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Embodied concept formation and reasoning via neural-symbolic integration

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A R T I C L E I N F O

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A B S T R A C T

Modern cognitive science [1] indicates that concepts stem from individual experience, which more concretely means that an agent's concept system is generated by interactions between an agent's body and the environment it lives in. In this study we present an approach that will enable Artificial Brains to generate embodied conceptual systems, including a sophisticated introspection mechanism that will allow them to transcend their initial conceptual limitations. Our approach is based on extensions to formal concept analysis. We use incomplete formal contexts to represent the sensorimotor information of the "body" of an Artificial Brain, and then use uncertain formal concept analysis as a mathematical tool to settle various problems related to embodied concept formation. After proving some theorems, we show that 3-valued Lukasiewicz logic is the right instrument for our purpose, overcoming the shortcomings of the existing methods. We also describe how to use neural-symbolic integration to allow this sort of approach to provide not only advanced AI functionality but also approximate simulation of aspects of human brain function.

1. Introduction

"*Concepts*" are vital in every aspect of human intelligence, so the ability for concept formation and the power of reasoning based on concepts are among the most important functions that human brain has. Therefore, concept formation and inference have deep significance for artificial general intelligence (AGI) [2], especially for the construction of Artificial Brains which are intended to display human-level intelligence with autonomy and self-awareness abilities, in a manner more or less closely inspired by human brain function.

In recent decades an increasing community of cognitive scientists has moved from regarding "cognition" as operations over a set of abstract formal symbols to considering it as a situated activity, realizing that "concepts" are not only a matter of "mind", but also of "environment"[1] as well as "body". All the three [2] play important roles in the process of concept formation. It has also become clear that individual experience plays an important role in the process of forming concepts, which helps explain why individuals with similar perceptual dynamics can form such distinct conceptual systems.

But nevertheless, the formal symbolic approach to concept formation and to cognition is powerful. The motivation underlying the current research is to explain how a traditional formal approach to concepts, i.e. formal concept analysis (FCA) [3], can be extended to encompass a broad philosophical view of concepts, that incorporates their entwinement with body and environment.

In modern philosophical circles, Representational Theory of Mind and Semantic Theory of Concepts [4] are the most influential approaches to formalizing the nature of concepts. The former holds that concepts are mental representation, whereas the later considers them as an abstract objects. Though there are differences between these two approaches, they both agree that concepts have two logical features: intent and extent. The intent of a concept is the innate characters of the objects reflected by the concept; while the extent means all the objects satisfying the concept. For any concept: more intent implies less extent, and vice versa.

Based on this viewpoint, Wille from Darmstadt University in Germany proposed Formal Concept Analysis. In essence, FCA uses lattice theory to formalize the relationship between "intent" and "extent", and then to investigate the relations between concepts thus formalized. In the first period after FCA was born, most of the relevant research was concentrated on mathematics, providing a solid theoretical foundation for FCA. In the last 10 years, people from computer science [5] and information science [6] have shown greater and greater interest in FCA, creating a body of work applying FCA to knowledge representation and Ontology building.

Attribute exploration, a method of knowledge acquisition based on FCA, allows a system to enrich its knowledge base in an interactive manner. Note that the interactive aspect means the development of knowledge base of such a system can be controlled; we can manipulate the process and get the result we

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[1] The meaning of "environment" is quite general, and social environment (context) are also covered.

[2] Mind, body and environment.

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want to some extent. This is similar to education in human society.

Most research related to FCA depends on the hypothesis of that the possession of an attribute by an object is crisp: either an object has an attribute, or not. But from a more realistic perspective, it sometimes makes more sense to admit the imperfection of knowledge. When facing the complex real world, it is impractical to expect that any individual has complete knowledge. In the present paper, we take the incomplete nature of an intelligent agent's information as a basic assumption.

We are also interested in a more brain-like way of achieving what FCA does. This is a special case of the more general problem of how to use brain-like structure to achieve mind-like functions. In the AI field, the former is represented by neural networks, while formal, symbolic methods attempt to embody the latter. For many decades these two AI approaches were considered as opposed, but in recent years, the neural-symbolic integration [7,8] has attracted considerable attention.

Based on the foregoing considerations, the fundamental premises of this research are as follows:

- Embodiment must be emphasized. Body, mind and environment play important, interlocking roles in the process of concept formation, which means concept formation is also a process of embodied learning.
- "Concepts" should not be *specified* by any Artificial Brain designer in any way, but be *formed* in the continuous interactions between the body of the Artificial Brain and the environment it lives in.
- The process of concept formation should be spontaneous, while the resulting concept system within an Artificial Brain must be similar to the human conceptual system in some sense.[3]

In brief, the purpose of this study is to describe a mechanism enabling an Artificial Brain to form an embodied concept hierarchy, with a partial isomorphism to the human concept system. To achieve this goal, we use incomplete formal contexts to represent the sensorimotor information of the "body" of the Artificial Brain, which means uncertain FCA is taken as the mathematical tool to settle the problems related to concept formation. After proving some theorems, we show 3-valued Lukasiewicz logic is a useful instrument in this context, overcoming some shortcomings of existing FCA techniques. Borrowing the idea of "attribute exploration," we explain a notion of introspection, which will allow an Artificial Brain to transcend the self-imposed limitations of its initial concept system. Finally, we explain how to use neural-symbolic computing to implement these ideas, thus more fully bridging the "mind-brain gap".

