A Computational Framework for Concept Formation for a Situated Design Agent

John S Gero
Key Centre of Design Computing and Cognition
University of Sydney
NSW 2006 Australia
john@arch.usyd.edu.au
and
Haruyuki Fujii
Department of Architecture
Tokyo Institute of Technology
Ookayama 2-12-1 Tokyo 140-0012 Japan
hfujii@arch.titech.ac.jp

Abstract
This paper takes the approach that designing is situated and that concepts are formed as a consequence od the this situatedness of designing. The papers presents a framework for concept formation that draws on a structure of a a design agent that includes sensors, perceptors and conceptors that interact with each other and the external and internal environment of the agent to produce the situation that is a contingent basis for the formation and use of concepts.

Keywords: concept formation, situatedness, design agent

1. INTRODUCTION

A designer interacts with the environment while designing. The environment contains the initial requirements and constraints about what is being designed, the developing design in the form of sketches and drawings as well as the designer's cognitive structures, the client, other designers, and other things. The designer as a design agent observes the environment and performs actions so as to change the design and the resulting environment as well as the relation between the agent and the environment. The changed environment gives a design agent new observations and the agent performs actions with respect to the new observations. The interactions make designing assume aspects of situatedness and emergence. This paper proposes a framework for concept formation in designing that has the potential to deal with aspects of situatedness and emergence in designing.

The ideas behind the proposed framework of concept formation are drawn largely from cognitive science and artificial intelligence. However, we are not aiming at proposing a computational model explaining human cognitive processes such as perception, conception, and action. Rather, we aim to make a computational agent produce and represent what we call a design process.

2. DESIGNING, ACTION, AND CONCEPT

2.1 Designing and Action

Designing may be treated as an activity that produces the structure of an artifact being capable of providing the behaviours and functions that are expected to be provided by the

artifact. The result of designing is design descriptions, which explicitly depict the specification of the structure of an artifact, and the consequences of designing are the behaviors of the artifact and the functions that the artifact has potential to provide.

Designing is treated as a course of actions whose goal is to produce adequate design descriptions. It is composed of actions including making a design description though a sketch, analyzing or interpreting sketches, formalizing a design problem, etc. The course of actions, however, is not based on the execution of a fixed plan or program that is given when a design activity starts or in advance with the purpose of accomplishing the goal. Nor is a design activity the result of the execution of arbitrary actions independent of what is designed as well as being of when, where, by whom, how, and why it is performed, either.

We assume that actions composing a design activity are determined and performed connected to some goals, the circumstance in which it is performed, and the internal state of an agent who performs the actions. An action is influenced by both external and internal factors of the agent that performs the action. In this sense, an action in design is situated. By situated we mean that there is an interaction between the some aspects of the environment and the agent. This implies that only part of the environment is the situation and that what is the situation is a function as much of the agent as the environment itself [1].

2.2 Action and Concept

We call one aspect of the internal state of an agent that is significant to designing concepts. A principal role of concepts in designing is to suggest an action that should be performed to achieve better results and consequences towards a design goal, in accordance with the current situation.

We presume that an action is performed under an uncertain environment and that the action is selected not only with respect to the environment but also to the relationships between the environment and an agent, i.e. it is situated. The concepts are the knowledge that enables an agent to reuse past situations in a new situation. An agent interacts with the environment in the following senses.

(1) An agent observes the environment and forms a situation,
(2) an agent performs an action and changes the situation as well as the environment, and
(3) an agent understands the relations among the situation before it performs an action and the situation after the action.

We assume that what is understood by an agent through its interactions with the environment plays a critical role in forming the agent's concepts. Concepts are composed of rich sets of categorized abstractions of the mutual relationships between observations and actions.

An action performed by an agent in the current environment is dependent on the concepts that the agent has at the moment. The current situation, which is a projection made on the basis of the current environment, is dependent on the agent's concepts. Therefore there is a parallel/recursive relationship between concepts used and the situation as perceived or constructed.

2.3 Designing and Concept

Both the external environment and the design agent's internal environment play a role in determining a course of actions in designing and the resulting structure of an artifact. If

only the external environment determined a course of actions in designing, then the same course of actions, which leads to the same artifact, is always performed in the same design environment. The claim that only the external causes specify a design, however, is not consistent with the results of empirical studies concerning designing[2].

