CONSTRUCTED REPRESENTATIONS AND THEIR FUNCTIONS IN COMPUTATIONAL MODELS OF DESIGNING

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Abstract. This paper re-examines the conclusions made by Schön and Wiggins in 1992 that computers were unable to reproduce processes crucial to designing. We propose that recent developments in artificial intelligence and design computing put us in a position where we can begin to computationally model designing as conceived by Schön and Wiggins. We present a computational model of designing using situated processes that construct representations. We show how constructed representations support computational processes that model the different kinds of seeing reported in designing. We also present recently developed computational processes that can identify unexpected consequences of design actions using *adaptive novelty detection.*

1. Introduction

In the paper "Kinds of Seeing and their Functions in Designing" Schön and Wiggins discussed how designers see their on-going designs in different ways and how these kinds of seeing affect the design process (Schön and Wiggins, 1992). The studies provide evidence that different kinds of seeing are essential to the intertwined processes of designing and discovering within and between design episodes.

Schön and Wiggins enumerated three kinds of seeing, literal apprehension of representations, apprehension of figures, and appreciative judgements of quality. To these different kinds of seeing they also added the recognition of unintended consequences of design actions. More recent protocol studies have provided additional evidence that unexpected discoveries play an important role in designing (Suwa, Gero et al., 1998).

In the concluding remarks of their paper, Schön and Wiggins made the following statement regarding the potential impact of their understanding of designing to the future of development of computationally models:

"When we think of designing … as a conversation with materials conducted in the medium of drawing and crucially dependent on seeing, we are bound to attend to processes that computers are unable — at least presently unable — to reproduce: the perception of figures or gestalts, the appreciation of qualities, the recognition of unintended consequences of moves."

Recent developments in design computing and artificial intelligence put us in a position where it is now possible to re-examine whether computers are now able to begin to model designing as conceived by Schön and Wiggins.

Computational processes already exist for the perception of figures and gestalts (Gero and Yan, 1994), the appreciation of qualities (Soufi and Edmonds, 1995; Reffat and Gero, 1998). We present here additional processes capable of recognizing unintended consequences of actions. Throughout this paper, reference to perception, appreciation and recognition within computational systems is assumed to mean the generation of appropriate representations to process figures, qualities and consequences within the limitations of the design system's goals.

The remainder of this paper will examine various aspects of a recently developed computational model of designing. Section 2 introduces constructed representations as they our defined for this work. In Section 3 we examine the creative design process of emergence and its relationship to expectations in learning agents and the concept of novelty. Section 4 presents an experimental implementation of the computational model. Subsection 4.5 introduces the computationally processes of novelty detection used to recognise unintended consequences of actions. Section 5 gives a demonstration of an experimental implementation learning of a new drawing action for a novel emergent shape.

2. Constructed Representations

We refer to *constructed representations* throughout this paper to differentiate representations produced by situated computational processes from *fixed representations* traditionally used in CAAD systems. Unlike fixed representations, constructed representations can have many interpretations of a design depending on the situation of the design agent.

Human designers use drawings to construct representations in response to goals and experiences during designing. As Mitchell points out the ambiguity of drawings plays an important role in this.

"… design is not description of what *is*, it is exploration of what *might be*. Drawings are valuable precisely because they are rich in suggestions of what might be … Thus the meaning of a drawing is not adequately captured by imposing *one* structure on it." (Mitchell, 1990)

Constructed representations take advantage of the ambiguity of drawings to support the "suggestions of what might be" for computational processes. Constructed representations are determined with respect to current design goals, strategies and knowledge learned from previous similar experiences. Learning plays an important role in processes that construct representations.

2.1. SITUATEDNESS

Situatedness holds that "where you are when you do what you do matters" (Clancey, 1997). Situatedness is an important concept for designers, human or otherwise. Designing is fundamentally a situated act because it is concerned with changing the world within which it operates (Gero, 1999).

Constructed representations situate computational design processes. Perceptual processes construct representations that are appropriate for a particular moment in time according to the current focus of interest determined by the accumulated knowledge of a design agent. As a consequence, constructed representations allow non-learning design processes to be sensitive to the design situation.

Situated perceptual processes may construct many representations from a single fixed representation of a design. To support the construction of new representations of a design it is often useful to choose an intermediary representation that relaxes some constraints. *Figure 1* illustrates how the infinite maximal line representation of a building can support many constructed representations each highlighting a different aspect of the design.

