Assisting design by analogy

Kazjon S Grace, John S Gero and Robert Saunders

Key Centre of Design Computing and Cognition, University of Sydney, Australia

ABSTRACT: This paper describes research into situated analogy-making and its application to digital design assistants. It is claimed that computational design support systems that provide designers with conceptually distant but contextually appropriate information can assist in designers with the synthesis of creative designs. This claim is supported by an example application of situated analogy-making to architectural design, adapting a solarium using analogy. The potential advantages of analogical design assistants are discussed independently of implementation and a number of possible directions and challenges for future work in design by computational analogy are presented.

Conference theme: Digital architecture.
Keywords: analogy-making, digital synthesis, design agents, situated computing.

INTRODUCTION

The majority of digital design tools focus on the representation of designs. These representations vary with use, from concept visualisation aids to precise machining specifications, but rarely expand beyond the documentation and presentation of the designer's intent. One of the goals of current research into the development of design agents is to enable computers to contribute to the development and synthesis of designs by actively assisting a designer during the design process. This paper outlines one methodology for artificial conceptual design: the use of analogy-making agents to adapt design strategies from domains not directly related to the design domain. This research draws on concepts from situated computing, notably the subjectivity of knowledge and the constructive nature of memory to develop design agents capable of analogical reasoning. The central tenet of situated computing is that knowledge is not encoded a priori but is developed and refined in the course of use (Gero 2003). Models of situated analogy have been presented previously (Kulinski 2002), the purpose of this work is to demonstrate capabilities and applications of these concepts.

The research presented here aims to develop a generalised design agent applicable to any domain, but the focus is on how situated analogical design assistants could be of use to architectural designers, particularly designing for harsh environments. Analogy can be applied directly to problems of climate as there are instances in the natural world of evolutionary adaptations that are well-suited to interpretation as architectural features; for example, the slope of an alpine conifer compared to a chalet roof that is well adapted to the prevention of snow build-up. While such literal analogies can be of value, the most useful analogies tend towards the more abstract, such as Jørn Utzon's famous analogy of the Opera House's sails as ribs of a sphere, allowing them to be constructed.

1. ANALOGY

Plato and Aristotle claimed that there can be a shared abstraction between two objects, an idea, pattern, effect or other regularity that is possessed by both of them, and Immanuel Kant argued in his *Critique of Judgement* that there can exist the same relation between two objects. The model of analogy adopted in this research is the Structure Mapping Theory (SMT), proposed by Gentner (1983). This defines analogy as a mapping of knowledge from one domain (the source) to another (the target) which supports a system of relations known to hold in both domains. In the SMT, a relation refers to an association between objects or properties of a domain, eg: "X revolves around Y", and the source and target are represented as a hierarchy of these relations and attributes. This identicality of relations contrasts with literal similarity, which is expressed as identicality of properties. SMT describes the mechanism of analogy but does not explain the construction of the representations or how they come to be homogenous.

In situated computing knowledge is constructed by an agent as a consequence of experiences that involve interactions between the agent and its environment. Representations developed through this process exhibit biases correlating to the situations from which they emerged. Situated analogy utilises representations constructed by an agent that subjectively reflect its context, the state of its environment, and its history. For this reason, representation-building cannot be considered a separate precursor to analogy or any other cognitive process, representations must be able to be perturbed dynamically as the situation and the demands of the cognitive process require.

The purpose of analogy-making is to permit knowledge transfer between the source and target, Figure 1. When an analogy is formed a mapping is developed between the source and target that describes the commonalities between them. These commonalities form the basis for knowledge transfer based on equivalence. For example, an umbrella and a conifer both divert precipitation; the mapping between the two is their shared conical shape. In this analogy it can be said that the spokes of an umbrella are equivalent to the branches of a pine tree and therefore knowledge about one object can be transferred to the other.

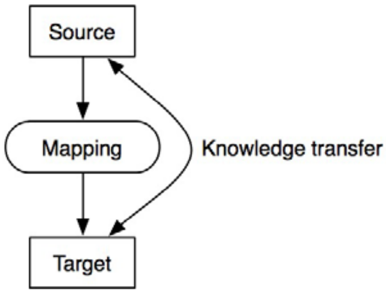


Figure 1: Analogy, the transfer of knowledge between a source and a target between which a relational mapping holds.

