COMPUTATIONAL ANALOGY-MAKING IN DESIGNING: A PROCESS ARCHITECTURE

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Abstract. This paper presents a model of computational analogy-making in designing based on the notion of situated similarity. Situated similarity is the idea that the relationship between two concepts is dependent not only on what the agent knows about those concepts but also on the way the agent is looking at them. Analogy-making is modelled as three interacting processes: formulation, matching and mapping. The model is developed and then its implications for developing situated analogy-making systems in design are discussed.

Keywords. Analogy-making; situatedness; similarity; designing.

1. Introduction

1.1. ANALOGY-MAKING IN DESIGNING

Analogical thinking (Gentner 1983, Kokinov 1998) pervades the design process. During designing, analogies are made between the designer's experiences and the current design task. These analogies enable reformulation of the current design space to accommodate existing knowledge applied in a new way. Analogies are also made between elements within a design problem, constructing relations between structure elements that provide new design constraints. Designers also use analogical reasoning to develop an understanding of new design tasks by viewing the unfamiliar in terms of the familiar. As Computer-Aided Design becomes more intelligent (Gero 2002) it becomes important to integrate computational models of design thinking into design tools. Such design tools will benefit from being able to reason analogically; this computational model is a step towards improving such capabilities.

1.2. SITUATEDNESS

The theory of situated cognition (Clancey 1997) claims that all of human thought and behaviours are adapted to their environment, or "situated". This claim is based on the idea that perception, conceptualisation and action are developed concurrently. An agent's situation is its interpretation of its environment and itself in that environment at that time. This notion of situation differs from the notion of "context" as an agent can intentionally re-represent its situation; it can construct a different situation and give a different perspective to its stimuli. Figure 1 illustrates this graphically: the image is either a white vase or a pair of faces depending on the figure/ground distinction imposed by the viewer's situation (Gero 2003).

Figure 1. Multiple interpretations: alternately a white vase or two black faces.

Designing is a situated act (Gero 2003) and a designer's actions change the world, which leads to a need to observe and interpret the effect of those actions, which in turn leads to further acts. The result of this cycle is that the conceptual domain of a design task changes rapidly, with the meanings of concepts changing and concepts entering and leaving the agent's focus. A model of analogy-making in designing must be robust to changing situations.

1.3. THE FBS ONTOLOGY OF PROCESSES

This paper uses the function-behaviour-structure (FBS) ontology as applied to processes (Gero and Kannengiesser 2006) to represent the process of analogy-making. The FBS model was originally developed to represent designed objects in terms of what they are for (their function), what they do (their behaviour) and what they are composed of (their structure). In the FBS view of processes, the notions of function and behaviour are directly transferable. The structure of a process requires three components (input, transformation and output) and two connections (input to transformation and transformation to output). Figure 2 shows the structure of a process in the FBS Process ontology.

Figure 2. The structure of a process (Gero and Kannengiesser 2006).

The input component to a process is the set of properties of other entities on which the process acts. The output component to a process is a set of properties that are produced or edited by the process. An object present in both the input and output of a process is affected by the transformation. The transformation component is a set of actions for transforming the input into the output. This is typically represented as a set of subordinate processes that can, in turn, be modelled in terms of their function, behaviour and structure (Gero and Kannengiesser 2006).

2. Concepts Underlying the Model

2.1. SITUATED SIMILARITY

Situated similarity is the notion that the relationship between two concepts is dependent on the situation in which the concepts are being compared. Models exist in which similarity is modelled as overlapping feature sets (Tversky 1977) and distances in conceptual space (G rdenfors 2000). These models do not centralise the idea that similarity is subjective to the perspective of the observer. A model of situated similarity would be able to adopt different interpretations of, and relationships between, objects that are being compared. Figure 3 is an example of two objects between which multiple possible relationships exist, and (as in Figure 1) the interpretation is determined by the viewer's situation.

Figure 3. Multiple associations: A box of matches (a) and a swarm of bees (b).

If the objects in Figure 3 are compared in a situation that involves shape, colour, size or another structural concept, it is immediately clear that bees and matches are dissimilar. Alternatively, if both objects are interpreted as resources then it is possible to conclude that they are similar in that they are both useful in cooking, or in the production of candles. The objects could also be viewed as harmful, in which case they are related by their shared ability to cause small and painful injuries. A situated model of similarity would allow an agent to construct these relations.

This research distinguishes between similarity relationships and associations. Similarity is defined by the situation in which you are considering two objects and is constructed when the objects are considered. Conversely, an association is a concept that is formed by reflective reasoning about a similarity relationship. In the model of analogy presented in Section 3, similarity relationships that are of interest to the agent attract attention and can cause associations to be constructed.

