Computational and Cognitive Models of Creative Design VI

Computational and Cognitive Models of Creative Design VI

Preprints of the
International Conference of
Computational and Cognitive Models of Creative Design VI
Heron Island, Australia
10-14 December 2005

edited by
John S Gero
Mary Lou Maher

International Conference on Computational and Cognitive Models of Creative Design VI
Heron Island, Australia
10-14 December 2005

ISBN 1 86487 789 8

2005

PUBLISHED BY
Key Centre of Design Computing and Cognition
University of Sydney NSW 2006 Australia
Email: kcdc@arch.usyd.edu.au

TABLE OF CONTENTS

Preface	**vii**
Keynote 1	**1**
On exploring parts and wholes Barbara Tversky	3
SOCIAL MODELS OF CREATIVITY	**17**
Social models of creativity Ricardo Sosa and John S Gero	19
Where creativity comes from Sean Hanna	45
Beyond Binary Choices: Understanding and exploiting trade-offs to enhance creativity Gerhard Fisher	71
COMPUTATIONAL CREATIVITY	**93**
Creativity as disruptive adaption: A computational case study Tapio Takala	95
Can designs themselves be creative? Mary Lou Maher, Kathryn Merrick and Owen Macindoe	111
Towards understanding human-computer c-creativity Oliver Hoffman	137
Keynote 2	153
Creativity•Rules Terry Knight	155
MODELS OF CREATIVE PROCESSES	**175**
Primitives and principles of synthetic process for creative design Toshiharu Taura and Yukari Nagai	177
Cue-based memory probing in idea generation Matti Perttula and Lassi Liikkanen	195
Keynote 3	**211**
Acquiring design expertise Bryan Lawson and Kees Dorst	213

COMPUTATIONAL SUPPORT FOR CREATIVE DESIGN **231**

Creative design in a tangible user interface environment 233
Mi Jeong Kim and Mary Lou Maher

Idea improvement in different design environments 251
Tom Kvan and Song Gao

Creative architectural design by ITC enhanced collaboration 275
Gianfranco Carrara and Antonio Fioravanti

CREATIVITY AND COMPUTERS **301**

On creative engagement 303
Ernest Edmonds and Lizzie Muller

Tales of the unexpected: Understanding emergence and its relationship to design 319
Martyn Evans

Computational suppert for personally-creative designs 333
Daryl Hepting

Modes of engineering design thinking 349
Pertti Saariluoma, Kevali Nevala and Mikko Karvinen

Methodologies for understanding social creativity during collaborative design activities 365
Elisabeth Sylvan

Contact Authors' Email Addresses **375**

Author Index **377**

PREFACE

This conference is the sixth in a series of round-table conferences on computational models of creative design. The first conference was held in December 1989, the second in December 1992, the third in December 1995, the fourth in December 1998, and the fifth in December 2001. This conference, held in December 2005 maintains the same venue. The venue is Heron Island on the Great Barrier Reef in Australia. Heron Island is the southern-most island of the Great Barrier Reef that is still part of the reef. For this reason the conference series has been referred to as the *Heron Island* conferences.

The purpose of this series of conferences is to provide a forum for the advancement of our understanding of computational and cognitive models of creative design. Rather than provide a venue for the presentation of research papers only, the conferences have been set up to provide more time for discussion than for presentation. The number of participants is intentionally kept low to allow for considerable interaction. The participants are primarily selected based on a review of submitted papers and the accepted papers provide the catalysts for discussion.

Many people equate designing with creativity, that is, all designs by their nature are creative. A common understanding throughout the papers in this proceedings maintains that computational and cognitive models of designing draw a distinction between two classes of designing: routine designing and non-routine designing, where there are clear definitional differences between the two classes. Creative designing falls into the class of non-routine designing.

With developments in interactive technology, the blurring between the physical and the digital, and advances in our understanding of design cognition, the scope of the papers discussed at this conference has broadened. As in previous years there is a subset of the papers that focus on models of creative processes, drawing on fields such as artificial intelligence, computer science, social networks, and cognitive science. In these papers, there are models that account for novel idea generation and synthesis of designs. A second group of papers show how new technologies influence and focus designers during a creative design process. These papers look at how different multimedia interaction technologies and computational decision support facilitate creative design. Finally, there are papers that look at specific examples of how designs are capable of being creative through the synthesis of generative systems with creative design products.

The papers have been selected on the basis of a reviewing process where each paper was reviewed by at least three referees and the final decision based on the referees' recommendations. The presenters in this round-table conference come from nine different countries providing an international forum. The countries are: Australia, Canada, Finland, Hong Kong, Italy, Japan, Mexico, UK and USA.

John Gero and **Mary Lou Maher**
Key Centre of Design Computing and Cognition
University of Sydney
November 2005

KEYNOTE 1

On exploring parts and wholes
Barbara Tversky

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 3-16

ON EXPLORING PARTS AND WHOLES

BARBARA TVERSKY
Stanford University, USA

Abstract. What does the mind work with to come up with new ideas? The objects of the mind include mental representations of things, places, events. One level of regarding things, places, and events, the *basic level*, is privileged; that is the level that connects appearance with function. The transformations that the mind performs on mental objects include mental transformations of things and mental transformations of perspective. Selecting levels and transformations allows different properties to emerge, promoting new ideas. In the summer of 2005, the Tate Modern in London honored its' architects, Herzog and de Meuron, with a comprehensive exhibit of dozens of their projects. The exhibit did not consist of stunning models of dazzling buildings, but of things far more evocative, stacks of wood, stone, cloth, concrete, brick, ceramic, paper, Styrofoam, plastic, glass in a wide range of sizes, shapes, and textures, artifacts Herzog termed "the waste products of a thought process." Many of these were parts of buildings, but not the traditional parts, rooms, corridors, floors. Some were three-dimensional units, large and small, that cut up buildings in unexpected ways, configurations of elongated square tubes, thick Lincoln Logs, thrusting at different angles, or open capsules arranged in rows and columns, design elements of the Prada building in Aoyama, Tokyo. These unusual building blocks served the designers as tools for thinking about design, allowing radically different ways of thinking about whole structures. As for any problem, there were parts and there was a whole, it was the partitioning into parts that was extraordinary, and that led to some extraordinary wholes. Why were those parts surprising? What did the unconventional partitioning contribute? To begin to answer that, let us first consider how partitioning is usually done.

1. How to Solve a Problem: Dividing into Parts.

Problems are usually too big; if they weren't too big, they wouldn't be problems. When something's too big, it's a good idea to divide into parts. Smaller parts might be easier to solve; at most their solutions might suggest solutions to other parts or at least provide motivation to tackle other parts. But how should a problem be divided into parts? It isn't obvious; a problem isn't like a radio that can be disassembled into its' parts or a chicken that can be carved at its' joints. Solving a problem entails more than dividing it into parts; it also entails doing something with the parts, transforming them or manipulating them or analyzing them.

2. How to Solve a Problem: Comparing to Other Kinds.

Dividing a problem into parts isn't the only way to approach solving a problem. Another venerable way to solve problems is to think about similar problems whose solutions may be known. Problems, like other things, get grouped by similarity. Good groups include exemplars that share many features and differ from other groups on many features. That means that good groups or good categories are informative; grouping on one feature predicts many other features. Vehicles, tools, musical instruments, trees, fish are examples, as are boats, cars, and airplanes within vehicles and violins, saxophones, and pianos within musical instruments (cf. Rosch 1978). Knowing that something is a vehicle or a musical instrument means knowing something about its' size, its' construction, its' purpose. Knowing that something is a car or a violin is even more informative about its' appearance and function. That is, good categories share features with good objects, and can be treated as such for many ends.

3. Organizing Knowledge: Partonomies and Taxonomies.

These two ways of solving a problem point to two major ways the mind organizes information, partonomically, by dividing into components, and taxonomically, by grouping by kinds (e. g., Miller and Johnson-Laird, 1976; Tversky 1985, 1990; Tversky and Hemenway 1984). Each of these ways of organizing information forms hierarchies. The body has as parts arms, legs, head, and torso; each of these has parts. Similarly, a building has an entrance, rooms, and corridors, again, each with parts. This is a partonomic perspective. By contrast, shirts, pants, and shoes are kinds of clothing, and dress shirts and t-shirts kinds of shirts, just as apples and oranges and bananas are kinds of fruit, and fuji and delicious are kinds of apples. This is a taxonomic perspective. One reason for the usefulness of taxonomies and partonomies is that they allow inferences or predictions (Tversky 1985). Partonomies, as shall be seen, allow inferences from appearance to function, from what parts look like to what they do or how they serve us. Taxonomies allow inferences about properties; if apples have peel, pulp, and seeds and are sweet, then so do fuji apples and delicious apples. If birds lay eggs and fly, then so do robins and finches. That these are just predictions is demonstrated by ostriches and other flightless birds.

4. From Concrete to Abstract.

Cognitive science has taught that insight into abstract concepts and processes can be gained from analysis of concrete ones. We talk about "objects" of thought and we "turn things over in our minds". If the mind reaches abstraction through the concrete, then research on how people think about the major entities of our lives should yield insight, and perhaps recommendations, into how people think about the abstract. What are the major entities of our lives? Objects, scenes, and the events that involve objects and take place in scenes. Understanding how people parse and organize objects, scenes, and events should provide added benefits for design problems, as design is about objects and settings, and how people use objects or behave in settings, the action sequences that constitute events.

Let's turn now to an overview of how people parse the primary entities of their lives, objects, scenes, and events, and then turn to how they transform them in their minds. For each of these entities, we consider prototypical common examples, the kind that many people list when asked to produce examples of objects, scenes, and events.

5. Mental Entities: Parceling Experience

Although the world as we experience it is a constantly changing multimodal barrage on our senses, our experience of the world is as a panorama of discrete and distinct scenes, objects, and people. Even our experience of time is discretized, into a parade of events, waking up, eating breakfast, going to work (e. g., Tversky, Zacks and Martin, in press). Parceling the sensory world into scenes, objects, and events is a way of making sense of it. The parcels package information into bundles that are useful in the sense that they allows us to anticipate what will happen and to select a course of action. Key to prediction is the connection between appearance and action.

6. Wholes.

Objects, scenes, and events have integrity, a natural wholeness. For objects, wholes are typically closed contours, and when moved, they move as a whole, they don't leave parts behind (Hochberg 1978; Spelke et al. 1995). The shapes of objects formed by their contours are typically recognizable, they distinguish one object from another, a chair from a table, a giraffe from a hippopotamus (e. g., Rosch 1978). Not so for scenes. Shape does not distinguish one restaurant from another or a restaurant from a grocery store. The integrity of scenes seems to derive from the sets of objects and activities characterizing them (e. g., Tversky and Hemenway 1983). Restaurants have chairs and tables and entail ordering, eating, and paying; grocery stores have shopping carts and racks of food and household products and involve putting things into carts, bringing them to a clerk, and paying. Similarly, outdoor scenes have characteristic objects and activities: beaches have sand and water used for playing and swimming. Note that for both objects and scenes, the characterizing features are features of appearance on the one hand--contours and objects—and features of action or behavior on the other—movements and activities. Watch this connection between appearance and action.

What about events? Events take place in time, in contrast to objects and scenes, which take place in space. An essential characteristic of an event (e. g., Casati and Varzi 1996; Zacks and Tversky 2001) is that it has a beginning, middle, and end, normally a set of goals and subgoals. *Running* is an activity; *running a race* is an event. *Knitting* is an activity; *knitting a sweater* is an event. And so on, for *cooking* and *cooking a meal*, *reading* and *reading a book*, *singing* and *singing a song.* Like scenes, one event is distinguished from another by actions and objects: doing the dishes, making a bed, going to a movie each entails a different set of actions and objects.

7. Partitioning Objects.

Now that we've seen what constitutes whole objects, scenes, and events, we can begin to consider how the wholes are partitioned into parts. Objects can be decomposed in many different ways, for example, into sides, such as top, bottom, front, and back, or into material components, such as plastic, metal, or stone. However, when people are asked to decompose common objects such as bodies and cars and apples into parts, they typically produce components such as arms and legs and wheels and doors and peel and stem. Fort this kind of object parts, we again begin with contour. Except for circles and ellipses, contours of objects normally have protuberances, discontinuities, things that stick out. The relatively large changes in the contours of objects are especially informative and signal parts (e. g., Attneave 1954; Hoffman and Richards 1984; Hoffman and Singh 1997; Tversky and Hemenway 1984). Think of the arms and legs of people, chairs, and tables. Interestingly, the parts that extend from an object's contour have some of the visual characteristics of object contours; in particular, they are almost closed figures. Good parts are good figures, in the Gestalt sense of good. But parts that are good because they are distinct from the contours of objects turn out to be good for more abstract reasons. Good parts are also those that have functional significance, the legs of chairs and tables and people support them, and the arms of people are used for reaching and carrying and writing and slicing and any number of important activities (Tversky and Hemenway 1984).