Computational models of analogy aim to both understand and apply analogical reasoning. The majority of research to date in the field has focussed on the use of analogy in problem-solving tasks, to support deductive reasoning using information from a distant domain. Computational models of analogy have two significant problems when compared to human analogical thought, retrieval and representation. Retrieval of appropriate source domain knowledge (and therefore the selection of an appropriate target for analogy) in most computational analogical systems is based on a database of objects and their properties. Selecting from these databases requires an exhaustive search based on similarity, a computationally intensive and psychologically implausible act. Computational analogy systems often also have serious methodological problems as a result of their representation of knowledge. Analogical reasoning systems are often given a set of objects with prescribed attributes and values that represents its domain knowledge. This type of knowledge representation often leads to criticism that the system has been blessed with “20/20 hindsight”, i.e. that the system has been given knowledge in the exact form required to solve a problem. In other words the program is being presented with the answer (Chalmers et al. 1992). Ontologically-based representations have been shown to address this (Qian and Gero 1996).

Computational analogy has been the aim of symbolic, connectionist and hybrid systems for over three decades. The process of mapping is understood, the challenges for the field now lie in the building of context-sensitive, experimenter-independent representations and the development of a better understanding of how long-term memory allows analogous situation retrieval (French 2002, Kokinov 1998).

1.1. Analogical processes

Analogical reasoning can be divided into two categories based on the aim of the process and the available information. This typology describes the different processes in analogy, not their motivations or applications. An analogy-making entity (hereafter referred to as an “agent”, either human or computational) that knows of a source/target pair seeks an explanatory analogy, a process referred to in this research as analogical comprehension. An agent that possesses a source object and desires a target is referred to in this research as analogical discovery.

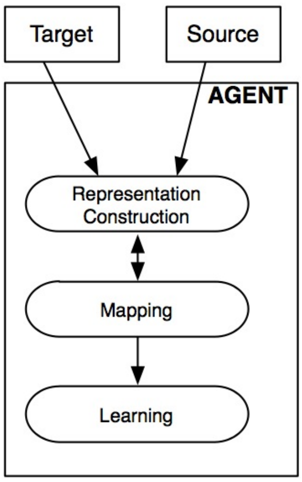


Figure 2: Analogical comprehension, the process whereby an agent receives a source and a target and develops the mapping between them.

Analogical comprehension (see Figure 2) occurs primarily when an agent is informed of the existence of an analogical relationship, but can also occur when an agent discovers a constraint or relation that it wasn’t previously aware of (see Section 2.2). The processes in analogical comprehension are not consecutive, the representations and mappings develop concurrently and are affected by each other. The source and target are presented here as being external to the agent, but their origins are irrelevant to the process. The process is situated, the behaviours of the agent are influenced by the context in which they are performed and the past experiences the agent has had with any of the objects under consideration. While these influences are not depicted here their effects manifest as biases in the representations and are reflected in the mappings produced. In an artificial design assistant, analogical comprehension can be an aid for perceptual actions (understanding the environment), learning tasks (building a model of the world) and communication (explaining ideas in terms another agent will understand).

Analogical discovery (see Figure 3) contrasts with comprehension in that the target is not known in advance. The process of target selection is required to determine what object would make a suitable analogy with the provided source. As with analogical comprehension, the processes are concurrent, situated and interactive rather than static consecutive modules that do not influence each other. Analogical discovery is an exploratory act and can be used to provide solutions to problems which are expressed to the analogical engine through situated biases that influence the component processes. In a design assistant analogical discovery can be used for synthesis (developing a design) and reflection (analysing a design and looking for associations).

