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## EXPERIENTIAL INFLUENCES ON COMPUTATIONAL ASSOCIATION IN DESIGN

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**Abstract.** This paper presents a computational model of association in design that incorporates the ability to learn from experience. Experiments with an implementation of our model of computational design association, the interpretation-driven model, demonstrate this experiential influence. The challenges inherent in building computational models of association, and the potential offered by the interpretation-driven approach are discussed with reference to a typology of association learning.

**Keywords.** Computational design; association; experiential learning.

### 1. Introduction

Association, the process of connecting ideas, objects or situations in new ways, is critical to design thinking. Making new associations can allow the unfamiliar to be represented in terms of the familiar, providing new design ideas or aiding in the comprehension of a design problem. Associations can also enable ad-hoc categorisation or judgements of similarity, allowing disparate design elements to be compared in a context-sensitive way. Computationally modelling the process of association as it is used in design presents the challenge of capturing this flexibility, context-sensitivity and breadth of application.

Designers are inextricably influenced by their prior experiences. Each new design problem is perceived through the lens of all past design acts; a designer's memory is constructive (Gero, 1998). Computational models of cognitive

processes in design must reflect this experiential quality. For example, Suwa et al. (1999) discuss the “unexpected invention of design requirements”, a process by which a designer observes something new in a representation of an emerging design, and that observation changes the course of the design process. That act of recognition is the designer drawing on their wealth of design experience, and its impact on the design process is one of many ways designers can “learn” from their past experiences. This research explores the ways in which learning from experience can be incorporated into computational models of association in design.

We have developed and implemented a model of computational association based on the principle of interpretation-driven search. The model and its capabilities have been previously documented in Grace et al. (2012). Our model is applied to the domain of perceptual associations between groups of shapes. In this model representations of each object to be associated are built, and then those representations are transformed until a new mapping can be made. These transformations are called “interpretations”.

We present a set of experiments investigating how the persistence and recollection of these interpretations can enable a kind of learning in association. This kind of learning, “domain association experience”, involves learning about how particular objects can be used to associate. Every association encapsulates a unique relationship between two objects, and it is challenging to generalise from this experience. Interpretation-driven association provides one method by which to approach this challenge.

## **2. Association and Experience**

Studies of association-based processes (notably analogy and metaphor) in cognitive psychology have found that a subject’s experience play a significant role in their associative abilities. Experiments suggest that significant training, examples or knowledge are required before a subject is likely to make deep, structural analogies rather than superficial surface-similarity comparisons (Forbus et al., 1994; Gick and Holyoak, 1980). This suggests the central role of well-structured domain knowledge as a precursor to association, and experiments in laboratory settings support the idea that analogical thinking is a domain of the expert. By contrast observational studies of analogy use in the real world (Dunbar, 2001) propose that familiarity with and immersion in a domain are sufficient, and that non-experts are still familiar with many potential analogical domains. Both of these hypotheses treat experience as a central component of association-based cognition, and psychological research in this area reflects this centrality.

By contrast computational models of associative reasoning are largely atemporal – they are not concerned with learning or with effects arising from the persistence of experiences. Association, analogy and metaphor are usually mod-

elled as independent processes that can be applied to arbitrary object representations. The nature of design as situated cognition (Gero, 1998) applied to a wicked problem (Rittel, 1988) makes it difficult to reconcile this approach with models of design thinking. Computational models of association can be and have been used as tools by designers, but the use of these tools is constrained by their inability to adapt to an evolving design context.

### **3. Kinds of Experiential Effects in Association and their Roles in Design**

Broadly there are three different ways in which experience can influence an association process. This typology serves to contextualise the kinds of learning possible in models of association, to highlight what kinds of learning are challenging and why, and to provide a framework in which to place the learning capabilities of our interpretation-driven model of association.

#### **3.1. DOMAIN OBJECT EXPERIENCE**

This kind of experience is with the objects of the domain(s) being associated. It manifests as richer, more detailed representations of objects, and as representations of a greater variety of objects. It is not necessarily derived from associative reasoning – experiencing objects through other processes can provide useful knowledge about them. It is this first kind of association-influencing experience that most models of association are equipped to deal with: add more objects, or more information to the representation of existing objects, and the effect of this kind of experience can be approximated.

Dunbar's (2001) experiments contrast analogical reasoning capabilities in laboratory situations where subjects had just been taught facts about analogues with natural situations where subjects had been working with analogues regularly. It was found that capacity for deep, structural analogies is developed through sustained engagement with objects and ideas. This suggests that how objects are interacted with and how subjects build their knowledge of those objects through experience plays a significant role in association. This is consistent with the constructive nature of memory (Rosenfield, 1988) and certainly has parallels in design – a first-year architecture student does not become a master by reading about masterful works. Exploring how to model constructive learning about objects to be associated through experience is a topic for future research in association in design.