Here again, the connection between appearance and action. For people, the appearance of objects often suggest or afford the actions appropriate for it; handles suggest grasping, flat solid things of a certain height suggest surfaces that can hold plates or computers, and flat solid things that are lower and smaller suggest sitting. An ancient adage reminds us that appearances can be deceiving, and indeed they can. Appearances are only suggestive, they are a starting point, a hypothesis; they bias the kinds of hypotheses people are likely to consider. Following this reasoning, different parts suggest different functions. The seat of chair is for sitting and the back for leaning. The peel of an apple protects the fruit, and the seeds insure the next generation. Contour discontinuities then provide two working hypotheses: distinctive parts have functional significance, and different parts have different functions.

This correspondence between appearance and function not only promotes inferences, it also seems to underlie a significant switch in the way that children group objects to form concepts. Before the school years, children tend to put together objects that share salient physical characteristics, typically shape or color, putting a fire engine with an apple because they are both red, or an orange with a ball because they are both round. Around six years of age, children make a major transition; they begin to sort objects by features not apparent from static objects, by function, fruit, vehicles, toys. This transition to categories based on function but not appearance happens earlier for objects that share parts, indicating that shared parts help children bootstrap to abstract categories (Tversky 1989).

A pile of arms and legs and heads and torsos doesn't make a person just as a pile of legs and tops doesn't make a table. The parts must be in the proper configuration. In fact, it is the proper configuration of parts that yields the contour characterizing a particular object.

8. Partitioning Scenes.

When asked to list parts of scenes, indoor ones like movie theaters and schools, as well as outdoor ones like beaches and farms, people list objects, like tables and desks and water and fields (Tversky and Hemenway 1984). Typically, the objects are associated with the activities that people list for scenes, chairs for viewing the movie and a screen for projecting it, fields for sowing and tractors for harvesting. As for objects, parts of scenes must be in the right configuration, but the constraints on configurations of scenes are far looser than those on objects. For a movie theater, the seats should face the screen, and the ticket booth and the food concession should be outside the auditorium; for a farm, the fields are separated by crop, and separate from the living quarters and the storage sheds.

9. Partitioning Events.

As we have seen, objects could be partitioned on two levels, a level of perceptual abstraction and a level of semantic meaning. These coincide to a large extent. Objects can be abstracted to contours, to shapes; discontinuities in the contour define segments, forming boundaries of parts. The specific parts of particular objects have meaning, the peel and stem of an apple, the handle and blade of a knife. An analogous phenomenon occurs for events. Events can be regarded as having a contour, amount of activity over time. Continuing the analogy from object parts, large changes in amount of activity should signal event parts. This has been found both for everyday events like making a bed or doing the dishes and for abstract events, geometric figures interacting in a rudimentary environment (Martinet al. in press; Martin et al. in preparation). The task of participants was to watch films of events, pressing a button every time they thought one event segment ended and another began. There was agreement within and across participants on event boundaries, and these tended to correlate with relatively large changes in action.

The semantic level of event parts can be revealed by asking participants to describe what happens in each segment as they segment events (Zacks et al. 2001). The vast majority of descriptions are actions on objects: rinse the dish, spread the sheet, pour the water, attach the sideboard. Event segments, then, are action-object couplets, inseparable as parts of specific events. Participants segmented at two levels, the coarsest level that made sense to them and the finest level that made sense to them. At the coarse level, making a bed consisted of taking off the bedding, putting on the bottom sheet, putting on the top sheet, putting on the blanket, putting the pillows in pillow cases. Thus, at the coarse level, each new segment entails acting on a new object (or object part). At the fine level, each new segment entails a new action on the same object; thus the segments composing putting on the bottom sheet consist of spreading the sheet, tucking in one corner, tucking in another corner, smoothing the sheet. If the coarse level of events is distinguished by new objects and the fine level by articulated actions on the same object, it makes sense that larger changes in action accompany coarse segments than fine and fine than in between segments.

Roughly two categories of events can be distinguished, events by hands and events by feet (Tversky et al. 2004). Events by hands include making a bed and putting together a piece of furniture; these involve complex, coordinated movements of hands, arms, head, legs, and body. Events by feet are finding one’s way in the world, typically routes. Events by feet tend to be simpler. Although they entail coordinated movements of all parts of the body, they can be abstracted as whole-body movements. Think of describing or depicting events by hands as opposed to events by feet. Events by feet can be abstracted visually as a line turning at intersections or verbally as a description of actions at landmarks (e. g., Denis 1997; Tversky and Lee 1998, 1999). Making a bed, tying a knot, assembling a TV cart are not so easily described or depicted. These two kinds of events, by hands and by feet, bind interestingly to two other entities central to our lives, objects and scenes. In events by hands, people manipulate objects; in events by feet, people move about in scenes. The relationships continue: manipulating objects and moving in scenes underlie two noteworthy ways of mentally transforming parts and wholes.

10. Mental Entities: Categorizing

Things can be grouped in many different ways, and at different levels. Let's begin with objects, as the considerable research on object categories has served as a paradigm for research and thinking about other categories (e. g., Rosch 1978). An easy way to group objects is by salient perceptual features, putting all the red things together, or all the square things. But red things, fire engines and apples and red shirts, don't share other features, so they don't constitute a good category. Shape, another salient perceptual feature, works for a while; it puts shirts together and separates them from bananas and violins. Shirts, bananas, and violins not only share appearance, they also share function. Shape won't work at a higher level; suitcases and TV sets and other rectangular tings don't form a good category for most purposes.

This brings us to levels. As we've seen, t-shirts are kinds of shirts and shirts are kinds of clothing, just as sedans and convertibles are kinds of cars and cars are kinds of vehicles. There is a tension in levels: the more specific the level, the more informative. Convertible has all the features of car and then some, just as car has all the features of vehicle and then some. But there is a cost to the informativeness: more categories to keep in mind. Long ago, Roger Brown observed that although objects can be referred to a variety of levels, one level, the level of chair and grapes and violin seems to be preferred across a broad range of contexts (Brown 1958). A student of his, Eleanor Rosch, took the challenge. It turns out that this level, the *basic* level, maximizes the informativeness of categories relative to the number of alternative categories that must be kept in mind. When asked to list attributes of categories at varying levels of specificity, people produce few shared features for the superordinate level, the level of vehicle and musical instrument, but a large number of features for the basic level, the level of car and guitar. The subordinate level, the level of sedan and acoustic guitar, yields few additional features. Perhaps because of its' greater informativeness, it turns out that the basic level is distinguished by the convergence of many cognitive operations, some based on appearance, some on behavior, some on communication: it is the highest level for which an image can be formed, the highest level for which a behavioral program can be generated, the level that children first use and that languages first develop, as well as the most frequent level (Rosch 1978). One feature especially prevalent at the basic level is parts, and parts seem to form the bridge between appearance and function or behavior (Tversky and Hemenway 1984). Another significant fact about the basic level is that because it is relatively more informative and relatively more frequent, it is the level that people have thought most about, so it serves as a paradigm or prototype, if only to contrast with other exemplars. So when we think about fruit, we are likely to think about apples and when we think about musical instruments, we are likely to think about pianos.

The notion of basic level has been extended from objects to other entities, by using the criteria for establishing a basic level in objects (Rosch 1978). The key to identifying the basic level is the relative proliferation of attributes listed by people indicative of the relative greater informativeness of the basic level. For scenes, the basic level for outdoor scenes is the level of beach and forest; for indoor scenes, the level of school or restaurant (Tversky and Hemenway 1983). For events, the basic level is the level of going to the movies or shopping for groceries (Rifkin 1985; Morris and Murphy 1990).

11. Emergence.

That one level of abstraction, of thought, of reference is privileged over others means implies that thinking at that level is different from thinking at other levels. There are features of objects, events, and places that emerge at the basic level that are not apparent at other levels of abstraction. The level of *fuji apple* or *Toyota Prius* or *Safeway Supermarket* call up properties like *sweet/sour* or *fuel-efficient* or *open 24* hour, that is, appearances, whereas the level of *fruit* or *vehicle* or *store* call up properties like *edible* or *transports people* or *place to buy things*, that is, functions. The basic level, the level of *apple*, *car*, and *grocery store*, calls up both properties of appearance and properties of use. These connections between form and function make for an especially productive level of thought. The choice of level of thought determines the kinds of properties that lemerge.

12. Mental Transformations

We have now characterized how people think about the major entities of the concrete world people interact with, objects, scenes, and events. To use these entities in creative thought requires transforming them. Let us now turn to characterizing the kinds of mental transformations the mind does. Thinking about events brings us naturally to manipulations as events entail acting on or with respect to objects. In events by hands, people act on objects, manipulating them, transforming them. In events by feet, people act in scenes, changing their locations or orientations. One remarkable feat of the human mind is that it can mentally perform many of the physical transformations hands, feet, and bodies can perform. Might the mental transformations people perform on objects and in scenes have analogs in abstract thought? First, let us examine some of the multitude of transformations the mind performs. What is notable about many mental transformations is that they have perceptual or physical analogs, suggesting that they are internalizations of perceptual or physical processes (cf. Finke and Shepard 1986; Shepard and Podgorny 1978; Tversky 2005).

13. Transformations of Objects.

Perhaps the most famous of the mental transformations is mental rotation (e, g., Shepard and Metzler 1971). In this task, participants judge whether two identical objects, such as blocks linked at varying angles or letters, that differ in spatial orientation are the same or mirror images of each other. The time to make the judgment increases with the angular disparity between the objects, as if people were mentally rotating them into congruence. The perceptual-physical counterpart of mental rotation is watching objects rotate in real life. The pattern of reaction times from this task is also consistent with piecemeal comparison as well as smooth, wholistic rotation. There are other mental transformations that can be performed on objects, some wholistic, like mental size transformations (Bundesen et al. 1981) and some piecemeal, like decomposing and reconfiguring parts (e. g., Kosslyn 1980). As with mental rotation, there are clear real-world perceptions and tranformations that seem to underlie the mental operations.

14. Transformations of Perspective.

These are mental transformations that can be performed on objects, as if looking at them or manipulating them from outside. There is another set of mental transformations, again corresponding to perceptual or physical transformations, that can be performed as if from inside the object. These have been termed mental transformations of perspective (Zacks and Tversky 2005). What is especially intriguing about mental transformations of one’s body is that they seem to entail motor imagery as well as visuospatial imagery. As for object transformations, perspective transformations include mental rotations in space (e. g., Bryant and Tversky 1999; Franklin and Tversky, 1990; Parsons, 1987a) as well as mental translations of position in space (e. g., Reiser 1989; Presson and Montello 1994). They also include mental transformations of parts of the body, notably, hands and feet (Parsons 1987b).

15. Spatial Mental Models and Mental Transformations from Language.

Significantly, language is an effective medium for inducing spatial mental representations as well as mental transformations of them, rotations, translations, and other mental transformations (e. g., Franklin and Tversky, 1990; Lee and Tversky 2005; Taylor and Tversky 1992a; Tversky 2005). These simple experiments illustrate the enormous power of the mind to imagine worlds and imagine changes in them. That said, some feats of the mind depend on the body. Actual movements of the body or parts of the body seem to be needed for certain feats of imagination, notably updating fine-grained mental rotation of perspective (e. g., Klatzky et al. 1998; Reiser 1989). The roles of movements of the body, including gestures, in promoting thought are just beginning to be explored. In one set of studies, participants who explain how to put something together or how to get from A to B using only gesture rather than the more natural speech and gesture produce explanations that are more effective for themselves and for learners (Lozano and Tversky 2005, in press). In another set of studies, imagined movements were needed to correctly solve spatial problems; imagined perceptions were insufficient (Schwartz 1999; Schwartz and Holton 2000).

16. Sequencing Mental Transformations in Service of Thought.

Solving problems and flights of creativity typically involve a sequence of mental transformations. In solving geometric analogy problems, people perform a series of mental transformations, translation, rotation, changing size, adding parts. There is a preferred order for performing the mental transformations, and requesting participants to use another order increases error and solution time (Novick and Tversky 1987). Significantly, the order corresponds to the order of decisions in drawing, yet another example of internalization of a physical process in the service of mental problem solving.