The concepts that a design agent uses control a course of actions performed by that agent. The concepts let a design agent determine the next actions that it can perform to make progress towards a better design solution from the current situation in a design process. A part of the concepts formed with respect to a past design decision in a certain situation would influence the design decision in a similar situation. If the past decision led the design to a better direction, a similar decision is more likely to be made. On the other hand, if the past decision led the design to a worse direction, a different decision is more likely to be made.

We do not assume that the all of an agent's concepts are employed simultaneously in designing. Rather, that only some of the concepts are activated and that the active parts change in accordance with a situation in designing. Therefore, the same design description can be analyzed in different ways, the same design sketch can be interpreted differently, and as a consequence different actions result in the same environment. Not only do the concepts influence the actions in designing, the actions and observations influence the concepts. The concepts are modified through a design agent's interaction with the situation so that the concepts can be useful in a future situation. It is also desirable that the existing concepts are modified so as to be useful in the current situation.

3. FRAMEWORK FOR CONCEPT FORMATION

We adopt an agent-based approach to construct a framework for concept formation [3]. In the agent approach, the agents, that are objects that have agency, are distinguished from the other objects in the environment. A situation is a projection in an agent of a state of the environment [4]. What is grasped is on the basis of the concepts that are formed through the interactions with the environment. From an agent's point of view, the agent interacts with the situation even if it is observed, from a point of view outside of the agent, that the agent interacts with the environment. There appears to be a complex mapping from the totality of a state of the environment to an agent's internal state – the situation. We posit that an agent recognizes an element in a state of the environment only when the agent is in a situation that the agent ought to distinguish the element from the other things. We use the notion of agency to refer to the following characteristics that an agent demonstrates:

- to interact with the environment to produce a situation,
- to be able to have expectations about the results of actions,
- to be able to react to unexpected situations, and
- to be able to perform consequential goal-directed actions.

Let an agent interact with the environment through sensors and effectors. Informally speaking, a sensor is a device, which an agent has, to sense something in the environment, and an effector is a device, which an agent has, to change something in the environment. The concepts are part of the internal structure of an agent that couples the sensors and effectors. The concepts, to some degree, correspond to the relationships between the environment and the agent, but they are not straightforward projections of the relations. Rather, the concepts are the result of a rich set of processes consisting of actions, sensations, perceptions, and conceptions.

The concepts that an agent has about designing are incrementally formed through the agent's interaction with situations. The process of concept formation involves the categorization of significant couplings of observations and relevant actions so as to be able to retrieve and apply them, through the processes of sensation, perception, and conception, to similar observations in designing. Concepts can be formed either by supervised learning or by unsupervised learning. In general, supervised learning is insufficient. The concepts are neither all given a priori nor completely derived from the environment.

3.1 Exogenesis and Autogenesis

Here we introduce autogenous variables: variables that come from inside the agent and that describe some aspect of the state of the agent. It is crucial for our framework to clarify how to distinguish the relevant situations from others. The criteria, which distinguish significant situations leading to desirable actions towards better designs, are updated and maintained in terms of the concepts. The functions, which an artifact has potential to provide, ought to be physically or psychologically benefit humans through the lifecycle of the artifact, as measured by the behaviours of the artifact. Therefore, it is rational to use the relations between exogenous and autogenous variables as the reinforcement that guides the concept formation process. Some of the autogenous variables may be analogs of the physical and intellectual conditions of human agents. The conditions, the values of the autogenous variables, change when an agent interacts with the environment. Among an agent's goals is the maintenance of desired conditions of the autogenous variables. If the concepts representing a coordination that distinguishes better situations, which ought to be approached, worse situations, which ought to be avoided, the concepts would be significant. If the criteria do not succeed in distinguishing these situations, then the criteria need to be revised.

3.2 Processes Enabling Concept Formation

Figure 1 depicts the full set of relations among the variables and processes constructing a framework of concept formation that aim to embody the characteristics mentioned above. Here we will provide a basic outline description of the process. The concept formation process is composed primarily of the sub-processes that we call sensation, perception, conception, and action. The terms are taken from those describing cognitive processes but they do not refer to such processes in a real world.