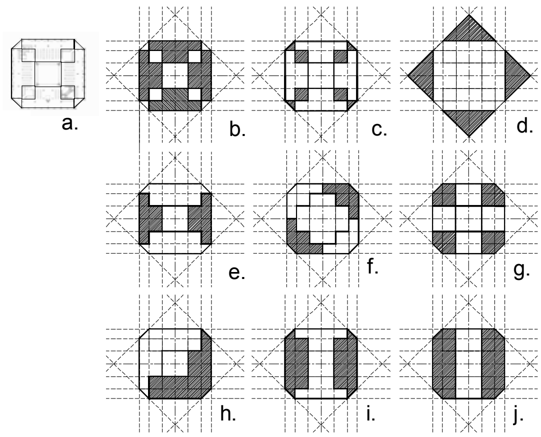

Figure 1. Multiple representations of a house generated using the infinite maximal line representation (Reffat and Gero 1998).

Choosing which representations to construct and the importance of each representation can be problematic because importance varies from situation to situation (Waltz, 1999). We propose that *design emergence* is an appropriate means of determining the importance of constructed representations.

3. Emergence, Expectations and Novelty

Design emergence has become the focus of much attention in the design computing research field in recent years as one of only a small number of design processes that can expand a design space and hence facilitate creative designing (Gero, 1990).

We use the term *design emergence* to differentiate the creative design process of emergence from its meanings in other fields of research, e.g. artificial life (Cariani, 1991). Design emergence is the recognition of unintended consequences that Schön and Wiggins mentioned

We use the definition of design emergence given by Gero: *emergence is the process of making implicit features explicit* (Gero, 1992). Hence, design emergence is defined relative to a conceptual model of the design situation held by an observer. It has been suggested that drawing can be considered as a means of externalising a conceptual model in order to look at it afresh and facilitate the process of emergence:

> "… we all externalise in order to find out what it is we have in our heads … We produce something in order to compare it with incoming data … It is through this externalisation process that we are able to know what we believe about the world." (Cohen, 1983)

Design emergence is therefore a process of constructing new representations of existing beliefs to make explicit features of those beliefs that were previously only implicit. Drawings afford designers the opportunity to construct new representations of their beliefs and test their expectations.

Expectations provide a basis for comparison between a designer's beliefs and reality. Differences between the designer's expectations and observations can be used to isolate, and subsequently explicitly represent, aspects the products and processes of designing that were partially or completely misunderstood.

A designer can thereby learn an explicit representation of the effects of a design action previously defined implicitly in its mechanics. This is the model of design emergence that Schön and Wiggins referred to when they wrote about the "the recognition of unintended consequences of moves". For example,

Figure *2* illustrates the emergence of shapes where drawing two overlapping squares implicitly define three emergent shapes that can be perceived by considering the spaces bounded by the lines, i.e. the intersection and differences of the two squares.

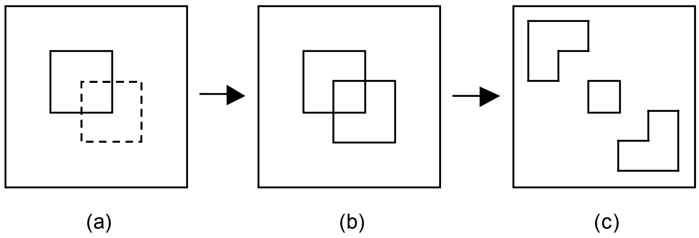

Figure 2. An illustration of shape emergence: (a) the two squares drawn, (b) the Gestalt figure formed, (c) the three emergent shapes perceived.

A computational model of design emergence must therefore include processes that monitor both the products and the processes of designing. Designing has to be monitored in order to detect significant changes in representation that indicate the addition of new knowledge. Determining the significance of changes in representation is a vital part of the process of design emergence. We present one approach to monitoring for design emergence by gauging the *novelty* of constructed representations.

3.1. NOVELTY

We define the novelty of constructed representations as the combination of its newness and its utility within a situation. Our definition of novelty is therefore related to *situated creativity* (Suwa, Gero et al., 1998), and hence to Boden's concepts of *psychological creativity* and *historical creativity* (Boden, 1991).

The definition of creative designing as the expansion of a design space (Gero, 1990) leads us to a generally useful property of novel representations to support emergence. To be novel within the context of creative designing, a constructed representation must expand the conceptual state space of a design agent.