The two major mental transformations of the body, rotation and translation, when organized and linked, constitute the backbone of route directions or descriptions (e. g., Denis 1997; Lee and Tversky 2005; Taylor and Tversky 1992a; 1992b; 1996; Tversky and Lee 1988; 1989). Route descriptions consist of a series of actions, typically turns, at landmarks. Importantly, when people are asked to describe environments large or small, they frequently take listeners on imaginary tours of the environments, both outside environments such as cities or parks and inside environments such as museums and hotels (e. g., Taylor and Tversky, 1992b; 1996). Moreover, from such descriptions, readers can construct accurate and detailed maps of the environments. These findings have significant implications: they highlight that continuous environments are segmented by critical landmarks, those at action points, and that these kinds of spatial descriptions are adequate to evoke rich mental representations.

Environments large and small, inside and outside, often elicit descriptions with another spatial perspective, a bird's view from above, or survey perspective (e. g., Taylor and Tversky 1992b; 1996). Characteristics of the environments influence which perspective is adopted (Taylor and Tversky 1996). Route and survey descriptions are equally successful in inducing integrated and accurate mental representations of the environments, as indicated by answers to inference questions from both perspectives and production of accurate sketch maps (Taylor and Tversky 1992b). These data, along with others, point to another remarkable feat of the human mind. From embedded experience in an environment, people can produce overview maps that integrate areas too large to be seen from a single glance. Similarly, from an overview map, people can imagine an embedded perspective, and generate routes to explore the environment (cf. Tversky 2005).

17. Implications

The richness of the world is reflected but abstracted in the richness of the mind. The mind constructs representations of the things and events in the world of import to humans and their activities. In order to successfully act in and on the world, the mind must also predict, simulate, and anticipate changes in the things in the world. These necessitate a rich set of mental manipulations. Mental transformations are also rooted in the world, in the actual manipulations that people observe or do. These representations and transformations of the concrete are available for the imagination. But the mind does not just reflect, it abstracts, both the representations and the transformations. This means that objects, places, and events can be regarded at different levels of abstraction, and can be manipulated by different mental transformations. From focusing on different levels and trying different transformations, a multitude of new properties emerge, the potential for new ideas.

This, then, is what the eccentric building parts of Herzog and de Meuron were meant to do. And judging from the completed models also in the exhibit, they did.

Footnote

The author wishes to express her appreciation to the Russell Sage Foundation for a congenial and scholarly atmosphere for thought and work, and to her collaborators on the various projects discussed here, in particular, Kathy Hemenway, Laura Novick, Nancy Franklin, Holly Taylor, David Bryant, Paul Lee, Jeff Zacks, Bridgette Martin, and Sandra Lozano.

References

Attneave F: 1954, Some informational aspects of visual perception, *Psychological Review* **61**:183-193.

Brown R: 1958, How shall a thing be called? *Psychological Review*, **65**: 14-21.

Bryant, DJ and Tversky B: 1999, Mental representations of spatial relations from diagrams and models, *Journal of Experimental Psychology: Learning, Memory and Cognition* **25**: 137-156.

Bundesen, C, Larsen, A and Farrell, JE: 1981, Mental transformations of size and orientation, In A Baddeley and J Long (eds), *Attention and Performance* IX, Hillsdale, NJ: Erlbaum pp. 279-294.

Casati R and Varzi, AC: 1996, *Events,* Aldershot, England ; Brookfield, Vt.: Dartmouth.

Denis M: 1997, The descriptions of routes: A cognitive approach to the production of spatial discourse, *Current Psychology of Cognition* **16**: 409-458.

Finke, R and Shepard, RN: 1986, Visual functions of mental imagery, *in* KR Boff, L Kaufman, and JP Thomas (eds), *Handbook of Perception and Human Performance*, Vol. II, NY: John Wiley & Sons. pp. 19-55.

Franklin N and Tversky B: 1990, Searching imagined environments, *Journal of Experimental Psychology: General* **119**, pp. 63-76.

J Hochberg: 1978, *Perception,* Englewood Cliffs, NJ: Prentice-Hall.

Hoffman, DD, Richards, WA: 1984, Parts of recognition, *Cognition* **18**: 65-96.

Hoffman, DD and Singh, M: 1997, Salience of visual parts, *Cognition* **63**: 29-78.

Klatzky, RL, Loomis, JM, Beall, AC, Chance, SS and Golledge, RG: 1998, Spatial updating of self-position and orientation during real, imagined, and virtual locomotion, *Psychological Science* **9**: 293-298.

Kosslyn, SM: 1980, *Image and Mind,* Cambridge: Harvard University Press.

Lee, PU and Tversky B: 2005, Interplay between visual and spatial: The effects of landmark descriptions on comprehension of route/survey descriptions, *Spatial Cognition and Computation* **5**(2 &3): 163-185.

Lozano, SC and Tversky B: (in press), Communicative gestures facilitate problem solving for both communicators and addressees, *Journal of Memory and Language*'

Lozano, SC and Tversky B: 2005, Gestures convey semantic content for self and others, *Proceedings of the Cognitive Science Society Meetings*. Mahwah, NJ: Erlbaum.

Malt, BC and Smith, EE: 1982, The role of familiarity in determining typicality, *Memory & Cognition* **10:** 69-75.

Mandler, JM, and Parker, RE: 1976, Memory for descriptive and spatial information in complex pictures, *Journal of Experimental Psychology: Human Learning and Memory,* **2**: 38-48.

Martin, BA, Recchia, G and Tversky B: (in preparation), Physical cues to intentional structure in everyday human action, *Manuscript*, Stanford University.

Martin, B, Tversky, B and Lang, D: (In press), Making sense of abstract events: Building event schemas. *Memory and Cognition*.

Miller, GA and Johnson-Laird, PN: 1976, *Language and Perception,* Cambridge, MA: Harvard University Press.

Morris, MW and Murphy, GL: 1990, Converging operations on a basic level in event taxonomies, *Memory & Cognition* **18**: 407-418.

Novick, LR and Tversky B: 1987, Cognitive constraints on ordering operations: The case of geometric analogies, *Journal of Experimental Psychology: General* **116**: 50-67.

Parsons, LM: 1987a, Imagined spatial transformation of one's body, *Journal of Experimental Psychology: General* **116**: 172-191.

Parsons, LM: 1987b, Imagined spatial transformations of one's hands and feet. *Cognitive Psychology* **19**: 192-191.

Podgorny, P and Shepard, RN: 1978, Functional representations common to visual perception and imagination, *Journal of Experimental Psychology: Human Perception & Performance* **4**: 21-35.

Presson, CC and D Montello: 1994, Updating after rotational and translational body movements: Coordinate structure of perspective space, *Perception* **23**: 1447-1455.

Rieser, JJ: 1989, Access to knowledge of spatial structure at novel points of observation, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **15**: 1157-1165.

Rifkin. A: 1985, Evidence for a basic level in event taxonomies, *Memory & Cognition* **13**: 538-556.

Rosch, E: 1978, Principles of categorization, *in* Rosch, E and Lloyd, B (eds), *Cognition and Categorization,* Hillsdale, NJ: Lawrence Erlbaum Associates. pp. 27-48.

Schwartz, DL: 1999, Physical imagery: Kinematic vs. dynamic models, *Cognitive Psychology* **38**: 433-464.

Schwartz, DL and Black T: 1999, Inferences through imagined actions: Knowing by simulated doing, *Journal of Experimental Psychology: Learning, Memory, and Cognition* **25**: 116-136.

Schwartz, DL and Holton, DL: 2000, Tool use and the effect of action on the imagination, *Journal of Experimental Psychology: Learning, Memory and Cognition* **26**: 1655-1665.

Shepard, RN and Metzler, J: 1971, Mental rotation of three-dimensional objects, *Science* **171**: 701-703.

Shepard, RN and Podgorny, P: 1978, Cognitive processes that resemble perceptual processes, *in* WK Estes (ed.), *Handbook of Learning and Cognitive Processes* **5**: 189-237. Hillsdale, NJ: Erlbaum.

Spelke, ES, Gutheil, G and Van der Valle, G: 1995, The development of objects perception, *in* Osherson, D (ed.), *An Invitation to Cognitive Science* **2**: 297-330. Cambridge, MA: MIT Press.

Taylor, HA and Tversky, B: 1992a, Descriptions and depictions of environments, *Memory and Cognition* **20**: 483-496.

Taylor, HA and Tversky, B: 1992b, Spatial mental models derived from survey and route descriptions, *Journal of Memory and Language* **31**: 261-282.

Taylor, HA, and Tversky, B: 1996, Perspective in spatial descriptions, *Journal of Memory and Language* **35**: 371-391.

Tversky, B: 1989, Parts, partonomies, and taxonomies, *Developmental Psychology* **25**: 983-995.

Tversky, B: 1985, Categories and parts, *in* Craig, C and Givon, T (eds), *Noun Classes and Categorization,* John Benjamins, Philadelphia, pp. 63-75,

Tversky, B: 1990, Where partonomies and taxonomies meet, *in* Tsohatzidis, SL (ed.), *Meanings and Prototypes: Studies in Linguistic Categorization,* London: Routledge, pp. 334-344.

Tversky, B: 2005, Visualspatial reasoning, *in* K. Holyoak and R. Morrison, (eds). *Handbook of Reasoniong,* Cambridge University Press, Cambridge.

Tversky, B and Hemenway, K: 1983, Categories of scenes. *Cognitive Psychology* **15**: 121-149.

Tversky, B and Hemenway, K: 1984, Objects, parts, and categories. *Journal of Experimental Psychology: General* **113**:169-193.

Tversky, B and Lee, PU: 1998, How space structures language, *in* Freksa, C, Habel, C and Wender, KF (eds), *Spatial Cognition. An Interdisciplinary Approach to Presenting and Processing Spatial Knowledge,* Berlin, Germany: Springer-Verlag Press, pp. 157-175.

Tversky, B and Lee, PU: 1999, Pictorial and verbal tools for conveying routes, *in* Freksa, C and Mark, DM (eds), *Spatial Information Theory: Cognitive and Computational Foundations of Geographic Information Science*, Berlin: Springer, pp. 51 64.

Tversky, B, Zacks, JM, and Lee, PU: 2004, Events by hand and feet, *Spatial Cognition and Computation* **4**: 5-14.

Zacks, JM, Mires, J, Tversky, B and Hazeltine, E: 2002, Mental spatial transformations of objects and perspective, *Spatial Cognition & Computation* **2**: 315-322.

Zacks, JM, and Tversky, B: 2001, Event structure in perception and conception. *Psychological Bulletin* **127**: 3-21.

Zacks, JM, and Tversky, B: 2005, Multiple systems for spatial imagery: Transformations of objects and perspective, *Spatial Cognition and Computation*

Zacks, JM, Tversky, B and Iyer, G: 2001, Perceiving, remembering, and communicating structure in events. *Journal of Experimental Psychology: General* **130**: 29–58.

SOCIAL MODELS OF CREATIVITY

Social models of creativity
Ricardo Sosa and John S Gero

Where creativity comes from
Sean Hanna

Beyond Binary Choices: Understanding and exploiting trade-offs to enhance creativity
Gerhard Fisher

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 19-44

SOCIAL MODELS OF CREATIVITY

Integrating the DIFI and FBS frameworks to study creative design

RICARDO SOSA
Instituto Tecnologico de Estudios Superiores de Monterrey, Mexico

and

JOHN S GERO
University of Sydney, Australia

Abstract. This paper presents a framework for experimentation about design as a social activity. It accounts for the complementarity of generative and evaluative processes by individuals and groups and is used to inspect phenomena associated with creativity in the interaction between designers and their societies. The results illustrate ways in which the role of designers as change agents of their societies can be largely determined by how evaluating groups self-organise over time. An implication is that the isolated characteristics of designers may be insufficient to formulate conclusions about the nature and effects of their behaviour. Instead, causality could be attributed to situational factors that define the relationship between designers and their evaluators.

1. Introduction

The study of creativity tends to concentrate on individual processes. Conventional creativity research has aimed at explaining the characteristics that distinguish a person, a product, or a generative process as creative. The often implicit assumption in the field is that creativity can be explained in terms of internal mechanisms or qualities that a few special individuals possess, and others lack. However, well-known concepts such as historical or H-creativity (Boden 1994; Sternberg 1999) and big-C creativity (Gardner 1993) have acknowledged social evaluation as central in the definition of creativity. Namely, creativity has been defined as "the generation of ideas that are both novel and valuable … and values are negotiated by social groups" (Sternberg 1999). A key question is therefore: How can we understand creative design based on the study of an independent generator (in laboratories or computational models) in isolation, leaving outside interaction with the social level?