#### **3.2. DOMAIN ASSOCIATION EXPERIENCE**

This is experience using a particular object or objects in association processes. Knowledge is gained about how and when particularly objects can be mapped, and how to best represent objects for mapping. In language, for example, this can be seen

in concepts that are familiar and frequent sources for metaphor: war, evolution, flowering, gravity, etc. These ideas are used regularly in metaphorical comparisons and experience is gained about how they are typically represented. When next an association is constructed using one of these ideas, the experience of how to associate with them will have an impact. This differs from simply knowing more about the object (domain object experience) as the knowledge is association-specific.

This kind of knowledge is difficult to represent computationally. Every association consists of a unique mapping, and there is no guarantee that mappings involving objects that have previously been associated will bear any similarity to those previous mappings. Association is a generative process that constructs a new relationship where previously none existed. Each new association task can bring with it new objects to relate, and the relationship constructed between those two objects may bear no resemblance to any association the system has previously constructed. Drawing directly on a previous mapping may even be counterproductive – knowing that a kitten and a magazine can both lead to unexpected bleeding is of little use when trying to build a new association between a kitten and a cup of tea.

Incorporating domain association experience into computational models is of particular interest in design contexts. Design has been characterised as a cyclical interaction of reformulation and re-representation tasks (Schön, 1983) in which unexpected discoveries (Suwa et al., 1999) can transform the design space and lead to creative designs (Gero, 1990). A designer's understanding of a design problem undergoes continual transformation, with many relationships being drawn to previous states, other designs and related ideas. Each of these relationships requires association, and these association tasks are tightly coupled with the designer's evolving understanding.

### 3.3. GENERAL ASSOCIATION EXPERIENCE

The final, and most abstract, kind of affect of experience on association is general association experience. This is knowledge about association itself – how and where to apply associative reasoning and how to approach association problems. Ball et al. (2004) find that not only do expert designers use significantly more analogical reasoning during design than novices, but that the analogies they use are more likely to be schematic – that is, based on familiar types or categories of problems rather than specific, concrete examples of prior experience. This suggests that experienced designers learn both how to apply association in different and more structured ways, in addition to just learning how to apply association more often; experienced designers possess more general association experience. This kind of abstract skill acquisition is beyond the scope of most current attempts to computationally model association.

#### 4. Experience in the Interpretation-driven Model of Association

We have developed a model of computational association in design that is founded on the principle of interpretation-driven search. The model has been previously described in Grace et al. (2011) with a discussion of an implementation of the model and the results it produced in Grace et al. (2012). This research explores the ability of the interpretation-driven model of association to learn from its experiences.

Interpretation-driven search is a framework for association in which the search for mappings occurs in a parallel, iterative interaction with an interpretation process. This interpretation process transforms the representations of the objects being associated, permitting new possible mappings that could not have existed between the untransformed representations. We have implemented the model in the domain of ornamental design, developing a computational system that can make visual associations between vector images based on shapes within those images and the relationships between those shapes. We have demonstrated that this implementation can produce a variety of interesting associations and that it is a viable framework for future association research.

The interpretation-driven model of association provides a potential new approach for domain association experience. The model constructs and stores interpretations that can be used to transform objects in ways that enable mappings between them. These interpretations are defined in a general way that allows them to be applied to any object, not just the objects involved in the association during which they were constructed. Interpretations are a “way of seeing” – to adopt a new interpretation is to adopt a different perspective. These interpretations can be stored and re-used in later association problems, allowing that different perspective to be adopted again.

The recollection of previously experienced interpretations is more generally applicable than the recollection of mappings. For example, the specific mapping in the example given earlier associating kittens and magazines is that the kittens claws can produce painful scratches while the paper’s thin edges can produce painful cuts. This association can be produced by interpreting the two objects in the context of the concept “unexpected danger”. That interpretation could then be re-used in another situation, such as associating online communication and painkillers, for which the specific mapping between claws and edges would be useless. Our computational association system is capable of this kind of interpretation re-use in the visual domain.

##### 4.1. EXPERIMENTAL SETUP

An experiment has been conducted to investigate the ability of the interpretation-driven model of association to learn from domain association experience. The degree to which an association problem with multiple possible outcomes can be influenced by priming the system with other association problems will be

assessed. It will be shown that, through recollection of interpretations, the system is capable of being influenced by previous association experiences even when those experiences involved different objects. The ability to prime the implementation of the model and bias it towards particular results will demonstrate that the model exhibits the potential for learning about how to associate within a domain.

The experiment is conducted using the five objects shown in Figure 1. The black-outlined shapes form the images themselves, the light grey borders indicate the boundaries of each image object, and the labels identify features extracted from the images by the system. There are three types of relationship between features in the objects in this experiment: “relative orientation”, “vertical distance” and “shared vertex”. Objects 1, 2 and 3 are used in associations to prime the system, and an association between Objects 4 and 5 with multiple possible outcomes is then affected by that priming.