The variables and their definitions in the proposed framework are as follows:

$\boldsymbol{a}$	*action candidates*
$\boldsymbol{c}$	*concepts*
$\boldsymbol{h}$	*focused concepts*
$\boldsymbol{m}_{coe}$	*COE-memory; memory of course of events; structure constructed from time-stamped collections of* $\boldsymbol{a}$, $\Delta\boldsymbol{s}_{e+a,}$ $\Delta\boldsymbol{p}$, $\Delta\boldsymbol{c}$ *by execution of* $\boldsymbol{a}$ *and a pointer to* $\boldsymbol{m}_{soa}$,.
$\boldsymbol{m}_{soa}$	*SOA-memory; memory of states of affairs; structure constructed from time-stamped collections of* $\boldsymbol{s}_{e+a,}$ $\boldsymbol{p}$,*and* $\boldsymbol{c}$.
$\boldsymbol{p}$	*percepts*
$\boldsymbol{q}$	*expected percepts*
$\boldsymbol{s}_{e+a}$	*sensory experience; the concatenation of* $\boldsymbol{s}_e$ *and* $\boldsymbol{s}_a$
$\boldsymbol{s}_a$	*autogenous sensory experience*
$\boldsymbol{s}_e$	*exogenous sensory experience*
$\boldsymbol{v}_a$	*autogenous variables*
$\boldsymbol{v}_e$	*exogenous variables*
$\Delta\boldsymbol{x}$	*differences in* $\boldsymbol{x}$*'s before and after a course of event, where* $\boldsymbol{x}$ *is* $\boldsymbol{c}$, $\boldsymbol{p}$, *or* $\boldsymbol{s}_{e+a}$.

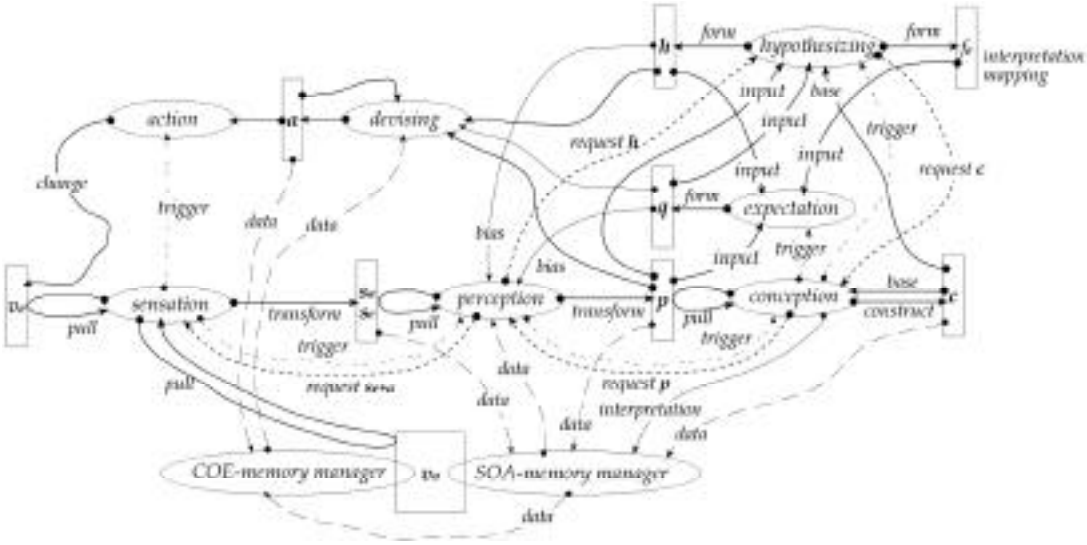

Figure 1. *A framework for concept formation*

3.2.1 Sensation

Sensation is the process of transforming changes in the exogenous variables and autogenous variables into the lowest level of description of the changes, i.e., sensory experiences. The description updates the current sensory experiences, which is a description corresponding to a state of the exogenous and autogenous variables, on the basis of the immediately antecedent sensory experiences and the changes. The sensation process works in two ways, i.e., data-driven and expectation-driven. In the data-driven sensation process, changes in the exogenous or autogenous variables, if some sensors detect them, trigger the transformation of the changes into the changes in the sensory experiences. In the expectation-driven sensation process, if the perception process, described later, expects or requires the sensation process to present a particular pattern of sensory experiences, then the transformation is biased so that some changes in the exogenous or autogenous variables are filtered out, emphasized, or distorted to present the expected sensory experiences. This expectation-driven process is critically important in the development of situations.