Communication between studies of generative and evaluative phenomena seems necessary to understand creativity as the product of the interaction between individual and social behaviours (Csikszentmihalyi 1988). To enable the study of the social nature of creativity in design, we have developed computational social simulations in recent years (Sosa 2005; Sosa and Gero 2002, 2003a, 2003c, 2004a, 2004c). This paper summarises some of the key aspects of our frameworks, their potential contributions, and a number of important insights based on this work.

2. Framework

This section introduces an experimental framework for the study of social aspects of creativity in design. The aim is to capture principles of behaviour and interaction in complex systems, which could help understand the dialectical relation of design and society.

2.1. CELLULAR AUTOMATA (CA)

In previous studies we have presented CA models to study the role of design in triggering social change (Sosa and Gero 2003b). These studies extend the canonical modelling of social influence used to explain the diffusion of values and the persistence of diversity in a social group. In such CA models, large groups or populations exhibit emergent coordination based on a set of simple rules of decentralised behaviour that instructs a large number of individuals to exchange values at the local level as a function of compatibility with their neighbours (Axelrod 1997).

Extensions that we have carried on these models include CA where a minority of individuals in the population is able to introduce new values instead of only exchanging existing values with their neighbours. The effects of this behaviour of 'dissent' over long periods of time provides a number of insights regarding the potential of design to trigger social change (Gero 2000). A new value originated by an individual or a minority may be first adopted by adjacent contacts, and it may continue to spread across the greater social group until it becomes dominant in a population. New subsequent values may be introduced and they may be adopted by all or a large majority of individuals in a group creating a cycle of 'creative destruction' (Schumpeter and Clemence 1989). The likelihood of any given value introduced is determined in a CA of this type by a number of factors. Firstly, our results have shown that individual dissent can remain at low levels and still be able to trigger cycles of collective change. Only if a majority of individuals interacting at the local level follow a convergent behaviour, can a value be spread and become dominant (Sosa and Gero

2002). In other words, a majority of imitators coupled with a minority of dissenters, is necessary and sufficient to support group formation or 'cultural emergence' (Axelrod 1997), as well as periodic transformations or 'revolutions' (Kuhn 1974) in these types of decentralised, self-organising, complex social systems.

We have also used CA models to show that the role and impact of a minority is importantly determined by different types of factors that are not always obvious. For instance, keeping the individual rules of behaviour unchanged, we have shown that by varying the 'degree of separation' in a social group, one can control the resulting emergent patterns of diffusion and group transformation. The higher the distance between neighbours of adjacent individuals, the higher the likelihood of sustaining diversity in a group. Consequently, in same-size social groups where acquaintances are less likely to be shared between individuals, novel ideas are more likely to be shared by groups and more alternative ideas may become dominant for shorter periods of time. In contrast, in same-size groups where acquaintances are largely the same between individuals, a novel idea is less likely to be spread, but once it does it will show more 'cultural resilience' (Sosa and Gero 2003b). The key implication is that in self-organising systems the probability of a design artefact of being adopted and of maintaining the preference of a society can be a function of social factors, which sit outside the artefact's properties.

Lastly, we have also used CA models to illustrate a fundamental social principle: non-linear causality of change. In decentralised systems where chaotic phase transitions can occur, individual properties of change agents are not strong determinants of group change (Sosa and Gero 2003a). Non-linearity refers to the observation that individuals or minorities may trigger an equivalent number of types of change episodes in their societies, even if their individual potential of dissent differs significantly. The first reason for this apparent paradox is that certain social conditions may be necessary for dissent behaviour to emerge in the first place; i.e., disagreement is only possible as a response to some convergent state of neighbours, which lies outside the control of the change agent. Secondly, social conditions may also be necessary for dissent behaviour to have an effect at the collective level; i.e., the success of novel ideas depends on the behaviour of others. For these reasons, it would be inaccurate to infer or attribute any special characteristic to individuals that trigger group changes in CA-like systems. The latter show that episodes of social change depend on a timely combination of individual and social processes.

The types of insights extracted from manipulating CA models are of interest because they enable analysis of interaction patterns in complex systems. However, the principles that one can formulate based on this type of evidence are too general to contribute towards a theory of creativity in design. Namely, CA models can be applied to many different systems including insect colonies, magnetic particles, and chemical structures (Wolfram 1986). The underlying characteristics of these social, biological, and physical systems is their ergodicity: the tendency to converge from any given initial state (Liggett 1985). This has been shown to be a product of recurrent randomness, which characterises one and two-dimensional modelling spaces like those usually used in CA representations (Wolfram 2002). However, no evidence exists to support the idea that social systems are one or two-dimensional, human societies are often described as multi-dimensional systems when represented by social networks. In such types of systems, transient random walks cause non-ergodicity, i.e. maintenance of diversity. CA have been shown to illustrate a number of ways in which design can be seen as a source of cultural diversity (Sosa and Gero 2002).

Nonetheless, the over-simplification inherent to CA models, equips them with little explanatory power. How, when and why change is triggered in CA societies, are all questions ultimately answered by their stochastic nature. All emergent group dynamics occur 'because of randomness'. To attempt anything else, one needs a degree of causality based on an idea of agency.

2.2. MULTI-AGENT BASED SIMULATION (MABS)

Social ability in multi-agent systems is still poorly understood. In the canonical multi-agent system, behaviour is described at the individual level with no explicit representation of collective structures (Wooldridge 2002). In such systems, the agent-environment divide conflates the social and the physical states of the system. Insects and particles may be veridically modelled in such way where sociality is construed by the observer outside the system. However, in human agency second-order emergence is necessary to support awareness of others (Conte et al. 2001).

To develop a multi-agent based simulation (MABS) of design, we adopt the basic units of a social system of design drawn from the Domain-Individual-Field Interaction (DIFI) map of creativity (Feldman et al. 1994). This framework can be used to locate creativity in the interrelations of three main parts of a design system: domain, field and individual designer. The domain consists of the set of shared knowledge, beliefs, techniques, and evaluation criteria shared by the members of a given community. Fields include groups of individuals who share a common domain. The key implication of the DIFI framework is that creativity is not reduced to the characteristics of individual designers, products, or processes. Instead, situated in a dynamic environment and in relation to external factors, creative designers generate 'the right product at the right place and at the right time' (Simonton 2000) where 'rightness' is largely defined by the society.

To specify the behaviours of DIFI components in a computational social model of design, we apply the FBS framework, a knowledge representation schema to represent design processes (Gero 1990). Designing is defined as the transformation of function (F) into the design description of an artefact capable of producing that function. The artefact's attributes and their relationships are labelled its structure (S). In designing, the behaviour of the structure (Bs) is directly derivable from structure. The expected behaviour (Be) provides the agreed means by which function can be achieved independent from structure. It also represents the knowledge about which behaviours of the structure are of interest.

The FBS framework can be applied into a social system to acknowledge the dual nature of design artefacts. Firstly, artefacts may be physical objects with behaviours (B) that one may call 'objective', i.e., properties derived from a structure's materials, topology and dimensions using a causal theory. An example is the strength behaviour of materials used to manufacture the body of a car. Secondly, artefacts may be social objects with behaviours (B) that one may call 'subjective' as they are derived by the designer(s) and by social consensus or norms (Kroes 2003). An example is the luxury status associated to certain brands of cars. The second type of behaviours (B) are often derived by non-designers, in particular in innovative practices by users (Von Hippel 2005).

The next subsections introduce in general terms the three main system components of our framework shown in Figure 1 including designer agents, fields of adopter groups, and domains or repositories.

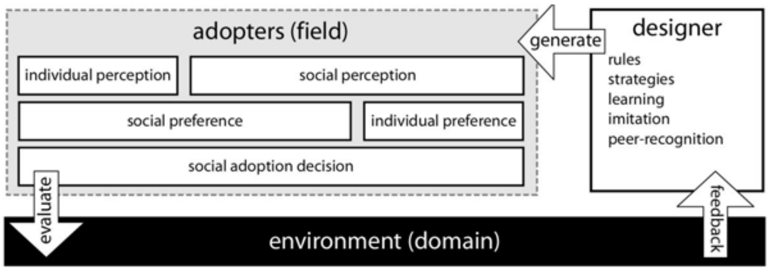


Figure 1. A multi-agent architecture that implements a social view of creativity.

2.2.1 Designers

Individual designers are represented by computational agents whose role is to specify the description (D) of new artefact structures (S). In certain design domains such as virtual design, designers not only provide descriptions but also build artefacts, so at least in that sense one can conflate design with production. Other design domains may require a differentiation between built and non-built artefacts to enable the study of certain phenomena. In our framework, we adopt the former viewpoint and interpret design output as directly available to and evaluated by societies. In this sense, 'synthesis' can be defined as the use of expected behaviour (Be) in the selection and combination of structure based on a knowledge of the behaviours produced by that structure (Bs).

Be → S

Individual designers can also be said to carry on 'analysis' of design artefacts, that is, the determination of behaviours produced by structure (Bs), which draws from existing knowledge of the behaviours produced by different structures and their combination.

S → Bs

Structure is represented in our framework by simple two-dimensional shapes. This representation is chosen because it supports generation and evaluation mechanisms based on intuitive visual geometric features. It also supports multiple perceptions and shape emergence. As a result, it enables experimentation with some of the key aspects of design problems in multi-objective decision making.

Behaviour is represented by geometric and topological variables whose values are derivable from such two-dimensional shapes and their combinations. Structural behaviour (Bs) is directly obtained from structure (i.e., two shapes with equal left-side coordinates yield a behaviour of alignment). Expected behaviour is represented by geometric preferences, which can be attributed based on different perceptions of design artefacts, and which can be manipulated by groups as the next subsection describes. Behaviour in our framework is a matter of degree and is determined by numerical values assigned to design artefacts based on geometric criteria, i.e., "how well an artefact 'performs' rotation or reflection".

Figure 2 shows a sample artefact based on a two-dimensional representation, and a number of structure features perceived by agents.

Each table is inserted in the text after the first reference to it. Tables are numbered and table captions (in 10 pt Times New Roman are placed above the table, centred, and have the following style:

Figure 2. Two-dimensional representation of design artefacts and perceived features

Figure 3 shows a sample set of behaviours represented by geometric relationships between shapes of a set: uniform scale, reflection, and rotation.

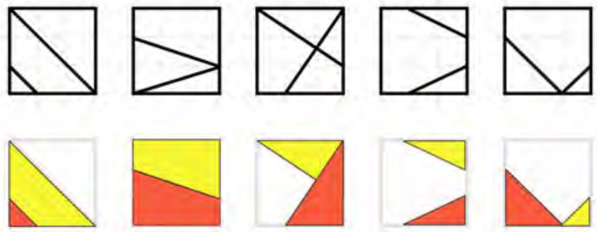


Figure 3. Behaviours represented as geometric relationships in artefact features

A range of relevant issues can be studied in relation to synthesis and analysis processes carried out by designers. For instance, differences in individual abilities, frequencies of behaviour, expertise, relation to competing designers and their knowledge, and strategies are some of the variables that we have started to explore (Sosa 2005). Individual abilities are made operational by parameter ranges that determine how a designer agent generates and applies knowledge to create or modify artefacts. This enables the simulation of scenarios where designer agents competing or collaborating in a system have different abilities and what role these differences play in triggering change cycles. Frequencies of behaviour are determined in relation to other component behaviours such as evaluation. This enables the study of design scenarios where groups take adoption decisions at different frequencies: for instance, packaging and domestic appliances clearly have different generation-evaluation ratios and this may play an important role in determining creative instances and innovation cycles. Expertise can be studied by implementing designer agents with similar abilities but different 'histories'. This enables the study of possible relation between knowledge and creativity, which have been said to follow an inverted-U shape (Simonton 2003). Individual designers could also be conceived and implemented as teams or firms, delegating different abilities and roles to separate agents.

The particular mechanisms and values considered in our studies have not been used to replicate previous findings; they are mostly hypotheses based in the literature and practice. However, this is often rather ambiguous since observations of social phenomena are usually not specific enough to be directly implemented. In such cases, we set parameters in order to explore a range of possible options and their effects. When these parameter ranges are set to extreme values, we do not assume them to be necessarily realistic; we are more interested in the transition values, which are more likely to capture real situations.

