A SITUATED APPROACH TO ANALOGY IN DESIGNING

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Abstract. Reasoning by analogy, applied into designing, is investigated from the perspective of situated cognition. This cognitive paradigm emphasizes the importance of the environment in which a particular cognitive task is performed. The paper describes a computational system for situated analogy in designing.

1. Introduction

The situated cognition paradigm that has been advanced in cognitive psychology claims that it is better adapted to interpretation and modeling of reasoning processes than the descriptive one. Research presented in this paper investigates analogical reasoning applicable in designing from the perspective of situated cognition. The methodology of this research involves devising a computational system whose behaviour is based on the situated paradigm. It is expected that such a system should more adequately, in comparison to non-situated ones, model design reasoning by analogy.

2. Conceptual Threads

A number of conceptual threads from the domains of design studies and cognitive studies contributed in establishing the conceptual basis of this work. Design studies have provided the main model of the design process using the function-behaviour-structure (FBS) framework as well as the situated hypothesis of design grounded in recent protocol studies, while the computational model of analogy along with the concept of constructive representation have come from cognitive studies. These have been brought together to develop a unified computational approach to situated analogy in design.

1.1. MODEL OF DESIGN

The model of design that has been utilized in this work was proposed by Gero (1990). In this approach the design process is considered as the task of producing a description, D, of the structure, S, which responds to functional requirements, F, through expected behaviours, B. In order to accomplish these design tasks one has to define the mapping between these three states. In such a framework it can be said that a design is represented as a triplet composed of those three states: function, behaviour and structure (FBS). The FBS triplet can also be defined as causal and abductive knowledge, since it represents a mapping between the design structure onto a set of behaviours that such a structure presents and onto a set of functions that can be attributed from the behaviours, and vice-versa. The use of this model provides an opportunity to represent any design as a graph of relations between states. Throughout the rest of this paper making a "design representation" means creating a graph of transitions between these three states.

1.2. COMPUTATIONAL MODEL OF ANALOGY

We use the computational model of analogical reasoning proposed by Gentner (1983), called "structure mapping theory". In its very simplified form, structure mapping theory claims that an analogy can be drawn between two compatible relational structures represented as a graph of relations. In this approach the basis for drawing an analogy in not a surface similarity but the compatibility of sets of underlying relations.

1.3. CONCEPT OF SITUATEDNESS

The theory of situated cognition, as presented by Clancey (1997), claims that every human thought and action is adapted to the environment, that is, situated, because what people perceive, how they conceive of their activity, and what they physically do develop together.

This approach formulates a specific concept of knowledge representation and long term memory. In the non-situated paradigm phenomena are represented in long-term memory as fixed, self-contained chunks of knowledge that can be uniquely addressed and retrieved. The essential characteristic of the storage-retrieval model of memory is that knowledge is stored statically. The content of the memory is valid without any relation to the ongoing process of reasoning.

On the other hand in the situated perspective, representations are built along with the reasoning process. As a consequence a different model of long-term memory is necessary to accommodate such variability, such model is called a "constructive" model. Clancey (1991) summarizes Rosenfield's (1988) findings about human memory, concluding that memory does not consist of addressable, localizable, retrievable structures (stored representations). Rather, memory gives the capability to produce structures, called representations.

1.4. DESIGN IN SITUATED PERSPECTIVE

Gero (1998) proposes that situatedness can be seen as a means by which a designer changes the trajectory of the developing design. He has noticed that “the particular behaviour and structure variables are not only chosen a priori but are produced in response to the various situations as they are encountered by the designer”. Schön (1983) has also presented the phenomenon of reshaping design concepts during the process of designing. Here, the designing process is seen as a conversational activity between the designer and the physical expression (representation) of his/her design ideas. Schön called this process “reflection-in-action”.

3. Situated Analogy in Design

3.1. CAPTURING THE “SITUATION”

The paradigm of knowledge representation plays a vital role in situating a reasoning process. Knowledge representation that allows situating of the process must accommodate situation dependant variability. This problem can be demonstrated, Figure 1, by the following example given by Partridge (1996).

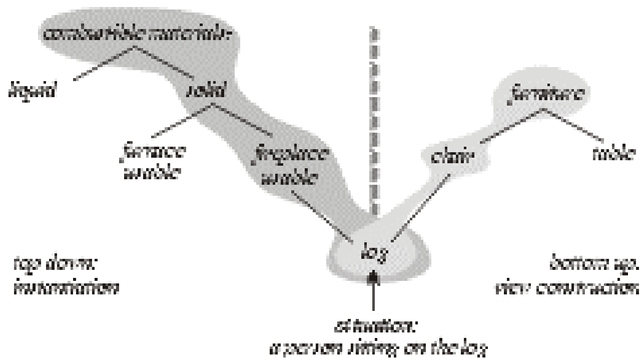

Figure 1. Instantiation and constructive view.

