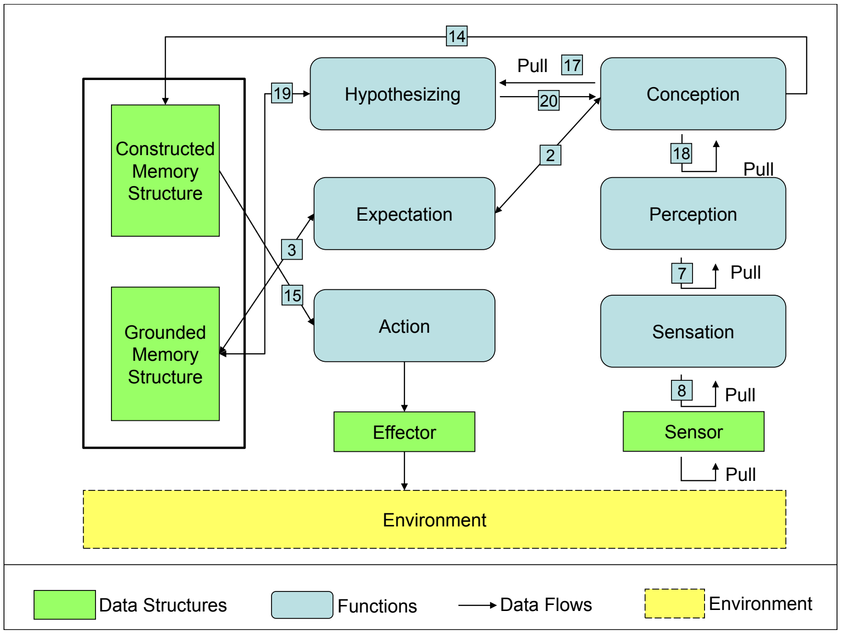

Figure 7. Reflection II involves conceptual experience and the hypothesizing process to reinterpret a situation.

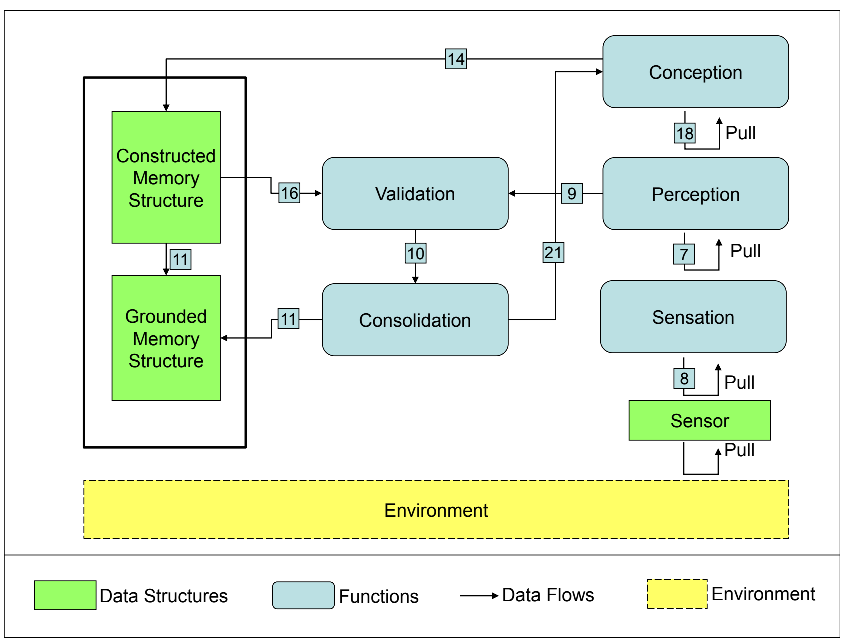

Figure 8. Verifying and consolidating (incorporating) proto-concepts constructed from Reflection II.

4. Conclusion and Discussion on Implementation

The cognitive foundation of situated concept formation has roots in theories of "situatedness" (Dewey, 1896) and "constructive memory" (Bartlett, 1932). Situatedness connects concept formation to the environment, while constructive memory is the basis of a situated memory formation and adaptation system. This paper presents a framework that contributes to bridging the gap between cognitive theories and computational implementable cognitive models by describing detailed structures and information processes. The software implementation based on this model has focused on two levels: the component and schema levels. At a component level, data structures provide concept formation functions relating to sensation, perception, conception, hypothesizing, expectation, validation, consolidation and action. The schema level is used to represent reasoning behaviors illustrated as micro-interaction in Section 3.5. It is coded in the main class of the software package which uses multi-threading to coordinate components of the system to generate "Reflexive", "Reactive" and "Reflective" behaviors. The lower-level processing components of "Sensor", "Preceptor" transform raw data into initially labeled categories which are used to create a cue for a memory based on experience. The "Experience" is implemented as an extended Interactive Competitive Neural Network (IAC), proposed by McClelland (1981; 1995), to model the associative nature of perceptual experience (Gero & Peng, 2006b). The "Concepter" is implemented as a decision-tree learning algorithm to generalize the cued perceptual experience into a proto-concept. The "Concepter" is also accumulates new instances of concepts, for example, sequences of percepts and the associated target concept. The "Hypothesizer" enables an agent to reflect and perform explanation-based learning. It is modelled as a rule-based engine (Bigus & Bigus, 1998), which takes the focused concept as input and applies backward chaining to re-focus on a new concept. The "Validator" verifies the usefulness of a proto-concept against the environmental changes. A feature-based matching function serves this end. The "Consolidator" is used to enhance the weight of edges of an IAC neural network, so that neurons that were fired together are more likely to be activated at a later time. The "Effector" can take the form of a standard graphic display when implemented in a human computer interaction scenario. It takes the results produced and presents them to the user. The implementation and behavior of a situated interface agent that uses constructive memory to learn concepts from interactions in design optimization have been elaborated in Gero & Peng (2009).

In summary, the current paper has presented the model of an implementable constructive memory based on cognitive constructs within a situated agent framework. Such a constructive memory model can learn new concepts through its interactions. As a consequence the agent develops adaptive behaviors through adapting memories and constructing memory structures.

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Nomenclature for internal interaction schema

A_c – actions and suggestions
C_a – constructive learning activation signal
C_d – consolidated experience or newly constructed memory
C_i – initial proto-concepts
C_j – current formed proto-concepts
E – the agent's effects on the environment
E_c – expected proto-concepts
E_f – expectation based on reflexive experience
E_p - expectation based on reactive experience
H_s – hypothesis
M_c – constructed memory
N_c – focused proto-concepts or new constructed proto-concepts
P_a – pulling activation signal
P_c – the pulled proto-concepts
P_{ev} – the pulled exogenous variables
P_i – initial percepts
P_j – current formed percepts
P_p – the pulled percepts
P_s – the pulled sensory data
R_a – reactivating experience signal
R_c – reflective conceptual experiences
R_e – reactive perceptual experience
R_f – reflexive experiences refer to strong experiences that directly affect actions
S_a – autogenous variables from sensory experience
S_e – sense-data captured by sensors
S_{e+a} – a combination of exogenous and autogenous sensory data
V_d – validation result