2.2.2 Field

Fields in the DIFI framework are social groups that share a domain (Feldman et al. 1994). In our studies, societies are integrated by agents that conduct evaluative behaviour of design artefacts. Namely,

Be ←→ Bs

The behaviour of the structure (Bs) of an artefact can be compared with the expected behaviour (Be) required to determine if the artefact is capable of producing the functions. This comparison can be seen as a social process of evaluation in design. Field evaluation is an aggregate process in which every adopter agent conducts an evaluation based on a multi-objective function. The product of this evaluation is exchanged in a social group through mechanisms of social influence based on threshold of behaviour (Granovetter 1978). Adopter agents need not have a standard evaluation behaviour, a range can be implemented by distributing different perceptions and different individual preferences randomly at initial time. These evaluative processes produce an emergent pattern of regular group convergence and interval transformations akin the non-ergodic collective coordination behaviour of the *n*-dimensional social models discussed earlier.

Adopter groups can be regarded as the source of artefact functions. However, in our models transforming function to expected behaviours (Be) remains in control of the experimenter, who formulates the type of geometric and topological properties and the distribution of random preferences and perception. Expected behaviour (Be) provides the syntax by which the semantics represented by function can be achieved. In our studies, the semantics are experimentally controlled whilst the artificial societies self-coordinate to 'grow' solutions. Moreover, we have replicated some of our findings changing those semantics in order to confirm the internal validity of our simulations (Sosa and Gero 2005).

Reformulation can be a change in expected behaviour (Be). The design process can be initiated (formulation) or transformed (reformulation) by social demands (social pressure) or by individual initiative (goal-based, opportunistic). In social groups, individual preferences and perceptions are exchanged. Whilst in our framework the experimenter initialises the design system, the dynamics of the system provide the means for reformulation. For each simulation it is impossible to predict what expected behaviours will emerge in a group, i.e. reformulation is self-organised in a society as an aggregate result of agent interaction.

F ←→ Be

Figure 4 illustrates how a design artefact can be perceived by different agents. Adopter agents can perceive different structure features of the sample artefact shown in Figure 2 as they build perceptions based on a branch limit used to guide a Hamiltonian search through the line set (Rubin

1974). The resulting closed shapes represent alternative structure features of the design artefact on which adopters will base their evaluation.

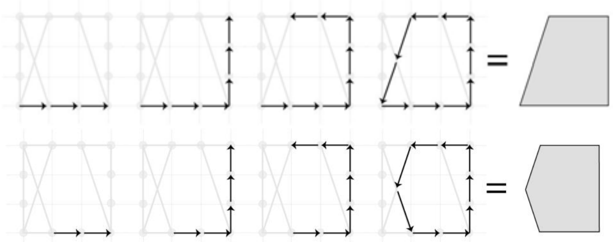


Figure 4. Hamiltonian search conducted by different adopter agents yield different perceptions of a design artefact

As a result of social interaction, adopter populations form aggregate hierarchical social structures. In this framework, these structures are determined by exchanges of preferences, percepts, and adoption decisions. Opinion leaders are defined as adopter agents with high influence over other agents as a result of social interaction. At initial time in a simulation, the set of opinion leaders is empty. The role of opinion leader is given to adopters whose influence is greater than one standard deviation above the mean of group influence. The role of opinion leaders in this framework is to enable interaction between adopters and designers. Firstly, leaders serve as adoption models providing designers with positive feedback for reinforcement learning. Secondly, they become 'gatekeepers' of the field by selecting artefacts for entry into the domain or repository, i.e. a collection of artefacts that defines the material culture of a population (Feldman et al. 1994).

Since the number of opinion leaders is, by definition, a small ratio of the adopter population, they are likely to spend more real and computational resources in the analysis of artefacts. This select group of specialised critics also determines behaviours produced by structure (Bs) in order to provide artefact performance feedback to design agents.

S → Bs

Field variables that we have explored in our studies include the size and the structure of social groups, the types of relationships between members of a group, the formation of hierarchies of influence, and frequencies of evaluation and decision making in relation to design behaviour. Social groups could also be conceived and implemented as teams by combining the roles of evaluation and generation to all the members of a small group. We have applied this view to study the potential effects of social interaction in production blocking in brainstorming groups (Sosa and Gero 2005).

2.2.3 Domain

The last model component to study creative design is the 'cultural' or epistemological source of a social system (Feldman et al. 1994). One can define domains as repositories of design structure (S) and knowledge (K). In our studies, designers and adopter groups mediate through the domain: some of the design artefacts that are generated by the former and evaluated by the latter may be regarded as high-rated solutions. Likewise, designers may draw from previous examples to guide their design strategies. The contents of a domain illustrate the 'material culture' of a society, as they are accumulated collectively by the population over a period of time.

A key threefold aspect of domains is that they are generated by designers, influenced by the adoption patterns of the field, and their content is ultimately determined by experts. Our studies have explored the assumption that certain rules of domains have significant effects in the interaction between individuals and fields. These aspects are set by the experimenter in simulations where all generative and evaluative mechanisms remain constant, and only domain variables are manipulated.

Firstly, the role of knowledge in creative design is addressed by defining two types of access to knowledge generated during the process of designing. These are defined by rules of protection or disclosure of information (i.e. Open-source vs. patenting systems). A series of experiments are conducted to analyse variations in all system levels: how designer agents design and how adopter agents evaluate under these conditions. Secondly, a series of rules and mechanisms of domain entry are explored including the cumulative increase of an 'entry bar' by which designers need to produce design artefacts that perform better than previous recent domain entries, and a novelty-seeking rule by which designers need to produce design artefacts that address different evaluation criteria from previous recent domain entries. Thirdly, the representation of design artefacts is modified by varying the size of the design space in order to assess the internal validity of the models.

Domain variables are often dependent variables in our experiments. We are interested in understanding what individual and social factors are likely to have an impact at the domain level including the size of design domains and the distribution of domain entries by designers (if selected artefacts are likely to be generated by all or most designers in the system, or if they may concentrate on one or a few of them).

3. Results

This section presents a summary of the main results obtained in our studies, and their potential relevance to the target phenomena of creativity and innovation in design.

3.1 DESIGNERS

The following subsections illustrate the complementary effects of individual and social aspects in the system.

3.1.1 Change Agents

One of the main aspects under inspection in our studies has been the role of designers as social change agents. Our results demonstrate in simple models of decentralised behaviour that dissenters can trigger change cycles in a bottom-up direction in a social group. The predominance of convergent behaviour in a population can be justified by its role as a key sense-making social element (Boyd and Richerson 1995). According to these results, ratios of up to 10% of dissent in a group are adequate to support group formation and cyclic transformations. When the possible number of individuals engaged in dissenting behaviour in human societies is considered, official census show that the ratio of creative occupations is a marginal proportion of the total population (United States Census Bureau 2000). Less rigorous definitions still yield a similar ratio of creative professions that aim to do things differently compared to "a vast majority engaged in doing the same things better" (Florida 2002).

This view of a minority of practitioners as change agents of their societies is pervasive in the literature. The principle of marginality has been used to imply that asynchrony or dissent is associated with creative behaviour (Gardner 1993). Moreover, creativity has been defined as a 'dialectical antithesis to intelligence' (Sternberg 2001), where intelligence is measured by adaptation to the customs of a society and creativity by the transformation of these customs. An implication of such a view is that creative individuals are 'a threat to the intellectual, social, and economic orders that societies create' (Sternberg 2001).

When creative designers are regarded as a minority group of dissenters, the effects of manipulating the rate of dissent in multi-agent models support the idea of creativity as a property of systems rather than isolated individuals since increasing the number of dissenters does not increase the rate of collective change linearly (Sosa 2005). Rather, we have shown that there may be a group-level 'ceiling' to the frequency of change that a group supports. Rates of dissent over such a threshold impede the basic processes of communication that generate the formation of coherent groups.

3.1.2 Individual Abilities

Although these agent models work with extremely simple generalisations, the results are consistent with the low predictability found in relation to individual differences measured in isolation (Ross and Nisbett 1991). This is typically expressed by low statistical correlations between measured individual differences on a given trait and observed behaviour in a situation that plausibly tests that dimension. For most novel behaviours, the predictive coefficient of individual differences is not significant (Ross and Nisbett 1991). This is not to imply that individual differences do not matter, but to indicate that their treatment as a sufficient condition of high performance has been probably exaggerated and oversimplified (Ceci and Williams 1999).

The role of individual differences can be considered in an additional way in social simulation. Experimentation with two types of individual abilities of designers has shown their insufficiency as predictors of task performance when individuals are considered as part of a dynamic group. Those experiments illustrate a key characteristic of complex systems: non-linear causality. Whilst initial individual differences stabilise over time due to contingencies modelled as stochastic processes, the potential effects of learning mechanisms further lessen the strength of initial individual differences. Our models demonstrate that learning and development of abilities allow individuals to circumvent their capacity limits, rendering some innate limitations largely irrelevant. This is consistent with the notion that instruction, support and practice often appears to be more important than innate talent in expert performance (Ericsson 1999).

Our studies have also suggested that an increase of individual traits need not be proportional to the effect of individual behaviour (Sosa 2005). For individual abilities of designers to adequately account for effects at the group level, differences between individuals would need to be considerably high. This would be inconsistent with what is known about distributions of intelligence and skills (Sternberg 1985). More importantly, even when certain abilities may account for some aspects of behaviour and possible effects, these need not be related to creativity. An example is provided in our modelling of knowledge formulation in design, where individuals with larger knowledge bases (more expertise) need not be more successful in measures potentially relevant to creativity and innovation than those with less knowledge available. Other researchers report similar types of interaction between expertise and creativity (Ericsson 1999). Furthermore, increases of individual abilities can also be associated to the improvement of competitors. Our models suggest that the degree of differences between competing designers need not have a direct effect in the triggering of social change. This observation can be related to the notion of 'spillovers' in innovation research. When individual agents in our experiments are assigned extremely high abilities, competing individuals with otherwise unchanged abilities also increase their performance as a side-effect of sharing information with more able competitors. Relevant empirical studies also conclude that competitors benefit from innovation within their industries regardless of its source (McGahan 1999).

3.1.3 Opportunities

Individual behaviour may combine with favourable circumstances to trigger social change. In CA models, such conditions are a product of the random location of cells on the environment. In contrast, MABS experiments capture the idea that the appropriateness of design behaviour in a system of generation and evaluation of design is collectively defined by the social group within which designers operate. A prime example of favourable conditions is the aphorism of the innovator standing 'on the shoulders of giants' attributed to Isaac Newton.

A key assumption in our studies has been the combination of habituation and novelty-seeking behaviour of adopters. Habituation refers to the tendency of adopters to increase their preferences for features with high scores, whereas novelty seeking is the process that allows adopters to update their preferences as a result of social convergence. If a design solution is considered as a compromise between conflicting objectives, it is generally assumed that a new artefact will displace an existing one when adopters perceive an advantage that the new holds over the existing artefacts (Rogers 1995). However, it has been shown that people tend to adapt to inconveniences or problems associated with long-existing artefacts (Petroski 1992). In our framework, causality of group change is attributed in two complementary directions. Firstly, the novelty-seeking behaviour of adopters demands the generation of new solutions by designers. Secondly, designer agents proactively seek new solutions that may reshape demand. This twofold mechanism in our model accounts for a type of non-ergodic 'cultural drift' (Axelrod 1997).

3.1.4 Peer Influence

An important component of creativity has been identified in the process of peer judgement (Amabile and Hennessey 1999). This is addressed in our studies mainly through the concept of influence between designer agents. During a system run, the cumulative number of instances where a designer receives recognition from imitative peers is recorded. The strongest effects in peer influence in our studies are registered from variations of design rate, where the frequency of design activity produces a linear correlation to peer recognition when plotted in a log-log scale. Namely, when design activity takes place frequently in comparison to gatekeeping and adoption processes, mean peer recognition increases nearly six times higher than on average. In contrast, as design activity gradually slows down, recognition between peers rapidly approaches the standard value recorded under all other independent variables considered. The effects of design rate in peer recognition are paralleled in our studies by its effects in the formulation of knowledge. Namely, frequent design cycles yield large knowledge bases and a high level of recognition between designers.

One way in which this insight could be verified empirically is to compare recognition between competitors in design domains with different mean lengths of product development cycles. Imitation of artefact features or payment of copyrighted material can be used as indicators of peer recognition in design. According to our studies, these indicators would be higher in domains where redesign occurs frequently as in car design than in domains where redesign is more sporadic as in truck design. In addition, innovation could be expected to be higher in design domains where larger knowledge bases are likely to exist.