Situations that *could not* have been predicted by the design agent from previous experience, and hence expand its conceptual state space, are defined as novel. Situations that *could* have been predicted from previous experiences, despite never having actually been experienced directly, are not novel under this definition. Interestingly, situated design systems that recollect previous situations dynamically by constructing representations can find previous experiences novel on a second encounter due the effects on memory of intervening experiences.

4. Sketch: A Computational Exploration

Sketch is an experimental system developed to explore the potential of various technologies to model simple creativity using emergence. Sketch constructs representations that capture different aspects of the ongoing design situation.

The computational system can be broken down into a generative subsystem that executes drawing actions and four layers of perceptual processes each layer corresponding to the different kinds of seeing as described by Schön and Wiggins. The perceptual layers are labelled from the lowest to the highest: literal syntactic apprehension, emergent syntactic apprehension, semantic appreciation and novelty detection.

4.1. DRAWING ACTIONS

Sketch supports two types of drawing action, shape drawing actions and affine transformations. Drawing actions can be specified either by the generative computational subsystem or by a human operator. Shape drawing actions consist of a number of horizontal and vertical line drawing actions that have been grouped together to form a closed boundary around a central location. Affine transformations affect the whole canvas and are used to quickly reproduce a drawn shape into new locations and orientations. A bitmap image is used as a canvas for all drawing actions as it is a convenient representation to pass on to perceptual processes.

4.2. LITERAL SYNTACTIC APPREHENSION

The literal syntactic layer contains the most primitive representations of the current design, i.e. bitmap images of the regions of interest of the design canvas. The determination of the regions of interest is done at higher levels of the hierarchy. The representations constructed within this layer are considered to be analogous to the literal apprehension of drawings by human designers.

The computational model of literal apprehension of shapes is the simplest of the perceptual processes. Literal apprehension of shapes is achieved by categorizing bitmap images of regions of interest using a self-organizing map neural network (Kohonen, 1997).

The self-organizing map constructs a classification of bitmap images representing shapes. Images are categorized by comparing them against previously learned classifications to identify the best matching category. The classification is then updated by adjusting the network's representation (i.e. its synaptic connection weights) to better capture the features of the new image. The self-organizing map learns continuously in this way throughout the design process, updating its classification of images to cover the shapes found.

4.3. EMERGENT SYNTACTIC APPREHENSION

The emergent syntactic apprehension layer processes construct emergent figures and gestalts not explicitly represented in the literal syntactic apprehension layer. This layer makes use of horizontal and vertical edge representations, infinite maximal line representations (Gero and Yan, 1994) and bounded space representations (Soufi and Edmonds, 1995). The emergent syntactic layer produces bitmap images suitable for further analysis to produce design actions for novel emergent shapes.

Modelling the apprehension of figures is more complex than the literal apprehension of shapes because it requires image processing for feature detection to support the generation of the edge, infinite maximal line and bounded space representations before recognition of emergent shapes can be done. However, the learning process is exactly the same as for literal apprehension, using a self-organizing map to construct a classification of the emergent figures.

4.4. SEMANTIC APPRECIATION

The semantic appreciation layer provides processes for the evaluating literal and emergent syntactic descriptions to produce appreciative judgements of qualities, e.g. geometric relationships between shapes.

Syntactic perceptual processes provide the inputs to the construction of semantic representations that model appreciative judgements of quality. The semantic appreciation processes compare original and transformed versions of an image pixel-by-pixel to produce quantitative measures of geometric qualities, e.g. rotational symmetry, reflectional symmetry etc.

4.5. NOVELTY DETECTION

The novelty detection layer contains the *adaptive novelty detection* processes that recognize unexpected consequences of design actions. Literal syntactic, emergent syntactic and semantic representations are used as the inputs to the adaptive novelty detection processes. Adaptive novelty detection uses the expectations and associated confidences generated by learning systems to construct representations of the relationships between perceptions and construct expectations of the consequences of taking design actions.

We have developed implementations of adaptive novelty detection processes that monitor the representations constructed by several different types of neural networks, e.g. self-organising maps, back-propagation networks, recurrent Hopfield networks and several ART-based networks. Many neural networks construct expectations during learning while only some provide an associated confidence, e.g. ARTMAP networks (Carpenter, Grossberg et al., 1991). Neural networks that do not provide measures of confidence require additional monitoring.