3.2.2 Perception

Perception is the process of transforming the changes in the sensory experiences into the changes in the percepts and structuring the current percepts on the basis of the immediately antecedent percepts and the changes in the percepts. Percepts are the intermediate and structured description corresponding to a set of states of the exogenous and autogenous variables. Percepts are, however, not direct projections of the states. They are, rather, acquired as a result of the interaction of sensory experiences and concepts. Sensory experiences are structured as percepts with respect to concepts. The perception processes also work in parallel, i.e., data-driven and expectation-driven. In the data-driven perception process, when some perceptors detect changes in the sensory experiences, the changes are transformed into changes in the percepts. The current percepts are updated on the basis of the past percepts and the changes in the percepts. In the expectation-driven perception process, if the conception process, described later, expects or requires the perception

process to present particular percepts, then the mechanism of the transformation is biased so that some changes in the percepts are filtered out, emphasized, or distorted to present the expected percepts.

3.2.3 Conception

Conception is the process of transforming the changes in the percepts into changes in the concepts and structuring the current concepts on the basis of the immediately antecedent concepts and the changes in the concepts. The conception process continuously interprets the changes in the percepts on the basis of the currently focused parts of the existing concepts and the current interpretation. An interpretation associates parts of the concepts with the percepts just as an interpretation function in semantics associates a language with its referent. One of crucial ideas is that an interpretation is not fixed, rather it is selected from a repertoire. All the concepts do not have to be directly associated with all the percepts, rather it is sufficient that the focused parts of concepts are associated with the relevant parts of the percepts.

Conception is the process of generating, based on the existing concepts, the grounded interpretation of the percepts and of the memories constructed through the agent's interactions with its environment. An interpretation is generated based on an interpretation mapping, from the concepts to the percepts or to the memories, in use. Some concepts are directly generated from the percepts based on an interpretation mapping, some concepts are generated from the memories also based on an interpretation mapping, and the other concepts are derived within concepts themselves. These classes of concepts are associated with each other beyond the classes. The concepts directly generated from the percepts are concept-laden. They are relative to the concepts generated from the memories and the agent's focus on the concepts in the sense that perception is affected by the concepts. The concepts derived within concepts (or derivatives) are either deduced, induced, or abduced from the observations or the derivatives themselves based on the concepts generated from memories. Some derivatives may be required to be verified with respect to further interactions with the environment. Since it is expensive to explore the whole range of possible concepts, portions of the concepts are employed instead of all the concepts to focus on particular aspects. We use the notion of focused concepts to refer to these aspects. By using the notion of focused concepts, it is not necessary to check for coherency and consistency of the entire set of concepts. Choices of focused concepts are performed within a sub-process of conception, which we refer to in the notion of hypothesizing.

The processes of conception and perception are closely related to each other through expectation and hypothesizing. They are autonomous process with their own goals and collectively compose a recursive process.

3.2.4 Perception-Conception Recursion

Here we present the outline of the recursion process that connects perception, conception and hypothesizing, where SOA-memory refers to a memory of the "state-of-affairs" of the agent at that time.

(a) *Perception*

1. Use the current focused concepts and the expected percepts.
2. (Re-)Organize a pair of sensory experiences, i.e., expected sensory experiences, and a transformation from the expected sensory experiences to the expected percepts based

on the current transformation and SOA-memory.
3. Request *sensation* to form the expected sensory experiences (given *sensation* biases).
4. "Pull" the exogenous sensory experiences and the autogenous sensory experiences from *sensation*.
5. Transform the sensory experiences into percepts.
6. Make the current percepts available so that other process can use them.
7. Check if the percepts are nearly in accordance with the expected percepts
   If YES
      then request SOA-memory to construct SOA-memory
      else execute *hypothesizing*
8. Execute *perception* unless a request from other process is sent.

(b) *Conception*
1. Use the current focused concepts and the current interpretation mapping.
2. Select the derivatives from the current concepts.
3. Request *expectation* to form the expected percepts that would support the derivatives on the basis of the current focused concepts and the current interpretation mapping.
4. Request *perception* to form the percepts by taking the current focused concepts and the expected percepts into consideration. (given *perception* biases)
5. "Pull" the percepts from *perception.*
6. Verify if the current focused concepts are consistent with the percepts by using the current interpretation mapping.
   If YES
      then construct concepts on the basis of the existing concepts, the percepts, and the memories
         and request SOA-memory to update memories
      else request *hypothesizing* to form new focused concepts and/or to change interpretation mappings
7. Execute *conception* unless a request from other process is sent.