3.1.5 Summary

An interdependent relationship between individual behaviour and the conditions and effects at the social level is observed in a number of findings from our research. To trigger a global change based on local behaviour, the actions of a change agent are importantly determined by necessary conditions that lie outside its control (i.e., previous knowledge). Once these adequate conditions exist, they ought to be perceived by the individual who has to be sufficiently able to execute the corresponding action. The frequency, independently of the actual content, of the action can determine influence between peers and the decisions and strategies in the design process.

Our studies demonstrate that at least some of the effects of design behaviour in society are determined by a range of situational conditions. The entire process can be seen as a match or adaptation between the individual and the social levels. This underlines the cautionary note that giving emphasis to either part of this chain of causation is misleading; an example being the recurring controversy whether causality of creativity originates at the individual or at the social level (Lloyd and Snelders 2003).

Other models of creativity from an evolutionary perspective have interpreted differences in creative activity among individuals as arising from a combination of innate and experiential factors (Findlay and Lumsden 1988). This view is consistent with the emphasis on the role of development. Our work in this regard demonstrates that the exceptionality of individuals that trigger group changes can be explained by a combination of individual and situational conditions. In relation to the individual processes of synthesis and analysis, the following can be summarised:

- Synthesis occurs less frequently than analysis and evaluation in creative design.
- Different synthesis processes can lead to creativity. No single process or set of processes can guarantee the generation of a creative solution, as the determination of creativity is product of two-level interaction in the system. There are a number of potential creative synthesis

processes, those which are relevant in place and time within a social environment are the ones that trigger cycles of change.

- The relationship between a synthesis process and its effects in evaluation is likely to be non-linear.
- A synthesis process that is not creative within a given situation, can be considered as creative and trigger a cycle of innovation in the same society if a situational factor or a set of situational factors change.

3.2 FIELD

The field has been defined in our studies as the collection of individuals that participate in the definition of a standard of what constitutes novelty and quality or utility, the two canonical elements in the definition of creativity (Feldman et al. 1994; Runco 2004). In this subsection some of the key aspects addressed in our work are analysed.

3.2.1 Group Size and Group Structure

Our studies have shown that the size of a social group may have key effects on the interaction between generators and evaluators of solutions. In CA models, very small populations do not support interaction between different individuals limiting the diffusion process. The apparent reason is that in smaller groups insufficient diversity yields incompatibility between evaluators that influence each other's decisions. In contrast, large populations where only local interaction takes place do support the exchange of opinions but take exponentially long periods to form consensus (Axelrod 1997). A clear implication from this result could be that large populations are likely to develop means of mass communication as a way to promote group coherence, an aspect that is outside the scope of CA modelling.

Whilst group size yields no further qualitative differences in our models, a constant population size is found to cause substantial differences when the arrangement of its members varies. One aspect is that with a constant type of local conditions, different common neighbours or 'friends-of-friends' network configurations have different effects. Experimentation with different grid structures has shown that besides local configuration, the degree of contact between individuals has an important effect on how new ideas are disseminated. When the neighbours of individuals are unlikely to be in contact with each other, diffusion can be expected to require substantially longer times and have qualitatively different outcomes than when the 'degree of separation' is lower. The degree of separation can be measured by the ratio of common neighbours between individuals in a social network.

Studies of field structure have served as a basis for the type of agent relations implemented in our studies. These assumptions are based on the widely accepted notion of the strength of social ties (Granovetter 1973). Ties represent contact between social actors represented by nodes in social networks (Wasserman and Faust 1994). One way to define the strength of social ties is by their duration over time, i.e., the probability that two nodes in a social graph remain connected over a period of time (Marsden and Campbell 1984). These assumptions account for the observation that for any given design field, potential adopters interact in a number of different social networks with different tie strengths such as kinship networks (strong ties) and acquaintance networks (weak ties). We have shown a number of insights in relation to tie strength and innovation including patterns in the design and adoption of artefacts, and the distribution of prominence for designers. In sum, our results reinforce the idea that populations where members are part of various contact networks are more likely to support the emergence and diffusion of new values. Recent studies of entrepreneurs consistently report that the most creative individuals spend more time than average networking with a diverse group that includes acquaintances and strangers (Ruef 2002). A combination of strong and weak ties is thus proposed as conducive to creativity.

A similar interpretation suggests that weak social ties facilitate the introduction of novel ideas (Florida 2002). In our studies, behavioural variety is supported by weak social ties where diversity of adoption opinions is higher than in equivalent social groups with strong ties. Others have suggested that societies that support more behavioural variety tend to go through rapid adoption cycles of new artefacts (Reinstaller and Sanditov 2004). Our studies further confirm that both the speed and scope of diffusion highly depend on the structure of a society.

3.2.2 Opinion Leaders

The behaviour and effects of opinion leadership in our studies contribute to the discussion of the link between individual designers and their societies. Biographic studies suggest that in more hierarchical fields (i.e., "where a few powerful critics render influential judgments about the quality of work") it is easier for a small number of creators to emerge and gain recognition and influence (Feldman et al. 1994). In agent societies with strong social ties, uneven hierarchies generate powerful opinion leaders that exert the role of gatekeepers to the domain. In contrast, in social networks with weak ties, influence is distributed among adopters and the expert judgements tend to vary over time. Consistent with Gardner's (1994) observation, the former social arrangement generates higher variance in the distribution of prominence whilst the latter yields more egalitarian distributions in our systems.

3.2.3 Evaluation Distribution

In our studies aggregate adoption decisions of a population are used to determine the distribution of adopters by designer. If the variance of adoption is high, then the artefacts generated by a few designers concentrate a high proportion of the adoption choices during a simulation run. If the variance of adoption is low, then adopters are said to distribute their choices across all available artefacts. In the former case prominence and differentiation are expected to be high whilst in the latter competition indices are likely to be high.

Our studies show that the distribution of adoption decisions is importantly determined by social factors such as the frequency of contact between adopters. In our studies when social connections between members of an evaluation group are replaced, social mobility is determined by the rate of link replacement. When no social mobility is possible, our studies show that variance of adoption rapidly increases to a mean level of 100%. However, even small amounts of social mobility proved sufficient to normalise this distribution. These differences in adoption variance are consistent with parallel effects of social ties in opinion leadership and domain characteristics.

3.2.4 Summary

Design behaviour has been addressed in the literature mainly as a cognitive phenomenon. This has advanced our understanding of creative design at the individual level but has shed little understanding on this activity as part of a social system. The general conclusion from our exploration of design as a social activity is summarised by the proposition that the ‘creative act’ does not end with the specification of a design solution. The synthesis of an artefact is only the starting point of a poorly understood process where creativity turns into innovation in the link between individual and social action, i.e., ‘design is a cognitive and a social process’.

The social forces acting on the creative individual can be classified in two periods, i.e., the earlier period in the production of ideas and the later period in their dissemination and evaluation. The relationship between collective factors and individual expression is extremely complex (Rudowicz 2003). Arguably, the main insight of situated behaviour is the principle that the same individual design behaviour can generate solutions that are regarded as creative within one social setting but not within a different one. In other words, macro conditions may provide the bases for particular generative processes, or they may facilitate particular effects on evaluative processes. The strongest evidence for this principle is the extemporaneous recognition of creativity. Whilst design artefacts remain unchanged, the social and cultural conditions may evolve to the point where evaluators are ready for such solutions.

One of the aims in this type of studies is to show that equivalent individuals and solutions could be considered creative or not by equivalent social groups depending on situational factors. This is an important challenge that would demonstrate that the creativeness of a solution is not an inherent property but one ascribed over time by others in a process which is subject to a range of circumstances.

In relation to the individual processes of synthesis and analysis, the following can be summarised:

- Who, how, and how many agents assess a design artefact will affect the outcome of such evaluation. If evaluators deliberate in large groups, solutions considered creative are likely to be more in number and more different from each other (a more diverse set). If evaluation is done without deliberation or in small groups, the result is likely to be a smaller set of creative solutions and more similar to each other. Namely, the set of expected behaviours (Be) and structure behaviours (Bs) are larger and of higher complexity in the former situations.
- Reformulation is likely to depend largely on social interaction. Expected behaviour (Be) can be shaped by social factors such as the types of social ties in a group, the structure of the group, and the mechanisms in place to define and operate opinion leadership. A Be-Bs mismatch can lead to new design processes (namely synthesis), or to new problems (formulation).
- Lastly, experts or critics in a social group (designers or not) can generate new knowledge via analysis by deriving new structure behaviour from design artefacts. Technological advances in materials and production are sample sources of new knowledge.

3.3 DOMAIN

Domains represent the epistemological level in a systems model of creativity (Csikszentmihalyi 1988).Whilst no formal criteria have been proposed for identifying a domain, in our studies design domains are defined as repositories or collections of artefacts and knowledge accumulated by a population over a period of time.

3.3.1 Knowledge

The learning mechanisms of design agents enable them to formulate knowledge in relation to the transformation of artefacts. Our studies have addressed two types of access to this knowledge or information generated during the process of designing. These are defined by rules of protection or disclosure of information.

When design activity is very frequent the generation of new knowledge increases. With small decreases in frequency of design activity, the size of knowledge bases reaches a stable level. The mechanism at work seems to be the collective production of knowledge. A parallel pattern is observed when designers have access to the knowledge generated by others. Disclosure of information causes an increase in generation of knowledge. Moreover, in both experiments other associated effects are observed: frequent rates of design activity and public disclosure of information yield lower variance of domain entries as well as higher domain scores and complexity. Seemingly, higher quality may be associated to the contributions of various sources supported by the disclosure of knowledge.

3.3.2 Gatekeeping

In practice, gatekeepers are individuals authorised to qualify the merits of creative solutions including their novelty and feasibility. Apart from patent examiners, other types of gatekeepers in design include venture capital firms, exhibition curators, journal editorial committees, and competition juries. Approval or endorsement of gatekeepers may be necessary to turn a new idea into an available product. Nonetheless, little is known about the role of gatekeeping in a) promoting or deterring the generation of creative solutions and b) initiating or promoting their diffusion and the social ascription of the 'creative' label to their creators. Gatekeepers such as patent examiners base their decisions prima facie, on references to other patents and ordinary skills, and on declarations from experts in the field. However, articulating these evaluations is often problematic and in many cases criteria are updated or made explicit based on litigations.

Gatekeeping in our studies is considered an emergent role that adopter populations assign to some of their members as an aggregate result of social interaction. In particular, influence of adoption opinions is taken as the condition to allocate the gatekeeping role, i.e., influential adopters become gatekeepers of the domain (Sosa and Gero 2004a). Our models show that the role of influential adopters as gatekeepers can be important in the rate and quality of design behaviour and the relation between designers and adopters. In particular, disclosure of information was shown to render larger domains with higher mean scores. This type of access also discourages the concentration of experts' selections on few designers. Therefore, under systems of high protection of information experts can be expected to concentrate their choices. Scores assigned by gatekeepers to domain entries are also higher when adopters' choices are more individualised.

A number of insights are motivated from our exploration of gatekeeping. Firstly, higher rates of gatekeeping generate a higher number of domain contributions and a decrease in the variance of contributors. This lower concentration of prominence is interpreted as more designers being responsible for contributing to the domain. This is in contradiction to the Price Law which states that the square root of N, where N is the number of contributors in the field, is the number of individuals who will account for 50 percent of creative contributions (Simonton 2003). Further research is necessary to understand the conditions under which these apparently contradictory patterns may occur.

3.3.3 Domain Size and Distribution

The selection of entries by gatekeepers in our studies is assumed to be based on an incremental scale where once a solution is presented and chosen for inclusion in the domain, other solutions even with identical features are not considered of merit. In fields of creative practice these are in fact labelled as forgeries. The score assigned to an entry becomes the new entry threshold for future candidates. For new artefacts to gain access, two conditions are considered in our studies: entries must receive a higher score in the same features than existing entries or they must present advantages in features other than those by which previous artefacts were chosen. An additional mechanism implemented in our framework addresses the decay of the entry threshold. The assumption is that as simulated time lapses, with no new entries being selected the entry bar gradually decays.

The main consideration on domain characteristics in our studies centred on their role as dependent variables. Various aspects in our models are found to determine the quantity and quality of domain entries including individual differences and situational factors such as rates of behaviour and type of access to knowledge. Our findings suggest that quantity (number of domain entires) and quality (score and complexity of domain entries) need not be correlated. For instance, the mean scores assigned by gatekeepers to domain entries are higher when adopters' choices are more individualised but no significant changes in domain size are observed. However, frequent adoption cycles generate both larger domains and higher scores.