5. An Example Problem

Figure 3 shows a screenshot of an early implementation of Sketch in operation. The number of representations constructed has been limited to literal pixel values, horizontal and vertical edges, bounded spaces and novelty. However, this reduced set of representations is sufficient to demonstrate the important design skill of learning a new drawing action for a novel emergent shape.

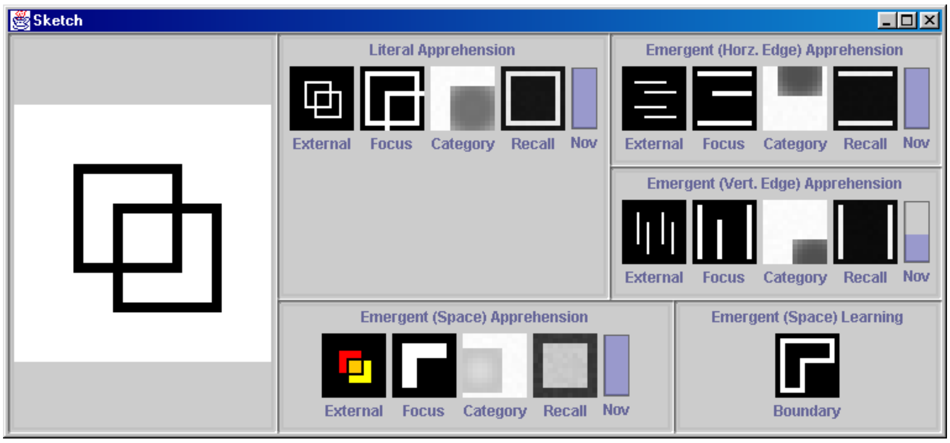

Figure 3. A screenshot of Sketch in operation showing the current design and the representations constructed.

5.1. FINDING REGIONS OF INTEREST

In order to find emergent shapes Sketch first has to be able to identify regions of interest in the input image. The current implementation analyses the entire drawing canvas to find closed spaces and produces a number of fixation points at the centre of each one. Each fixation point is used to extract a set of smaller bitmap images of the surrounding area that is used for input to the perceptual processes.

5.2. PERCEIVING EMERGENT SHAPES

The perceptual processes of Sketch are designed to identify novel emergent shapes. Adaptive novelty detection compares input bounded space representations with representations the best matching shapes previously categorized by a self-organising map. Adaptive novelty detection also compares representations constructed by learning systems from bounded shapes with those constructed from literal pixel values and edges. Representations are assigned measures of novelty proportional to the measures of contradiction calculated between pairings.

Figure 3 shows that, at the current fixation point, the inputs and the representations constructed by the literal and bounded space learning systems contradict. The input bounded space representation shows a rotated L-shape while the learning systems have both constructed equivalent representations of a square. Novelty is measured proportional to the highest confidence of the two learning systems, which in this case is the confidence of the literal apprehension learning system.

5.3. LEARNING NEW DRAWING ACTIONS

Sketch can learn new design actions during the design process to enable it to draw novel emergent shapes that have been discovered. Sketch computationally models an *interest* in reproducing novel emergent shapes. It has been designed to isolate and analyse significantly novel shapes to produce a sequence of line drawing actions relative to the current fixation point that are grouped together into a new drawing action.

Figure 3 shows that the novel emergent rotated L-shaped figure perceived by the bounded space processes has been analysed and an image of the boundary of the emergent shape has been generated. Scanning the boundary image, row-by-row and column-by-column, making note of the end points of line-coloured pixels produces a set of line drawing actions. The line drawing actions are grouped together into a shape drawing action that represents the novel emergent shape and is added to the repertoire of drawing actions available.

6. Conclusion

In this paper we have introduced *constructed representations*. We have paid particular attention to the role of learning in processes that construct representations and examined constructed representations called expectations that support the processes of *adaptive novelty detection*.

We have demonstrated with an implementation some of the functions that constructed representations can support. In particular, we have examined the role of expectations and adaptive novelty detection in the process of learning of novel emergent shapes by providing a basis for the recognition of unexpected consequences of design actions.

This paper presents work that took as its starting point the cognitive studies of designers by Schön and Wiggins. The computational system developed has built upon previous work in design computing with the addition of adaptive novelty detection processes to produce a system that Schön and Wiggins believed could not be produced in 1992.

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