Three trials were performed using these objects, each culminating in an association between Objects 4 and 5. The first trial serves as a priming-free control while the second and third trials involve a priming association. The trial setups are shown in Table 1, which describes the objects and association problems used in

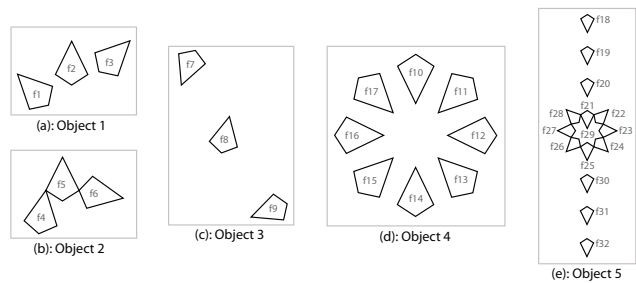


Figure 1. The objects used in the priming experiment. An association between either Objects 1 and 2 or between Objects 1 and 3 is used to prime the interpretation system. An association between Objects 4 and 5 is then constructed.

Table 1. The priming association and the dependent association of each of the three trials. The result of each trial is the distribution of interpretations used in constructing associations.

	Priming association	Dependent association
Trial 1	None	Object 4 and Object 5
Trial 2	Object 1 and Object 2	Object 4 and Object 5
Trial 3	Object 1 and Object 3	Object 4 and Object 5

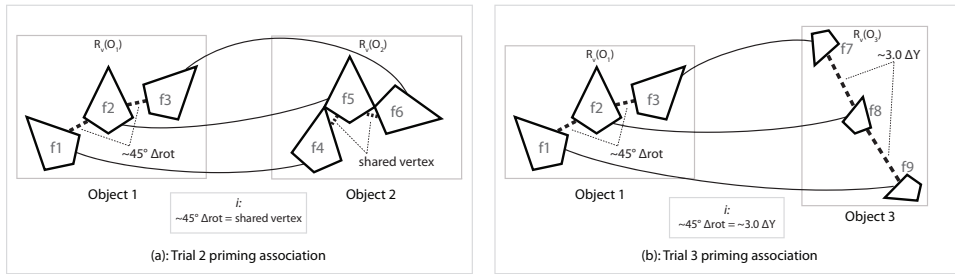


Figure 2. The association produced in the priming steps of Trials 2 and 3. The interpretations used in these associations influence the dependent association.

each step of each trial. Each trial is repeated 100 times, re-initialising the system between trials to erase the effects of priming. A distribution of the interpretations used in the association solutions is produced.

Each of the priming associations has been constructed to produce the same interpretation every time it is run. These predictable associations can be seen in Figure 2. The notation is the same as in Figure 1 with the addition of solid lines joining the two objects indicating what features have been mapped, and thick dashed lines joining features within each object indicating the relationships on which those mappings are based. The priming association used in Trial 2 (shown in Figure 2a) uses an interpretation in which the relationship “ $\sim 45^\circ$  difference in rotation” is treated as being the same as the relationship “share a vertex”, and therefore that interpretation is known to the system when it performs the dependent association in that trial. The priming association used in Trial 3 (shown in Figure 2b) uses an interpretation in which the relationship “ $\sim 45^\circ$  difference in rotation” is instead treated as being the same as the relationship “3.0 units above”, which instead makes that interpretation known to the system.

#### 4.2. EXPERIMENTAL RESULTS

After priming in Trials 2 and 3, or the lack thereof in Trial 1, the system constructs an association between Objects 4 and 5. The interpretations used to produce that association in each trial are shown in Figure 3, which shows the percentage of associations that use each of the two primed interpretations. The percentage of associations that used all other possible interpretations is also shown.

Figure 3 shows that priming significantly increases the likelihood of an interpretation being used in association. The primed representations (the dark grey one in Trial 2 and the medium grey in Trial 3) were all capable of being independently



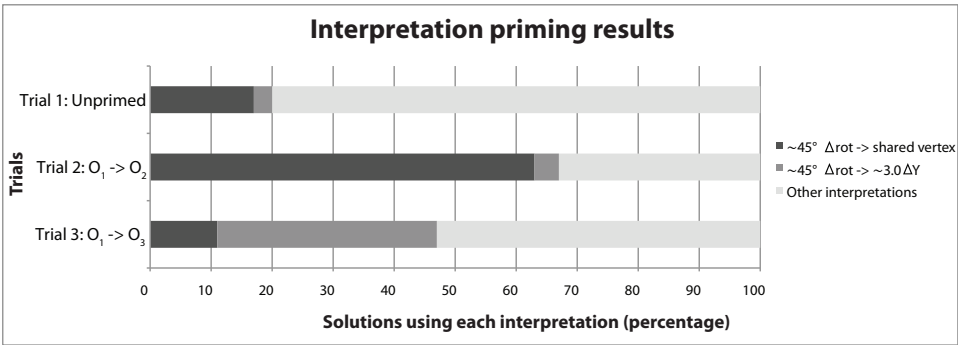


Figure 3. The distribution of results in each trial, showing the percentage of associations that used each of the primed associations.