(c) *Hypothesizing*
1. Use the current concepts, the expected percepts, the current percepts, and the current interpretation mapping.
2. Find the portion of concepts that describes both the expected percepts and the current concepts under the current interpretation mapping.
   If found (re-framing succeeded)
      then make the focused concepts available
      else find an interpretation function
         and if not found (re-interpretation failed)
      then modify the most plausible interpretation mapping
         and execute *conception*
         and execute *hypothesizing*

(d) *Expectation*
1. Use the current focused concepts, the current percepts, and the current interpretation mapping.

2. Form a collection of the possible percepts that are consistent with the current focused concepts with respect to the current interpretation mapping.

3.2.5 Action

Action is the process of changing a state of some of exogenous and autogenous variables. An action is one of concepts corresponding to actuation of the effectors. When an effector is actuated, some exogenous variables and autogenous variables change their values. Some of the changes in these variables are detected by the sensors and activate the sensation process. It is not always the case that the effectors are actuated directly by activation of the sensors. An agent governs the activation of the couplings between the sensors and effectors on the basis of the concepts that the agent forms.

3.3 Phenomena Explained by the Proposed Framework

3.3.1 Emergence of Self-learning Organization

The mechanism described above implies that some processes composing the concept formation process might emerge through the interaction between an agent and the environment.

3.3.2 Reinterpreting a Situation

A situation is usually recognized based on the expectation of that situation. Actions, sensation, perception, and conception are governed in an expectation-driven manner, which is described later. However, sometimes, the expectation-driven processes do not succeed in letting the expected situation be recognized because the biases based on the expectation are not strong enough or the data-driven processes, described later, override the expectation-driven processes.

When an unexpected situation is recognized, it needs to be reinterpreted. The situation is interpreted on the basis of other focused concepts, which are different from the concepts on which the prior expectation is based, or with respect to another interpretation mapping, which is different from the one used for the prior expectation. On the basis of the new focused concepts and with respect to the new interpretation mapping, the current situation is recognized in an expectation-driven manner, again. In addition, the use of the new current focused concepts and the new interpretation mapping is propagated to re-form the concepts. Then, the past situations are reinterpreted on the basis of the re-formed concepts [5].

4. A SEMI-COMPUTATIONAL FRAMEWORK

The previous section explained the proposed framework of concept formation. This section articulates the framework in a slightly more formal manner.

4.1 Variables

Here we show, again, the variables that are used in the proposed framework for the readers' convenience.

$\boldsymbol{a}$	*action candidates*
$\boldsymbol{c}$	*concepts*
$\boldsymbol{h}$	*focused concepts*
$\boldsymbol{m}_{coe}$	*COE-memory; memory of course of events; structure constructed from time-stamped collections of* $\boldsymbol{a}$, $\Delta\boldsymbol{s}_{e+a,}$ $\Delta\boldsymbol{p}$, $\Delta\boldsymbol{c}$ *by execution of* $\boldsymbol{a}$ *and a pointer to* $\boldsymbol{m}_{soa}$,.
$\boldsymbol{m}_{soa}$	*SOA-memory; memory of states of affairs; structure*

	constructed from time-stamped collections of $\boldsymbol{s}_{e+a}$, $\boldsymbol{p}$,*and* $\boldsymbol{c}$.
$\boldsymbol{p}$	*percepts*
$\boldsymbol{q}$	*expected percepts*
$\boldsymbol{s}_{e+a}$	*sensory experience; the concatenation of* $\boldsymbol{s}_e$ *and* $\boldsymbol{s}_a$
$\boldsymbol{s}_a$	*autogenous sensory experience*
$\boldsymbol{s}_e$	*exogenous sensory experience*
$\boldsymbol{v}_a$	*autogenous variables*
$\boldsymbol{v}_e$	*exogenous variables*
$\Delta\boldsymbol{x}$	*differences in* $\boldsymbol{x}$*'s before and after a course of event, where* $\boldsymbol{x}$ *is* $\boldsymbol{c}$, $\boldsymbol{p}$, *or* $\boldsymbol{s}_{e+a}$.