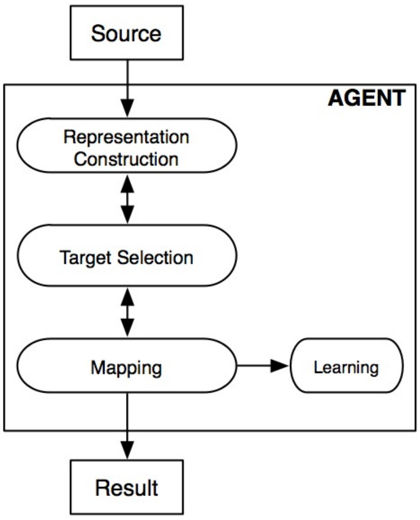
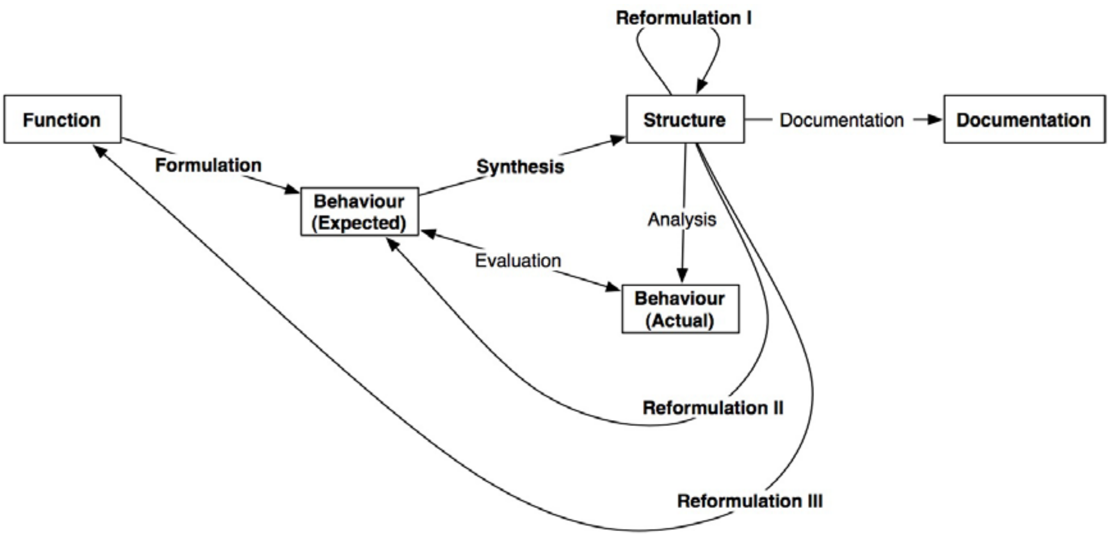


Figure 3: Analogical discovery, the process whereby
an agent, given a source, finds an appropriate analogical target and returns it.

2. ANALOGY IN DESIGN

2.1. Agents in design

The development of computational agents in design research is motivated both by the desire for simulation of human designers for analysis and by the desire for artificial agents capable of some aspects of design. In design problems the solution space is often ill-defined and there is no deductive path to a solution. Design solutions must be synthesised abductively from the requirements and the designer's knowledge. Analogy offers one mechanism by which external knowledge can be used to delimit the solution space.



(adapted from Gero, 1990)

Figure 4: The FBS model. Processes which can be augmented by analogical reasoning are in bold.

To expand the role of the computer beyond design representation a model of the design process is needed to define the role of a design assistant. In this research the Function, Behaviour, Structure ontolog-based model (Gero 1990) of design is used. This model divides design into five elements, Function: the design requirements and the design object's purpose, Expected Behaviour: the behaviours the designer believes the design will need to exhibit), Structure: the properties and components of the designed object, Actual Behaviour: the behaviours the design, once constructed, actually exhibits and Documentation: the description of the designed object.

The FBS model also describes eight processes which make up design, Formulation: production of behaviours from function, Synthesis: production of structure from behaviours, Analysis: analysis of structure to determine actual behaviours, Evaluation: comparison between actual and expected behaviours, the process of Documentation and three processes of Re-formulation: reflecting on structure and changing it, reflecting on structure and changing behaviour and reflecting on structure and changing function. The FBS model is depicted in Figure 4.