There are always situations that do not fit any particular frame or schema very comfortably. If I sit on a log, it becomes, to some extent, a chair (therefore, a friend might say, “Can I share your chair?”). In a static representation this possibility is quite unlikely to be in a included in the chair representation.

This example refers to an everyday situation, though in design terms an equivalent change occurs due to the change in design focus. For example, in architectural design, a topologically correct layout of rooms may be reconsidered in terms of its shape aesthetic. The change of view of the design induces its re-representation within different categories. The room layout could have been through an instantiation of a particular building prototype, while its re-representation can be built upon an aesthetic prototype of order, rhythm, etc.

Thus, in the situated paradigm constructing a representation is a bottom up process, where the choice of variables that describe an object depends on situation within which an object is considered.

Chalmers, French and Hofstadter (1995) address this issue within the discourse on perception. They consider perception processes on two levels: low-level perception, which includes all basic sensorial processes and high-level perception where the low-level percepts become meaningful by using concepts. Thus, high-level perception is bound to the problem of mental representation. As a result, a given set of input data may be perceived in a number of different ways, depending on the context and the state of the perceiver.

3.2. DESIGN PROCESS IN SITUATED PERSPECTIVE

Designing can be considered as a complex process in which concurrent goals are to be fulfilled. Research based on protocol analysis of the design process shows that design requirements that drive the process are built inside the design process itself. In other words, the brief, which states the objective of the design, does not contain all the requirements that in a retrospective analysis are shown to have conditioned the design process. Suwa, Gero and Purcell (1999) examined the notion of unexpected discoveries (UXDs) that occur to the designer during the design process. They looked at their correlation with the formulation of more general design strategies called situated-inventions (S-inventions). S-inventions are defined as the generation of issues or requirements for the first time in the current design task. Since such formulations occur during the design process they are situated in this process. The S-inventions form the basis for the formulation of new design goals. The study pointed out an important bi-directional causality between unexpected discoveries and the formulation of design goals. A conclusion of this study suggests that the pursuit of various design goals is mutually interwoven. A solution found for a particular set of design goals may potentially trigger reformulation of the design problem through generation of alternative goals. The conclusion drawn by that study provide evidentiary support for the design analysis presented by Schön in the concept of “reflection-in-action”.

3.3. SITUATED ANALOGY IN FBS MODEL

The notions of unexpected discoveries, s-inventions and modifiable design goals form the basis of conceptual framework for this work on analogical reasoning. These notions allow placing analogy used in design within a situated perspective. A comparison between situated and non-situated analogical reasoning processes is symbolically shown in Figure 2.

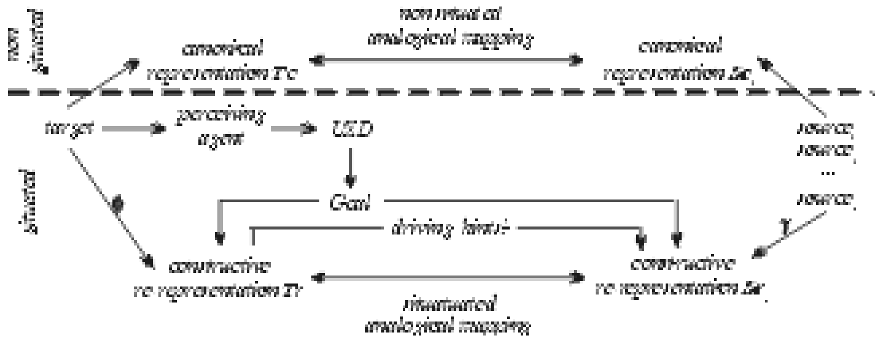

Figure 2. Situated and non-situated analogy making.

It shows the relation between various elements involved in analogy making along with the situational components of the process.