4.2 Processes

4.2.1 Sensation

(a) *Exogenous Sensation Process* (f_{se})

The process transforming $\boldsymbol{v}_e$ into $\boldsymbol{s}_e$: the purpose of this process is to transform the values of the elements composing the sensed environment, i.e., exogenous variables, which are expressed from a viewpoint outside an agent, into elements employed to construct the agent's own view of the environment. It may appear that $\boldsymbol{v}_e$ and $\boldsymbol{s}_e$ are bound by a one-to-one correspondence, but because more than one percept may be the driver, they are bound by a many-to-many mapping so that the transformation makes up any incorrect input from faulty sensors.

An agent may not sense some elements of $\boldsymbol{v}_e$ even if they exist. An agent may bias the value of an element of $\boldsymbol{v}_e$. These effects in exogenous sensation process are caused by an agent's own parameterization of the transformation mechanism. The parameterization is performed through interaction between an agent and its environment.

(b) *Autogenous Sensation Process* (f_{sa})

The process transforms $\boldsymbol{v}_a$ into $\boldsymbol{s}_a$: the purpose of the process is to translate the values of some elements composing an agent, i.e., autogenous variables, which are expressed from a viewpoint inside the agent, into elements being employed to construct the agent's own view of itself. Again, it may appear that $\boldsymbol{v}_a$ and $\boldsymbol{s}_a$ are bound by one-to-one correspondence, but because more than one percept may be the driver, they are bound by a many-to-many mapping so that the transformation makes up the incorrect input from faulty sensors.

An agent may not sense some elements of $\boldsymbol{v}_a$ even if they exist. An agent may bias the value of an element of $\boldsymbol{v}_a$. These effects in exogenous sensation process are caused by an agent's own parameterization of the transformation mechanism. The parameterization is performed through interaction between an agent and its environment or through some mechanism inside the agent.

4.2.2 Perception and Conception

(a) *Perception* (f_p)

Perception is a process of forming percepts from sensory experiences. Perception also involves a goal-driven top-down process as well as a data-driven bottom-up process. The goal of perception is to derive the percepts from sensory experiences that fulfill the requirements given by conception. As described above, perception is not a process independent of conception. Percepts, which are taken as the input by conception, are not independent of conception, either. In this sense, perception and conception form a set of parallel processes that are modeled recursively.

The process transforms $\boldsymbol{s}_{e+a}$ into $\boldsymbol{p}$ on the basis of $\boldsymbol{h}$, $\boldsymbol{q}$ and $\boldsymbol{m}_{soa}$. $\boldsymbol{m}_{soa}$. is employed to find the past conversions from $\boldsymbol{s}_{e+a}$ to $\boldsymbol{p}$. Where $\boldsymbol{s}_{e+a}$, sensory experiences, is the concatenation of $\boldsymbol{s}_e$ and $\boldsymbol{s}_a$.

The conversions of $\boldsymbol{s}_{e+a}$ are not necessary the same even with the same $\boldsymbol{s}_{e+a}$ since the result is affected by some factors such as the current focused concepts, $\boldsymbol{h}$, and the expected perception, $\boldsymbol{q}$, which comes from another process, .i.e., expectation.

Perception is a process that converges when $\boldsymbol{p}$ is nearly equal to $\boldsymbol{q}$. Some parameters in the transformation are biased by $\boldsymbol{h}$ and $\boldsymbol{q}$.

(b) *Conception* ($f_{\boldsymbol{c}}$)

Conception is composed of both a data-driven bottom-up process and a goal-driven top-down process. Conception is data-driven and bottom-up in the sense that the result of the process, i.e., concepts, $\boldsymbol{c}$, are formed through transformation of percepts, $\boldsymbol{p}$. One goal of conception is to produce and maintain coherent and consistent concepts, or groupings of concepts, based on the concepts that an agent already has and the memories constructed through the experience of sensation, perception, conception, and action. Conception is goal-driven and top-down in the sense that the process "pulls" expected percepts from the perception process. To achieve the goal of maintaining the coherence and the consistency of the concepts, the interpretation mapping and/or the focused concepts are changed. The process, recursively, revises $\boldsymbol{c}$ on the basis of the antecedent $\boldsymbol{c}$, the current $\boldsymbol{p}$, the last $\boldsymbol{a}$ and $\boldsymbol{m}_{soa}$.