Within the framework of FBS, analogy is most visibly present in the synthesis of design structure, but analogy can be applied to the production of behaviours from design requirements if knowledge of previous design requirements and behaviours is available. Analogical reflection can also occur in the processes of reformulation, when a designer searches for an analogy which fits something observed in the emerging design, or when a designer realises there is some correlation between elements of the design and seeks to understand it.

2.2. Analogical reasoning in design

Rowe (1987) identifies the role of analogy in design development as a type of autonomous constraint applied by the designer to an ill-defined problem. These constraints can take two forms, an iconic analogy, where the designer attaches symbolic importance to design elements based on an analogical target, or a canonic analogy, where the target is an “ideal” or formal system, such as Cartesian grids or Platonic solids.

Rowe's autonomous constraints describes the literal application of analogy to design as a means of synthesis. Design is an iterative and reflective process, with the designer producing a representation (often an externalised representation such as a sketch) and then reflecting on it, leading to unexpected discoveries where the designer recognises constraints or requirements that they were not previously aware of. This has been defined as the discovery of a new perceptual action with a dependency on a prior representation and is known as a “situated-invention” (Suwa et al. 1999). These unexpected discoveries can take the form of a correlation or similarity between elements of the design, or between a design element and an external object. This triggers a reflective form of analogical comprehension, as the designer attempts to understand the discovered relation. An agent capable of analogical reflection would therefore be able to refine designs through reflection.

2.3. An example of situated analogy

To demonstrate the applicability of situated analogy to a design assistant, an example of analogical synthesis will be presented. The design is for a glass solarium, but an adaptation is required to let in sunlight but block some of the excess heat which makes enclosed, exposed areas unliveable in harsh climates. The solarium is also an important part of the overall house design, and therefore aesthetic appeal is a notable secondary factor.

An artificial design agent creates a representation of the design problem. The agent then uses situated matching to select a target analogy (another constructed representation) from its memory. In this case, an analogy is made between the solarium and the human liver. The liver performs drug metabolisation using specialised enzymes to neutralise and carry away toxins from the blood stream. The solarium needs to perform an analogous process to absorb and draw away heat from the interior. Another object is needed to be equivalent to the enzymes in the solarium. An analogy is drawn between the liver enzymes that neutralise and remove toxins and flowing water that absorbs and carries off heat. The “liver” solarium design uses water as an “enzyme” to carry “toxic” heat away from the “blood”, sunlight. Water passing over the roof of the solarium will absorb heat from the sun, directly and through the glass, and transmit it away from the solarium and down the glass walls to a collection point. The friction of passage through the air in droplets will help cool the water, but a cooling system will need to be used to prevent the system becoming heat-saturated and to begin evaporating. The completed design is shown in Figure 5.

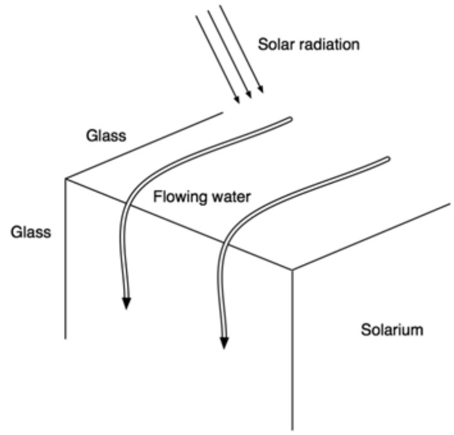


Figure 5: The solarium design produced by an analogy to the human liver.

The mechanism underlying this analogy is shown in Figures 6 and 7. The representations of both liver and solarium are specific to this analogy and do not contain all the knowledge the designer possesses about either object, only those elements critical to the analogy. This specialisation is a result of the situated representation-construction process that occurs in parallel with the target selection and mapping development.

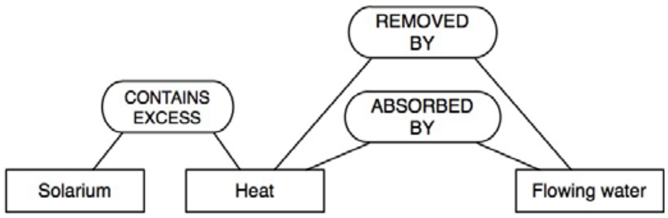


Figure 6: The Structure-mapping graph of the source, the solarium.