In sum, situational aspects that may facilitate domain entry include frequent adoption decisions, frequent expert selection, disclosure of information between designers, number of adopters, and the strength of their ties (Sosa and Gero 2004b).

3.3.4 Artefact Structure

The effects of manipulating the composition of solutions or artefacts have been assessed in our framework. The main conclusion is that under equivalent processes of diffusion, values that consist of a few variables a) tend to spread rapidly through a population, but b) reach only a segment of the population. In contrast, artefacts that are formed by a large range of variables require longer periods to be spread but provide a large number of options of which gradual acceptance is supported. Number of variables of an artefact refers to the range of possible features that can be assigned a number of values. Examples of this distinction in design artefacts are first-generation of consumer products such as bicycles, cars, digital cameras, telephones and personal computers which have tended to have a minimum of options whereas in subsequent versions more product features and optional accessories become available. This principle suggests that artefacts such as early consumer products would tend to be adopted relatively fast but only by small segments of the market whereas second and third-generation products would take longer but would reach a wide spectrum of consumers.

Increasing the number of variables or features of an artefact and not the range of values or traits for each variable is likely to affect the diffusion process (Sosa and Gero 2003c). Artefacts with a combination of more features and less traits present a balance between diffusion time and scope. As more features are added, diffusion times increase without changes in scope. Likewise, increasing the number of traits causes minor changes in diffusion times whilst significantly affecting the scope of diffusion. A balance between number of variables and value range is expected to provide optimal conditions for diffusion. One way to explain this assumed optimal balance is through the study of compatibility and complexity in innovation studies. Compatibility has been defined as the perceived degree of consistency between existing and new solutions, whilst complexity of an innovation generally refers to the degree to which it is perceived as difficult to understand and use by potential adopters (Rogers 1995).

The general assumption in the literature is that high compatibility and low complexity facilitate innovation (Rogers 1995). These two requirements support our findings since design artefacts with more potentially common features can be expected to be more compatible with existing solutions. On the other hand, artefacts with a smaller range of values per variable can be expected to be perceived as less complex. Table 1 summarises the notion that artefacts that spread relatively fast and have a larger scope of diffusion would consist of more features and less traits per feature. Such artefacts would be potentially highly compatible with existing solutions, yet have low complexity.

TABLE 1 Characteristics of artefacts with rapid diffusion speed and large scope

ARTEFACT TYPE	DIFFUSION SPEED	DIFFUSION SCOPE
High compatibility + low complexity	Intermediate	Medium

Our findings suggest that design artefacts with a large number of variables require longer initial stages of adoption, or a larger critical mass of early adopters to reach the ‘tipping point’, i.e. the stage in the diffusion process where a majority of individuals rapidly adopt a solution. In contrast, the diffusion of artefacts with a small number of variables would reach this point with a smaller group of early adopters.

The ‘tipping point’ in the case of artefacts with a small range of variables in our studies reaches only a small portion of the universe of potential adopters. For artefact structures with more features, diffusion only takes off later but it reaches larger adopter groups. The importance of this distinction is that it only takes into account the type and number of characteristics of the artefacts being adopted preceding any consideration of their actual values, their designers, or the adoption population.

3.3.5 Summary

Our studies reveal a comprehensive role of domains in the link between individual behaviour and social change. These collections from which individuals retrieve existing information and fields incorporate changes may have significant qualitative and quantitative differences depending on a number of factors, most of which have been only marginally addressed in the literature.

A prevalent assumption is that creativity can be estimated from the creator’s total output or from the number of works commended by experts (Simonton 2003). However, individual differences are only one of the factors that determine the quantity and quality of a domain. The 1,093 patents granted to Thomas A. Edison (Israel 1998) need not indicate much about his individual characteristics. Some of the factors addressed in our studies that may be responsible for such exceptional contribution include a) spillovers from other inventors, b) social characteristics that value and promote production, c) frequent rates and diverse sources of gatekeeping including investors, d) rapid increase of target population size, and e) disclosure of new knowledge. The combination of these factors is likely to determine the output and distribution of prominence across competitors.

Extensions to these models include more than one society having contact through their domains, which could enable the modelling of distant analogies in creativity (Qian and Gero 1995). Other extensions could include further domain mechanisms such as when a new solution renders some or all past entries obsolete.

3.4 DISCUSSION

These computational studies point towards a promising line of inquiry focused on the complex interaction between individuals, fields and domains. The most important theoretical construct that frames this interaction is the notion of ‘design situations’. As a result of the dominant individualistic focus in the literature, important questions have been under-emphasised, specifically the study of ‘creative situations’ which Amabile (1983) defines as ‘circumstances conducive to creativity’.

A design situation represents the combination of individual and external factors as construed in a context. A situation in design can be defined as the confluence of individual and external conditions within which generative and evaluative behaviour is determined. Situations can be characterised as conducive to a number of effects including prominence, influence upon peers, increased rates of creation, rapid diffusion curves, etc.

An important implication of the notion of design situations is the degree to which individuals are able to choose and manipulate aspects of the situations within which they operate. An important role of individual differences may be in the disposition to choose or transform certain situations (Ross and Nisbett 1991). Different scenarios can be described based on our studies such as:

- Situations where one designer is likely to concentrate adoption
- The distribution of adoption choices by designers does not seem to be significantly affected by individual differences in our framework.
- Situations where designers are likely to receive high peer influence
- Recognition from peer designers emerges when features of an exemplary artefact are copied by other designers.
- Situations where one designer is likely to concentrate contributions
- In fields of frequent design rate, contributions selected by gatekeepers to enter the domain originate from a small number of designers.
- Situations where adopters are likely to be more satisfied
- When the individual bias of adopters is a strong factor of the adoption decision, their satisfaction (as a post-adoption measure) is likely to increase, but it is also very unpredictable.
- Situations where more contributions of high quality are likely
- Where quality is defined by the scores assigned by gatekeepers to domain contributions. .

3.4.1 The Power of Situations

Situational factors need not be externally imposed but could be chosen and modified by designers as a result of their experience. Namely, a designer could choose to target smaller/larger populations, to target groups with stronger/weaker social ties, to exercise design updates more/less frequently, to encourage opinion leaders to manifest their opinions more/less frequently, etc. Obviously these are factors only partially accessible to the designer, some require external change or negotiation with other stakeholders. This research aims to draw attention into these types of factors and to demonstrate an experimental system of analysis. Future research will be extended to include other situational factors that can determine creativity and innovation in important ways. Whilst the likely effects of situational factors can be identified, the power of a situation has been regarded as variable (Bem and Allen 1974).

4. Discussion

This paper has presented a framework that enables experimentation with the dual nature of creativity in design: the derivable attributes of objects and the social ascription by subjects. This framework applies two influential models in the fields of creativity and design. Experimentation with this framework demonstrates how computational social simulation can be applied to model design beyond purely cognitive processes. It provides alternative computational means to explore a complex subject, and results should be taken carefully as hypotheses rather than theoretical principles. Further work is necessary where experimenters need to try different assumptions, views, applications, domains, and system components.

An ‘in-silico’ approach of this type can complement in-vitro (laboratory) and in-vivo (biographical) studies; they can inform each other to test results, to build alternative hypotheses, to design new experiments, to consider other variables; and to conceive the relation of different processes particularly at different levels of analysis.

References

Amabile, T: 1983, *The Social Psychology of Creativity*, Springer-Verlag, New York.

Amabile, T and Hennessey, BA: 1999, Consensual assessment, *in* MA Runco and SR Pritzer (eds), *Encyclopedia of Creativity*, Academic Press, San Diego, pp. 347-360.

Axelrod, R: 1997, The dissemination of culture: A model with local convergence and global polarization, *The Journal of Conflict Resolution* **41**(2): 203-226.

Bem, DJ and Allen, A: 1974, On predicting some of the people some of the time: The search for cross-situational consistencies in behavior, *Psychological Review* **81**: 506-520.

Boden, M (ed.): 1994, *Dimensions of Creativity*, MIT Press, Cambridge.

Boyd, R and Richerson, PJ: 1995, Why does culture increase human adaptability? *Ethology and Sociobiology* **16**(2): 125-143.

Ceci, SJ and Williams, WM: 1999, *The Nature-Nurture Debate: The Essential Readings*, Blackwell, Malden.

Conte, R, Edmonds, B, Moss, S and Sawyer, RK: 2001, Sociology and social theory in agent based social simulation: A symposium, *Computational and Mathematical Organization Theory* **7**(3): 183-205.

Csikszentmihalyi, M: 1988: Society, culture, and person: a systems view of creativity, *in* RJ Sternberg (ed.), *The Nature of Creativity, Contemporary Psychological Perspectives*, Cambridge University Press, pp. 325-339.

Ericsson, KA: 1999, Creative expertise as superior reproducible performance: Innovative and flexible aspects of expert performance, *Psychological Inquiry* **10**(4): 329-333.

Feldman, DH, Csikszentmihalyi, M and Gardner, H: 1994, *Changing the World: A Framework for the Study of Creativity*, Praeger, Westport.

Findlay, CS and Lumsden, CJ: 1988, *The Creative Mind*, Academic Press, Orlando.

Florida, RL: 2002, *The Rise of the Creative Class: And How It's Transforming Work, Leisure, Community and Everyday Life*, Basic Books, New York.

Gardner, H: 1993, *Creating Minds: An Anatomy of Creativity Seen Through the Lives of Freud, Einstein, Picasso, Stravinsky, Eliot, Graham, and Gandhi*, BasicBooks, New York.

Gero, JS: 1990, Design prototypes. A knowledge representation schema for design, *AI Magazine* **11**(4): 26-36.

Gero, JS: 2000, Computational models of innovative and creative design processes, *Technological Forecasting and Social Change* **64**(2-3): 183-196.

Granovetter, M: 1973, The strength of weak ties, *American Journal of Sociology* **78**(6): 1360-1380.

Granovetter, M: 1978, Threshold models of collective behavior, *American Journal of Sociology* **83**(6): 1420-1443.

Israel, P: 1998, *Edison: A Life of Invention*, John Wiley, New York.

Kroes, P: 2003, Screwdriver philosophy: Searle's analysis of technical functions, *Techné* **6**(3): 22-35.

Kuhn, TS: 1974, Second thoughts on paradigms, *in* F Suppe (ed.) *The Structure of Scientific Theories*, University of Chicago Press, Chicago, pp. 459-482.

Liggett, TM: 1985, *Interacting Particle Systems*, Springer-Verlag, New York.

Lloyd, P and Snelders, D: 2003, What was Philippe Starck thinking of? *Design Studies* **24**(3): 237-253.

Marsden, PV and Campbell, K: 1984, Measuring tie strength, *Social Forces* **63**(2): 482-501.

McGahan, AM: 1999, Competition, strategy, and business performance, *California Management Review* **41**(3): 74-101.

Petroski, H: 1992, *The Evolution of Useful Things*, Knopf, New York.

Qian, L and Gero, JS: 1995, An approach to design exploration using analogy, *in* JS Gero and ML Maher (eds) *Computational Models of Creative Design*, University of Sydney, Key Centre of Design Computing, pp. 3-36.

Reinstaller, A and Sanditov, B: 2004, Social structure and consumption: on the diffusion of consumer good innovation, *in* J Archer (ed.) *DRUID Summer Conference 2004 on Industrial Dynamics, Innovation and Development*, Elsinore, Denmark.

Rogers, EM: 1995, *Diffusion of Innovations*, Free Press, New York.

Ross, L and Nisbett, RE: 1991, *The Person and the Situation: Perspectives of Social Psychology*, Temple University Press, Philadelphia.

Rubin, F: 1974, A search procedure for Hamilton paths and circuits, *Journal of the ACM* **21**(4): 576-580.

Rudowicz, E: 2003, Creativity and culture: a two way interaction, *Scandinavian Journal of Educational Research* **47**(3): 273-290

Ruef, M: 2002, Strong ties, weak ties and islands: structural and cultural predictors of organizational innovation, *Industrial and Corporate Change* **11**(3): 427-449.

Runco, MA: 2004, Creativity, *Annual Review of Psychology* **55**(1): 657-687.

Schumpeter, JA and Clemence, RV: 1989, *Essays: On Entrepreneurs, Innovations, Business Cycles, and the Evolution of Capitalism*, Transaction Publishers, New Brunswick.

Simonton, DK: 2000, Creativity, *American Psychologist* **55**(1): 151-172.