Analogy making as adopted here relies on finding a mapping between two relational structures (that is two representations). Each design is represented as a relational graph that indicates the relational dependencies between three essential states: structure, behaviour and function. The top part of Figure 2 shows the non-situated process, where representations are stored statically, that is throughout the reasoning process the respective representations remain unchanged. Tc and Sc signify canonical representations of target and source respectively in Figure 2. The bottom part of the diagram incorporates the elements of the design process interpreted from a situated perspective. The situated input to the process is driven via findings of unexpected discoveries; those discoveries modify the current focal goal. This change is reflected in the construction of alternative representations of knowledge domains of target and source. The target domain is a single item while the source domain is as a set of candidates. The process of making target canonical representation is written as

$$Tc = \phi\{C_T, R, G\}$$

where:

C_T target design structure

G default focal goal that is associated with a particular design

R design requirements

Tc target design in canonical representation

ϕ representation function

Target re-representation involves finding a different causal path that leads from structure to function, taking account of a change in focal goal. Target re-representation is written as

$Tr = \phi\{C_T, R, G_{A},\}$

where:

G_A alternative design goal induced by finding an UXD

Tr target design re-represented in alternative goal

In a similar way re-representation of the source design occurs. However, in the case of making a re-representation of the source design, this process is biased by the form of the target re-representation. In making the source candidate representation account is taken of elements present in the target representation. In a competitive manner the representation that more closely matches the form of target representation is selected. The process of source re-representation is written as

$Sr_n = \gamma\{ C_{Sn}, G_A, Tr \}$

where:

C_{Sn} n-th source design structure

G_A alternative design goal induced by finding an UXD

Sr_n target design re-represented in alternative goal

Tr re-representation of the target, the biasing "hint"

γ biased representation function

4. Situated Analogy Engine

4.1. SYSTEM ARCHITECTURE

The system can be described through the interaction between four agents, Figure 3. The prototype chooser agent uses the strategy of designing by prototype refinement. The role of this agent is to initiate the reasoning process. The prototype chooser agent selects the initial target design. This selection is passed to the representation agent. This agent generates a canonical representation of the target design in a form of transformational paths within the FBS framework. The representation of the target design is then presented to the perceptual agent called the design analyzer. The role of the analyzer agent is to evaluate how well the selected design prototype, in its current representation, responds to the design problem. The mode of operation of this agent is grounded in protocol studies of designing. Thus, it can be expected that apart from a simple evaluation of the design in the current framework, the analyzer may find aspects of the design problem that were not considered initially, what is termed as an unexpected discovery.

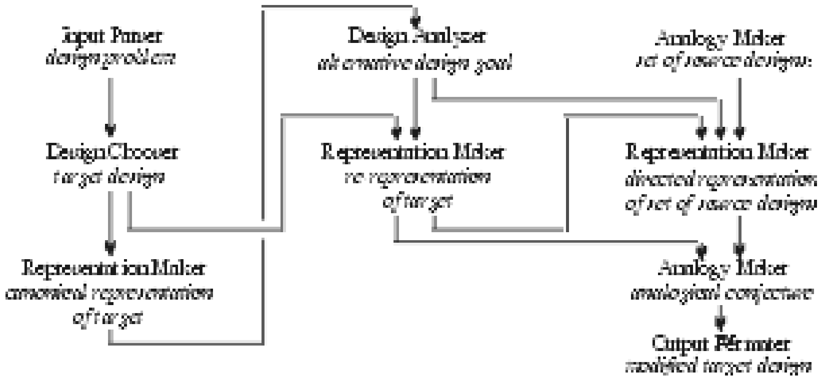

Figure 3. System architecture.

UXD invokes a potential local alternative goal; this goal becomes a basis for design re-representation. The representation agent is invoked and presented with the target structure and the newly found alternative goal. On such a basis a new representation of the target is built. The behaviour set of the newly built target representation becomes the new key to search for an analogical match. Once the key for an analogical match is established it is passed to the analogy maker agent. The role of that agent is to find a match for the analogical key in the database of known designs (potential source designs). Each potential source design is presented to the representation agent, along with driving hint derived from target re-representation and a local goal established by analyzer. This agent uses this input data to generate “situationally biased” representations of source candidates. The mode of operation of representation maker requires provision of design structure and the context in which it is placed. The representation agent uses a competitive approach for creating representations, adding a key being sought may change the balance of forces and increase the probability that it will be included in the FBS representation produced. Thus, providing an additional key derived from the target re-representation that biases or directs the operation of representer can be interpreted as a factor that situates the representation process. Once a satisfactory representation of a source is found it can be matched against the target design and a structure conjecture can be proposed.

4.2. IMPLEMENTATION

The system is considered as a support for a human agent and there is no attempt to make it completely autonomous. Out of three cognitive processes, i.e. conception, representation, perception only the representational task is carried out by an artificial agent.