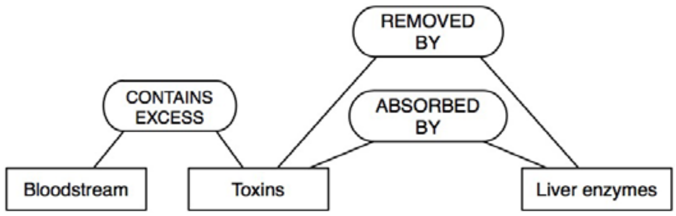


Figure 7: The Structure-mapping graph of the target, the liver.

Correlations between objects can only be performed when there is a commonality of representation, this is a difficult task for any knowledge repository broad enough to span both internal organs and recreational rooms. A situated agent could overcome this problem by constructing the representations from prior experiences with the objects and biasing the representations based on experiences with overheating problems (water being a common coolant), the aesthetics of outdoor living areas and previous experiences with any of the factors involved. The representations developed from the interactions between the two objects and became homogenous as the analogy developed from focussing on the “contains excess” relationship to the “absorbed/removed by” relationships. A non-situated agent may not have been able to make the generalisation from enzymes “neutralising” toxins to “removing” them and in that case would not have produced this analogy.

Analogies where the target is entirely semantically removed from the domain and the mapping is based on a behavioural property rather than a structural similarity can be difficult for a human designer to produce, especially in circumstances where the designer does not have extensive experience with the adaptations necessary for a particular situation. It is through providing ideas such as this one that design can be assisted by computational analogy.

CONCLUSION

This paper has presented a set of ideas and approaches for the use of analogy to assist design through the development of situated analogy-making design agents. It has discussed analogy as an aid to synthesis, where an analogy is made between an aspect of the design problem and another object and some property of that object becomes an element of the design. It has mentioned the possibilities of analogy being used as part of a more general cognitive architecture, with opportunities in perception and reflection and has considered the relation between unexpected discoveries and analogies in design. Analogy-making in design is a situated act and that computational models of it need to include this.

Future work will focus on the production of a computational system capable of empirically demonstrating the ideas presented here. One approach being investigated is to build an agent that can make analogies between visual forms (initially simple geometric shapes) in a situated fashion. This analogy-making agent could then be used to assist a designer making conceptual sketches, providing ideas and approaches to broaden the designer’s considerations.

Further research into the computational representation of situations and the construction of memory is required for the development of integrated design assistants capable of analogy as a general process to be utilised at many levels within a cognitive architecture. As this field develops, analogical design assistants have the potential to change how designers approach designs, particularly when working in environments that can require unfamiliar or novel (on behalf of the designer) adaptations, such as architectural design in difficult climates.

REFERENCES

Chalmers, D., French, R. and Hofstadter, D. (1992) High-level perception, representation and analogy: a critique of artificial intelligence methodology, *Technical Report* Indiana University: Bloomington.

French, R. (2002) The computational modelling of analogy-making, *Trends in Computer Science* **6**: 200-205.
Gentner, D. (1983) Structure-mapping: A theoretical framework for analogy, *Cognitive Science* **7**: 155-170.
Gero, J.S. (1990) Design prototypes: a knowledge representation schema for design, *AI Magazine* **11**(4): 26-36.
Gero, J.S. (2003) Situated computing: A new paradigm for design computing, *Proceedings of the 8th international conference on Computer-Aided Architectural Design Research,* CAADRIA2003: Thailand, pp 579-587.
Kokinov, B. (1998) Analogy is like cognition: dynamic, emergent and context sensitive, *Advances in Analogy Research: Integration of Theory and Data from the Cognitive, Computational and Neural Sciences.* NBU Press: Sofia, pp 96-105.
Kulinski, J. (2002) *A Model of Situated Analogy in Design,* M. Phil. Thesis, University of Sydney.
Rowe, P. (1987) *Design Thinking*, MIT Press: Boston.
Qian, L. and Gero, J.S. (1996) Function-behaviour-structure paths and their role in analogy-based design, *AIEDAM* **10**: 289-312.