2.2. FORMULATION IN ANALOGY-MAKING

The model of analogy-making presented in this paper incorporates the process of formulation as the means by which situations are constructed. Formulation interacts with the other processes in analogy-making to model the effect of the situation on interpretation, similarity and attention. Formulation can occur throughout the analogy-making attempt; the situation can be reformulated in response to other parts of the process. Situated analogy-making can be viewed as the process of constructing a situation such that two previously unrelated concepts can be viewed as analogous.

Existing models of analogy-making (Gentner 1983, Hofstadter and Mitchell 1994, Holyoak & Thagard 1995 and Kokinov 1998) contain two stages; the search for a source (matching) and the creation of a map (mapping). The model presented in this paper incorporates a third process, formulation, that affects the behaviour of the matching and mapping processes.

3. A Computational Model of Situated Analogy-making

3.1. ANALOGY-MAKING

3.1.1. Function

The function of analogy-making is the creation of knowledge about a target concept.

3.1.2. Behaviour

As a computational process, analogy-making exhibits the behaviours of computation time, memory requirements and convergence/divergence. In analogy-making, convergence is the degree to which the process settles on one possible analogy. Convergence can be measured by the relative times taken to produce analogies or by the number of different analogies produced by the system. An analogy-making attempt that produces one highly valued analogy can be said to be highly convergent. An attempt that produces many possible analogies of similar value can be said to be highly divergent.

3.1.3. Structure

The structure of the process of analogy-making is shown in Figure 4.

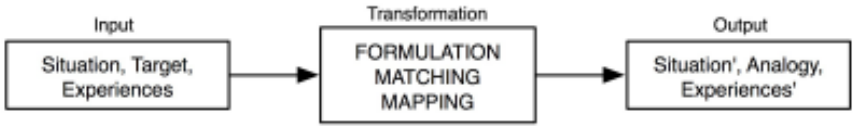

Figure 4. The FBS structure of analogy-making.

Analogy-making has three inputs: a target concept, a situation and the agent's experiences. The target concept is the entity with which an analogous association is being sought. The situation is the manner in which the agent is observing its world, in this case how it was doing so at the start of the analogy-making attempt. The agent's experiences are its knowledge of the past applied to the present (Gero 2003).

The transformation that occurs in analogy-making consists of three subordinate processes; formulation, matching and mapping. Formulation is the process of constructing the way in which an agent observes its world; its situation. Matching is the process by which potential source objects are discovered and associated with the target. Mapping is the construction of associations between elements of the source and the target, the transfer of knowledge between them and the evaluation of the associations that are produced.

Analogy-making outputs a new analogy, a changed situation and a changed body of experiences. In this model an analogy consists of an interpretation of a source object, an interpretation of a target object and a set of associations that exist between them. The situation at the end of the process will have changed as a side-effect of making the analogy and that change may affect future behaviour. The experiences of the agent contain knowledge about the target that reflects what has been transferred from the source.

3.2. FORMULATION

3.2.1. Function

The function of formulation in analogy-making is to construct the situation in which the agent is making an analogy and affect the way that concepts are related.

3.2.2. Behaviour

Like analogy-making, formulation exhibits the behaviours of computation time, memory size, convergence and divergence. Convergence and divergence in formulation relate to the number of possible ways of looking at the world the agent can currently formulate.

3.2.3. Structure

The structure of the process of formulation is shown in Figure 5.

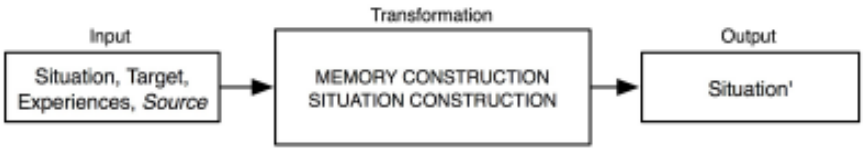

Figure 5. The FBS structure of formulation.

The inputs to formulation match those of analogy-making; a target, a situation and experiences. The inputs may also include a source if the formulation (in this case, reformulation) is occurring after successful matching. The target object impacts the way the agent will look at its world. The situation input is initially the situation that exists before the analogy-making begins, but it may be an already-formulated situation that is being re-constructed during the process. The agent's experiences are a source of knowledge that will impact how it views the world.

The transformation of the above inputs into a situation involves two processes; memory and situation construction. Memory construction produces a memory in response to a cue from the situation. The memory may encode knowledge that affects the way the situation is formulated and the way the agent is interpreting particular concepts. The process of situation construction creates and/or modifies the set of expectations and assumptions that constitute the situation. This produces a new perspective from which the agent can interpret its environment.