One of the purposes of conception is to give meaning to the current percepts and to maintain and update concepts composed of grounded interpretation and understanding of the percepts. Intuitively, concepts describe an agent's belief about the environment and the relations between the agent and that environment. The relations are extracted from the history of the interaction between the agent and the environment stored in SOA-memory and course-of-events-memory (COE-memory). The relations are composed of the causal relations among the elements of percepts, the causal relations between action and the percept change caused by it, and the applicability of actions with respect to the percepts before the actions.

(c) *Expectation* (f_e)

Expectation plays a role of forming expected percepts, $\boldsymbol{q}$. Percepts expected to be taken by conception, $\boldsymbol{q}$, are derived from the current focused concepts, $\boldsymbol{h}$, by the current interpretation, i.e., mapping from concepts to percepts. The current interpretation is dependent on conception. The mapping could be replaced by another mapping in the repertoire to maintain the coherence of the current focused concepts, $\boldsymbol{h}$, which subsumes the concept, $\boldsymbol{c}$, with respect to the percepts, $\boldsymbol{p}$. Expectation is a goal-driven process whose goal is to derive the expected percepts from the current focused concepts, $\boldsymbol{h}$, that are accordant to the current percepts, $\boldsymbol{p}$, derived from sensation by changing the interpretation mappings. The process derives $\boldsymbol{q}$ from $\boldsymbol{p}$, $\boldsymbol{h}$, and $\boldsymbol{a}$.

The purpose of the expectation process is to predict, on the basis of the current focused concepts, the succeeding percepts if a certain action is performed in the environment perceived.

(d) *Hypothesizing* ($f_{\mathbf{f}}$)

Hypothesizing is a sub-process of conception. Its main role is to retrieve from the existing concepts, or to generate, the portions of the concepts that ought to be focused on, $\boldsymbol{h}$, and to find the interpretation mapping in the repertoire to satisfy the coherence and the consistency of the focused concepts, $\boldsymbol{h}$, with respect to the current percepts, $\boldsymbol{p}$. The process activates portions of $\boldsymbol{c}$ on the basis of $\boldsymbol{p}$ and $\boldsymbol{q}$, and returns the portions as $\boldsymbol{h}$.

The purpose of hypothesizing is to highlight portions of concepts that explain the percepts acquired through perception and the difference between these percepts and the percepts previously expected (and to construct possible percepts). Intuitively speaking, $\boldsymbol{h}$ represents the currently focused parts of $\boldsymbol{c}$. By taking hypothesizing into consideration, we try to represent two ideas. One is that percepts transformed from the same sensory experience could differ if the focused concepts differ. The other is that different actions are performed in the same environment if the focused concepts differ in two cases although the environment is perceived as the same.

One trigger of hypothesizing is the gap between the current percepts and the previously expected percepts that cannot be resolved in perception. When hypothesizing occurs because of this trigger, construction of the updated focused concepts upon perception is triggered. Reinterpretation of the trail of perception is performed here. Another trigger of hypothesizing is the revision of concepts.

4.2.3 Memory Management

(a) *SOA-Memory Construction* ($f_{mc\text{-}soa}$)

This process constructs $\boldsymbol{m}_{soa}$ by adding the result of the current sensory experience, perception, and conception, i.e., $\boldsymbol{s}_{e+a}$, $\boldsymbol{p}$, and $\boldsymbol{c}$, with time-stamp to the antecedent $\boldsymbol{m}_{soa}$. The purpose of SOA-memory construction is to store information about a state of affairs described as the bindings among sensory experiences, perception, and conception, and retrieve the past memory in some form to be useful for retrieval of similar bindings in the future. Newer bindings with respect to time are stored as they are obtained. As bindings become older, they are abstracted and generalized.

(b) *COE-Memory Construction* ($f_{mc\text{-}coe}$)

This process constructs $\boldsymbol{m}_{coe}$ by adding a pointer to the result of the current sensory experience, perception, and conception, i.e., $\boldsymbol{s}_{e+a}$, $\boldsymbol{p}$, $\boldsymbol{c}$, action performed according to $\boldsymbol{a}$, and the changes caused and brought about by execution of $\boldsymbol{a}$, i.e., $\Delta\boldsymbol{s}_{e+a}$, $\Delta\boldsymbol{p}$, $\Delta\boldsymbol{c}$, with time-stamp to the antecedent $\boldsymbol{m}_{coe}$.