The rest of this paper is organized as follows: in Section 2, we introduce some basic concepts regarding FCA and uncertain FCA; in Section 3, we present our approach to formal embodied concept formation. In Section 4, we show that 3-valued Lukasiewicz logic is an appropriate mathematical tool to handle relevant problems by proving some theorems; in Section 5, we argue that the Core method and Stenning and Lambalgen's immediate consequence operator, which translate the concept represented by the 3-valued logic into a connectionist model, can help an Artificial Brain do certain inference tasks in a humanlike manner.

[3] From the practical point of view, there must be an intersection between Artificial Brain and human conceptual systems, and the intersection enables Artificial Brain and human to interact with each other. But from the theoretic perspective, the intersection is surely not necessary since Artificial Brain can produce concepts that are based on its unique hardware that is not available to humans.

2. Preliminaries

2.1. Uncertain FCA and incomplete formal context

Uncertain formal concept analysis stems from FCA [3], the major difference between them regards the notion of formal context. In FCA, a formal context is a triple $\mathbb{K} := (G,M,I)$, in which G,M are two sets: G represents an object set, M represent an attribute set, and I is the relationship between the sets. For $g \in G, m \in M$, we use $(g,m) \in I$ or gIm to denote that object g has attribute m.

Some important definitions [3] for FCA are introduced as follows:

Definition 1. Given a formal context $\mathbb{K} := (G,M,I)$, let $X \subseteq G, Y \subseteq M$, two derivation operators are defined as

$$f(X) := \{m \in M | \forall g \in X, (g,m) \in I\}$$

which describes a set of attributes possessed by all objects from set X, and

$$g(Y) := \{g \in G | \forall m \in Y, (g,m) \in I\}$$

which is a set of objects, and those objects have all the attributes in set Y.

Definition 2. A formal concept is a pair $C := \langle A,B \rangle, A \subseteq G, B \subseteq M$ over $\mathbb{K} := (G,M,I)$, where $f(A) = B$, and $g(B) = A$. We call A the "extent" of the concept and B the "intent". For 2 formal concepts $C_1 := \langle A_1,B_1 \rangle, C_2 := \langle A_2,B_2 \rangle$, we say C_1 is a super-concept of C_2 if $C_2 \subseteq C_1$ (or $B_1 \subseteq B_2$). By contrast, we say C_2 is a sub-concept of C_1.

The simplest and most intuitive method for representing FCA is using a table. In such a table, every row represents an object, while every column represents an attribute. e.g. if we have a mark "+" in the cross of the row i and the column j, it means object i has attribute j. On the contrary, if the mark is "$-$", this means that the object i does not have attribute "j", i.e. $(g,m) \notin I$.

The major difference between an incomplete formal context [9] and a traditional formal context is the expression on $(g,m) \notin I$. An incomplete formal context is built on a formal context, dividing $(g,m) \notin I$ into the following two cases:

1. object g does not have attribute m;
2. whether g has attribute m is not known;

So, an incomplete context $\mathbb{K}\mathbb{I} := (G,M,\{+,?,-\},J)$ can be considered as a 3-valued context which consists of a set M of attributes and a set G of objects, the set $+,?,-$ of values, and a mapping $J : G \times M \to \{+,?,-\}$. For every $g \in G, m \in M, J(g,m) = +$ means the object g has the attribute; $J(g,m) = -$ means the object does not have the attribute and the question mark means we do not know whether the object has the attribute or not.

Obviously, based on this change, in the incomplete context $\mathbb{K}\mathbb{I} := (G,M,\{+,?,-\},J)$, the derivation operators defined in Definition 1 should be revisited.

Definition 3. $\mathbb{K}\mathbb{I} := (G,M,\{+,?,-\},J)$ is an incomplete formal context, and let $X \subseteq G, Y \subseteq M$.

- $f^{J\Box}(X) := \{m \in M | \forall g \in X, (g,m,+) \in J\}$,
- $f^{J\Diamond}(X) := \{m \in M | \forall g \in X, (g,m,-) \notin J\}$,
- $g^{J\Box}(Y) := \{g \in G | \forall m \in Y, (g,m,+) \in J\}$,
- $g^{J\Diamond}(Y) := \{g \in G | \forall m \in Y, (g,m,-) \notin J\}$,

where $g^{J\Box}(Y)$ is the set of all objects which certainly have all attributes of Y, and the possible extent $g^{J\Diamond}(Y)$ is the set of all objects which possibly have all the attributes of Y. $f^{J\Box}(X)$ and $f^{J\Diamond}(X)$ are defined analogously.

A simple explanation of the definitions is given in Table 1.