Formulation outputs a situation that has been constructed to represent the agent's new world view. The changed situation influences the interpretations and relationships between concepts involved in matching and mapping.

3.3. MATCHING

3.3.1. Function

The function of matching in analogy-making is to discover potential source concepts that may be able to be used in an analogy with the target.

3.3.2. Behaviour

Matching exhibits the behaviours of computation time, memory size, convergence/divergence and congruence with the situation. Convergence in matching is the degree to which a single potential source is chosen, while divergence is the number of competing possible sources or the number of possible associations with a particular source. Congruence in matching is the degree to which the process reflects the expectations of the situation; a matching process that produces an unexpected or surprising result is not congruent with the situation.

3.3.3. Structure
The structure of the process of matching is shown in Figure 6.

Figure 6. The FBS structure of matching.

Matching takes two inputs, the target object to be matched and the situation in which the matching occurs. The target is a concept with which an association is to be created. The situation is a set of expectations about the world that shape the way association occurs. It is possible for matching to occur when a source has already been chosen, an example being if two objects are presented to an agent and it is given the task of comprehending the relationship between them. In this case matching produces an association between the chosen concepts.

The transformation involved in the matching process is composed of three processes that interact to produce novel associations: interpretation, attention and association. Interpretation is the process by which the agent changes the meaning of a concept (in the current situation) by constructing a different interpretation of it. Interpretation and the situation influence how the similarity between concepts is constructed. The processes within matching interact iteratively; interpretation can reveal new similarities causing the focus of attention to change, causing new associations and further re-interpretation.

Attention is the process by which the agent selects which similarity relationships are to be constructed into associations and accordingly what concept is chosen as a source. Attention is paid to relationships that the agent finds interesting, with interest being modelled as a combination of potential utility, novelty and other situated motivations (Saunders and Gero 2001). Association is the process of constructing a concept about a relationship that exists between a target and another concept, which becomes the source.

Matching outputs a new association, a source and a target. The interpretation of the target will have changed to reflect the selected source.

3.4. MAPPING

3.4.1. Function

The function of mapping in analogy-making is to create new knowledge by transferring knowledge from the source to the target.

3.4.2. Behaviour

Mapping exhibits the behaviours of computation time, memory size, convergence/divergence and congruence with the situation. Convergence and divergence in mapping relate to the number of facts about the source that can be transferred to the target. Congruence in mapping is the degree to which the resulting reinterpretations and transfers reflect the situation.

3.4.3. Structure
The structure of the process of mapping is shown in Figure 7.

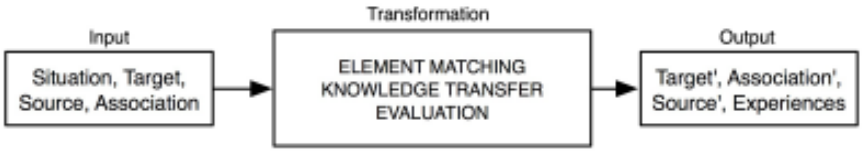

Figure 7. The FBS structure of mapping.

Mapping takes as its input the situation and the outputs of matching: a target, a source and an association between them. Mapping develops the association between the analogues and then attempts to transfer knowledge between them.

Element matching is the search for properties of the target that can be associated with properties of the source. It is conducted after matching has produced an association between the source and target concepts, but is itself a form of matching. The search for which element of the source corresponds with a chosen element of the target is a matching process, with the chosen element becoming a new "sub-target". In element matching the existing association between the source and target influences the process through the situation.

Knowledge transfer involves the reinterpretation of the target to reflect knowledge deduced via its association with the source. What is transferred is dependent on what elements have been matched and what is known about those elements of the source. Once the interpretation of the source incorporates transferred knowledge the analogy can be evaluated. An analogy's value can be determined by whether it has enabled the transfer of knowledge that is useful to the agent's goals.

Mapping produces a reinterpreted target, a changed set of associations, a (potentially reinterpreted) source and a set of new experiences reflecting what the agent has learnt from the potential analogies that were produced.

4. Conclusions

This paper has produced a model for situated analogy-making that is based on three processes: formulation, matching and mapping. The argument is made that situated analogy-making will be of benefit for computational analogy-making systems used in designing.

The model incorporates the formulation of situations into analogy-making. The model of similarity presented makes relationships between concepts subjective to the agent's situation. The model introduces the idea that the analogy making system's interests and motivations are situated in its experiences. The model puts forward the notion that the process of mapping between elements of the target and a chosen source can be represented as a matching process operating on a sub-target.

Future work is necessary to produce a computational architecture for the model presented here and to investigate its application to the field of computational design assistants.

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