The purpose of COE-memory construction is to store information about a course of events, such as actions, described as a state of affairs and its changes caused and brought about by the events occurring in the state, for retrieval of similar cases in the future. Newer bindings with respect to time are stored as they are obtained. As bindings become older, they are abstracted and generalized.

(c) *SOA-Memory Retrieval* ($f_{mr\text{-}soa}$)

Memory retrieval might affect other processes as follows:

(1) *perception-bias*: when the current sensory experience is similar to past $\boldsymbol{s}_{e+a}$, the past bindings between $\boldsymbol{s}_{e+a}$ and $\boldsymbol{p}$ bias the current bindings so that percepts would be similar to the past $\boldsymbol{p}$ if it led to a good result.

(2) *conception-bias*: when the current percepts are similar to past ***p***, the past bindings between ***p*** and ***c*** bias the current bindings so that concepts would be similar to the past ***c*** if it led to a good result. Or, if an agent gets stuck with the concepts obtained without conception-bias, the agent seeks past ***p-c*** bindings whose ***p*** is similar to the current percepts.

(d) *COE-Memory Retrieval* ($f_{mr\text{-}coe}$)
Memory retrieval might affect other processes as follows. In this process, one issue is how to define similarity.
(1) *devising-bias*: when the current concepts are similar to past ***c***, the past bindings between ***c*** and ***a*** bias the current bindings so that action would be similar to the past ***a*** if it led to a good result.

(e) *Memory Introspection* (f_{mi})
If the current focused concepts are replaced so as to reinterpret the current percepts, SOA-memory and COE-memory are adjusted to reflect new concepts.

4.2.4 Action

(a) *Devising* (f_a)
This process derives ***a*** on the basis of the current conception of the environment, i.e., ***h***, the current ***p***, and the antecedent ***a***.

The purpose of the process is to enumerate applicable and promising actions with respect to the current focused concepts of the environment. Different actions are enumerated under the same perception if the current focused concepts are different. The history of enumeration, which is contained in the antecedent ***a***, affects the enumeration. This effect may represent that a succeeding action is constrained by the course of prior actions.

Whether an action is applicable and promising may depend not only on ***p***, ***h***, and ***a*** but also on a prior goal and current sub-goals that an agent has. It is under consideration how to deal with goals.

(b) *External Effect* (g_{ae})
This process updates, $\boldsymbol{v}_e$ on the basis of ***a***. The purpose of the process is to represent the environment transition corresponding to actions performed by an agent. It is given as a function composing the structure of an agent in which elements of exogenous variables replace their value.

(c) *Internal Effect* (g_{aa})
This process updates $\boldsymbol{v}_a$ on the basis of ***a***. The purpose of the process is to represent a part of agent's internal state change corresponding to actions performed by the agent. It is given as a function composing the structure of an agent in which elements of autogenous variables replace their value. It should be considered whether this process also affects memory.

5. CONCLUSION

This paper has proposed a framework for concept formation. The primary characteristics of the framework are:

- distinction of exogenesis and autogenesis in concept formation and
- articulation of the interaction between an agent and the environment as the processes of sensation, perception, conception, and action.

One way to evaluate the proposed framework of concept formation is as follows. If identical agents are exposed to different environments over a specified time sequence, then the agents might form different concepts. If agents have different concepts, then they would interact in different ways when exposed to the same world at a later time. Those interactions, if different, would support our hypothesis about the situatedness of concept formation.

Acknowledgments

This work has been supported by an Overseas Postgraduate Research Award and an Australian Research Council grant .

REFERENCES

[1] Clancey, W. *Situated Cognition,* Cambridge University Press, Cambridge, 1977.

[2] Suwa, M., Gero, J. S. and Purcell, T. Unexpected discoveries and s-inventions of design requirements: A key to creative designs, *in* J. S. Gero and M. L. Maher (eds), *Computational Models of Creative Design IV*, Key Centre of Design Computing and Cognition, University of Sydney, Sydney, Australia, 1999, 297-320.

[3] Russell, s and Norvig, P. *Artificial Intelligence,* Prentice-Hall, New Jersey, 1995.

[4] Gero, J. S. Towards a model of designing which includes its situatedness, *in* H. Grabowski, S. Rude and G. Grein (eds), *Universal Design Theory*, Shaker Verlag, Aachen, 1998, 47-55.

[5] Gero, J. S. Recent design science research: Constructive memory in design thinking, *Architectural Science Review*, 1999; **42**(2): 97-99.