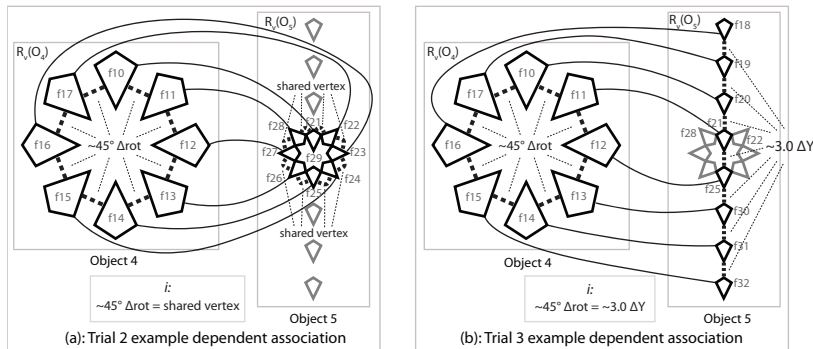


Figure 4. Associations between Objects 4 and 5 produced in Trial 2 (a) and Trial 3 (b).

constructed by the system and thus both appeared in all three trials. However, the experience of using the primed interpretation in a past association significantly increased the percentage of runs in which that interpretation was used in both primed trials.

The interpretation equating  $45^\circ$  of orientation difference with sharing a vertex was used in 17% of associations without priming in Trial 1, but this increased to 63% of associations performed after having previously used that interpretation successfully in Trial 2. Likewise the interpretation equating the orientation difference with vertical spacing increased from 3% of all associations to 36% after priming in Trial 3. Examples of each of these primed associations between Objects 4 and 5 can be seen in Figure 4.

The difference between absolute likelihood of these two solutions is explained by differences in the underlying graph structures, which serves to demonstrate that experience can affect the adoption of interpretations common and rare alike. The other interpretations used to construct this association which are not relevant to the priming in this experiment included equating  $90^\circ$  or  $135^\circ$  with various distances and the shared vertex relationships.

These results show that the association system is able to learn from experiences by applying interpretations that it has used before. This demonstrates the interpretation-driven model of association's capacity for domain association learning.

## 5. Discussion

This proof-of-concept experiment with simple visual objects demonstrates that associations produced in the past by the interpretation-driven model of association can directly affect the associations it will produce in the future, even when those associations involve different objects. In our typology of kinds of experiential influence in association this constitutes domain association learning, a useful behaviour for application in design.

Applying knowledge gained from constructing an association between two objects to the construction of a new association between two different objects is a challenging problem. Interpretation-driven association makes this possible through the explicit representation of the transformations applied to object representations. Interpretations can be constructed, evaluated and stored for later use in this approach to computational association. These interpretations are transferable to different problems in a way that the specific mappings possible by applying those interpretations are not. This approach is applicable to domains other than the simple vector images used in our experiments as the behaviours are properties of the model not the computational implementation of that model we have developed.

The tendency of the re-use of past experience to lead to over-convergence upon known solutions is mitigated in the interpretation-driven model by the discounting of commonly found interpretations. Known interpretations are far more likely to be found first, but all interpretations remain discoverable.

The interpretation-driven model of association incorporates processes that enable the remembering of previously successful interpretations. In the current implementation these processes are only partially implemented, permitting literal recall of past experiences without re-constructing them to fit the current situation. The current system can only reapply interpretations exactly as they were previously used, and does not possess the capacity to abstract, generalise or contextualise the experiences it has learnt. The experiments performed in this paper have demonstrated that even this simple, literal recall of past experiences can influence behaviour.

Previous interpretations that can be applied to a problem could all theoretically have been constructed by the interpretation generation system and used in association without previous experience. Demonstration of this can be seen in Trial 1 of the experiment, where both “priming” solutions were still found even though they were not primed for. This means that any interpretations applied through experience could always have been found without experience – given enough time. This limits the possibility for creativity according to some definitions (Boden 1990, Gero 1990). However, interpretation recall can lead to solutions that would have been extremely unlikely.

This research has demonstrated that it is possible to learn from experience in computational association and reapply that experience to different problems. This is significant for research in computational association in design as design presents an environment with rapidly evolving representations in which the ability to reconstruct and reapply past knowledge is critical. Schön (1983) describes design as a “reflective conversation, a product of repeatedly associating the current design with past experiences, and this research is a step towards computationally representing that discourse”.

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