4.2.1. Representation Maker

The representation maker is built around a design knowledge base implemented as a semantic network, called *knownet*. The physical structure of all nodes is identical, though the contents stored in each node differentiates all nodes into six categories: compound, element, attribute, relation, behaviour, function and context. Figure 4 presents the concept of *knownet*. Compound and elements nodes both represent design structure but at a different level of granularity. Compound nodes represent entire designs while element nodes represent their identifiable parts. Directed arcs (causal links) link nodes adhering to different categories, while nodes within the same category are connected by non-directed arcs (slip links).

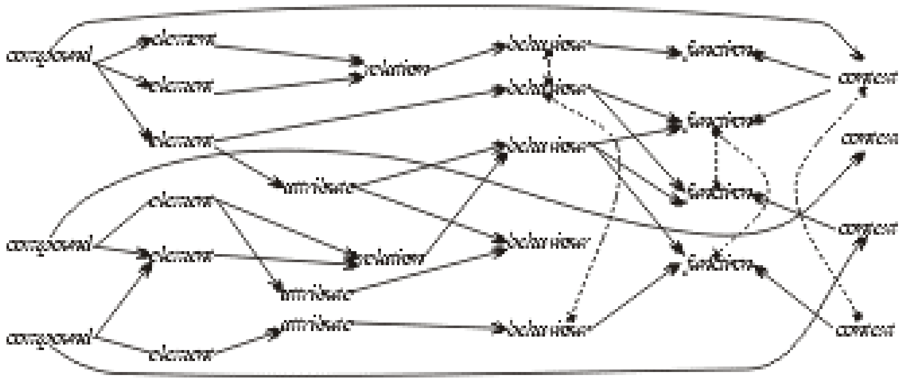

Figure 4. Outline of *knownet*.

The function that generates a representation explores *knownet* from two directions: from compound nodes and from context nodes. The exploration meets at the function level. As shown in Figure 3, the representation maker works in three modes depending on the input data. These modes are: canonical, alternative and biased. In the canonical mode representation of a design is generated in the canonical context which is associated with each compound node. In the alternative mode, the design is placed in a different context. In the biased mode, the process of making representations incorporates a “hint” that operates as a method that selects a preferred representation when competing ones have been found. The exploration of casual links allows the construction of the FBS representation of a design. Slip links allow lateral slippage between nodes in the same category. Thus, under the pressure that comes from the biasing hint the generation of a representation can be directed by substituting nodes that are connected by slip links. In this way properties (i.e. behaviours) that are not a priori associated with encoded structures within *knownet* can be derived under the situational pressure.

4.2.2. Analogy maker

This module takes the input from the representation agent and provides an analogical conjecture built on the basis of behaviour matching between the target and the source representations. This module was adapted from the non-situated analogical system, DESSUA, developed by Qian & Gero (1996).

4.3. EXAMPLE FROM SYSTEM

The process is initiated by selecting a target design in its canonical context. The target design here is a device that controls the flow of liquid (tap in the context of water). A canonical representation generated by the representer is:

F: conduit	B: long-shape	S(b): pipe
F: allow	B: fit	S(b): valve
		S(b): pipe

Context imposes certain kind of functions that might be useful. A relevant function for the context of towel is for example the function of "hanging" that can be abstracted to a function of "attaching". Thus the system can generate an alternative representation of the tap design placed in the context of towel:

F: attach	B: outstanding-shape	S(b): handle
	B: long-shape	S(b): pipe

When the rest of the designs are represented within the same context, for example, hanger as a type hook can be represented as:

F: attach	B: protrude	R: perpendicular	S(r): hook
			S(r): fixture

The analogy engine constructs the index on the basis of the same function in both designs. Thus, what can be transferred to the tap design is the spatial relation between two parts that is reflected by the behaviour "protrude" arising from the relation of perpendicularity between parts. The analogical conjecture that can be proposed is a transfer of the relation of perpendicularity between parts from the source design into parts the target design.

F: attach	B: protrude	R: perpendicular	S(r): pipe
			S(r): valve, handle

5. Discussion

The use of constructive representations allows for rich and variable representations for the analogy engine. In a non-situated paradigm related results could only be obtained by storing multiple representations of each design. In the constructive representation the variability of representations is obtained through exploration of *knownet*. Thus, constructing the representations on demand is a more compact way of storing rich representations. The process of analogical matching and mapping remains the same in both paradigms. The difference between situated and non-situated runs is grounded in a difference of available design representations.

Acknowledgments

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