Simonton, DK: 2003, Scientific creativity as constrained stochastic behavior: the integration of product, person, and process perspectives, *Psychological Bulletin* **129**(4): 475-494.

Sosa, R: 2005, *Computational Explorations of Creativity and Innovation in Design,* PhD Thesis, Key Centre of Design Computing and Cognition, University of Sydney.

Sosa, R and Gero, JS: 2002, Cellular automata models of creative design situations, *in* JS Gero and F Brazier (eds) *Agents in Design 2002*, Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp. 165-180.

Sosa, R and Gero, JS: 2003a, Design and change: A model of situated creativity, *in* C Bento, A Cardoso and JS Gero (eds) *Approaches to Creativity in Artificial Intelligence and Cognitive Science*, Acapulco, pp. 25-34.

Sosa, R and Gero, JS: 2003b, Social change: Exploring design influence, *in* D Hales, B Edmonds, E Norling and J Rouchier (eds), *Multi-Agent-Based Simulation III*, Springer, pp. 106-119.

Sosa, R and Gero, JS: 2003c, Social change: Exploring design influence, *in* D Hales, E Norling and J Rouchier (eds) *Multi-Agent Based Simulation Workshop*, Melbourne, pp. 106-119.

Sosa, R and Gero, JS: 2004a, A computational framework for the study of creativity and innovation in design: Effects of social ties, *in* JS Gero (ed.) *Design Computing and Cognition '04*, Kluwer Academic Publishers, Dordrecht, pp. 499-517.

Sosa, R and Gero, JS: 2004b, Diffusion of creative design: Gatekeeping effects, *International Journal of Architectural Computing* **4**(4): 518-531.

Sosa, R and Gero, JS: 2004c, The role of gatekeepers in creativity, *in* P Gervas and K Moy Gupta (eds.) *Computational Creativity Workshop*, Universidad Complutense de Madrid, pp. 257-268.

Sosa, R and Gero, JS: 2005, Group brainstorming: Insights from computational social simulation, *in preparation*.

Sternberg, RJ: 1985, *Beyond IQ: A Triarchic Theory of Human Intelligence*, Cambridge University Press, Cambridge.

Sternberg, RJ: 1999, *Handbook of Creativity*, Cambridge University Press, Cambridge.

Sternberg, RJ: 2001, What is the common thread of creativity? Its dialectical relation to intelligence and wisdom, *American Psychologist* **56**(4): 360-362.

United States Census Bureau: 2000, *Indexes of Industry and Occupations*, Washington, D.C.

Von Hippel, E: 2005, *Democratizing Innovation*, MIT Press, Cambridge.

Wasserman, S and Faust, K: 1994, *Social Network Analysis: Methods and Applications*, Cambridge University Press, New York.

Wolfram, S: 1986, *Theory and Applications of Cellular Automata: Including Selected Papers, 1983-1986*, World Scientific, Singapore.

Wolfram, S: 2002, *A New Kind of Science*, Wolfram Media, Champaign.

Wooldridge, MJ: 2002, *An Introduction to Multiagent Systems*, John Wiley, Chichester.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 45-70

WHERE CREATIVITY COMES FROM

The social spaces of embodied minds

SEAN HANNA
University College London, United Kingdom

Abstract: This paper explores creative design, social interaction and perception. It proposes that creativity at a social level is not a result of many individuals trying to be creative at a personal level, but occurs naturally in the social interaction between comparatively simple minds embodied in a complex world. Particle swarm algorithms can model group interaction in shared spaces, but design space is not necessarily one pre-defined space of set parameters on which everyone can agree, as individual minds are very different. A computational model is proposed that allows a similar swarm to occur between spaces of different description and even dimensionality.

1 Introduction

Where does creativity originate? Does the push to innovate come from the individual, as our own point of view suggests? Or is it the group?

It is the natural assumption that we are the instigators. Margaret Boden (1990) draws a distinction between the psychological 'P-creativity' of the individual, and the historical 'H-creativity' of ideas that are fundamentally novel for the whole of a culture. Referring to Alan Turing, Friedrich von Kekulé, Mozart, and other historical innovators, she states the capacity for P-creative ideas means there is a good chance for H-creativity. Implied in the usual view is both that the creativity of the group is an accumulation of creative leaps of individual people, and that these individuals are varied in ability. H-creativity is wholly dependent on P-creativity.

This paper proposes an alternative: that creativity at a social level is not a result of many individuals trying to be creative at a personal level, but emerges naturally from the social interaction between comparatively simple minds embodied in a complex world. While individuals may differ in ability, such differences are not necessary for variety and innovation to occur. Nor is group innovation based on randomness, or even an internal drive to generate novelty, but a continual change in how we perceive the world around us and how we are affected by others.

A computational model is proposed that takes after the coordinated social dynamics of bee swarms, ant colonies, schools of fish and flocks of birds, all of which appear in motion to have a sophisticated group mind, and the swarm algorithms inspired by these. The interactive creativity of large groups of designers can be seen as a type of swarm behaviour involving the thoughts of agents (Kennedy & Eberhart 2001), but models to explain this require the predefinition of a single uniform problem space in which to interact. Designers' minds can be vastly different, and private, so what is this space? In this proposed model swarming can occur, but takes place via three distinct, abstract spaces aligned with Czikszentmihalyi's (1988) systems model of creativity, and linked in such a way that creativity happens in the process of mapping from one space to the next.

The practical aims of this work are twofold. The first is to show how the parts of a creative system (based on Czikszentmihalyi's model) can be represented as a set of three abstract spaces with a structure that allows swarming to occur. The second is to use these to model a social system that appears to exhibit creative behaviours: namely cultural innovation, coalescence to socially established norms, and clique differentiation.

The overall goal is to show that the first is sufficient cause for the next: that is, to show that the structure of the spaces yields an emergent behaviour resembling creativity. In doing so, the model proposed and tested is minimal, and omits features often associated with a system of creative agents. The agents are not goal-motivated, novelty-seeking or of varied abilities. They have no intentionality other than the differentiation of perceptions required by neurons or machine classifiers. There is no objective measurement of utility to rate one example of creative output against the next. Also, there are no random processes to introduce innovation internal or external to the agents. This does not deny the fact that these features may exist in real, human designers, but it suggests that these are not strictly necessary to produce the creative behaviours mentioned.

The design context is a basic architectural one, with each agent able to contribute to an overall building pattern in a shared world. As there is no objective measure of utility, *novelty* is measured relative to agents' prior work, and *innovation* is simply defined as a difference between an agent's or a group's building pattern and what has come before. The overall movement of group activity in the model ensures that styles and cultural norms are always changing, and as this happens, the innovation of individuals is a result of trying to make sense of the new world. In trying to choose what they see as the norm, they create novelty unintentionally.

The following section of the paper gives a brief background to swarm models and creativity in a social context. This is followed by an example design situation to illustrate the process of single individual learning and designing to cultural norms. The model of multi-agent behaviour is next introduced, and the spaces in which it occurs described in detail, to outline how embodiment in a shared environment allows differently constructed minds to swarm together. Finally the behaviour of these agents over time is reviewed to show how the diversity of agents' perception can result in cliques, interdisciplinary activity and cultural innovation.

2 Background

2.1 DESIGN AS EXPLORATION AND SELECTION OF AFFORDANCES

While optimisation problems typically begin with a preset objective, design is acknowledged as an exploratory process, without necessarily fixed goals. Rosenman (1997) uses the lack of predetermination to define creative design, suggesting "the lesser the knowledge about existing relationships between the requirements and the form to satisfy those requirements, the more a design problem tends toward creative design". Gero (1993) goes further to suggest "… exploration in design can be characterised as a process which creates new design state spaces", changing the framework in which optimisation occurs. But optimisation methods can satisfy this creative requirement. Maher and Poon (1996), for example, use a genetic algorithm to co-evolve goals and solutions simultaneously as changing 'problem' and 'solution' spaces.

2.1.1 Embodiment and affordances in creative systems

The alternative to representing problem spaces is to accept the space of the environment as its own representation. The act of being 'in the world' described as *embodiment* (Quick et al. 1999; Dourish 2001) or *structural coupling* (Maturana and Varela 1987) requires that there is two way perturbation between an individual and the environment. As the designer makes a design, the world is also affecting his or her brain.

Design for an embodied individual consists of the creation of a product that will also be embodied in the environment. Realisation of the design in the world is not only for communication to others, but is an intrinsic necessity of the creative act, in that the internal representation of a concept in the mind of an individual is so unique to that individual, so different from the external world, that the concept itself can not be said to fully exist until it is embodied. The idea in an artist's mind of a painting is not the same as what is actually painted, as this may be affected by external events during the act of painting.

This ongoing negotiation can be seen as a process of constantly choosing between the perceived *affordances* of the work at each point in its evolution.

Related to Heidegger's notion of *zuhanden* (ready-to-hand), Gibson (1979) coined the term *affordance* to refer to the properties the environment offers an animal in terms of action, such as the support afforded by a flat, horizontal surface. Norman (1988) discusses affordances in design, but chiefly in relation to how designs are used, as it is a principle of good design practice to be aware of the affordances that will suggest themselves to the user: a chair affords sitting, a handle lifting, pulling, opening, etc. Affordances can also be considered in terms of how we interact with the world in the process of making a design. Tang and Gero (2001) suggest the act of sketching, with constant drawing and re-evaluation is such a process, and the explicit representation of choices as decision trees has also been implemented in CAD environments (Brockman and Director 1991). At any stage of the process there are only certain possibilities open to the designer, and the act of design can be seen in this sense as a selection from the afforded alternatives.

2.2 SWARM AND GROUP INTELLIGENCE

2.2.1 Simple agents in abstract spaces

Particle swarm algorithms have also been applied to the exploration of design problem spaces. Several varieties exist, all sharing the principle that an emergent intelligence arises from the interaction of groups of simple agents, each of which behaves according to simple rules and has no knowledge of the global behaviour of the group.

Axelrod's model of the dissemination of culture (Axelrod 1997) allows agents in fixed locations to communicate with one another with a probability equal to their cultural similarity, resulting in a polarisation of cultures as these similarities are strengthened. Individuals split into stable non-communicating groups. The same rules applied to freely moving agents in a space result in swarm behaviour. Three broad types of swarm model have been proposed: deterministic groups resembling complex behaviour such as that in bird flocks (Reynolds 1987), and optimisation algorithms either representing stochastic particles with a goal (Kennedy and Eberhart 2001), or those modelled on the (not necessarily spatial) social communication of groups such as ant colonies (Dorigo 1997). Although the methods for optimisation incorporate randomness into the agents' paths, it is purposely left out of the model proposed here.

The rules of the algorithms differ in their specifics, but interactions between agents take one of two basic forms: they either *attract* or *repel* one another in space. The update of an artificial bird's velocity in (Reynolds, 1987), for instance, would be of the form:

$$\mathbf{v}_{t+1} = \mu\mathbf{v}_t + (1-\mu)(\, w_{\mathrm{avoid}}\mathbf{v}_{\mathrm{avoid}} + w_{\mathrm{match}}\mathbf{v}_{\mathrm{match}} + w_{\mathrm{centre}}\mathbf{v}_{\mathrm{centre}}\,), \tag{1}$$

where $\mathbf{v}_{match}$ and $\mathbf{v}_{centre}$ cause the agent to imitate the others and $\mathbf{v}_{avoid}$ to keep away from its neighbours. Attraction allows for a focused local search and exchange of information with similarly inclined neighbours, and repulsion causes groups and individuals to explore new areas of the space.

2.2.2 More complex Agents in the world

Designers influence one another in the abstract space of their work, so it is necessary for this to be embodied in a shared world. Nehaniv and Dautenhahn (1999) suggest an algebraic framework for imitation in which dissimilar bodies can imitate one another by producing similar *effects on the environment*. Individual actions, or internal representations are not important, but rather the ability to meet a series of sub-goals such as covering a wall with paint when imitating the task of painting. This stresses embodiment in the environment, but requires that the goals – the real motivators of creativity – must be predetermined explicitly.

Luc Steels' Talking Heads project shows that even these goals can be determined, in a point and guessing game played by robots that evolve a language. (Steels 2000) The two are also embodied, and must communicate through a shared environment consisting of coloured geometric shapes and a white board. Words and even syntax are generated from the need to express concepts the robots may hold differently in their minds, the creativity springing from an interruption in full communication between the two agents. Edwin Hutchins' research with parallel constraint satisfaction networks suggests this interruption is actually beneficial (Hutchins 1995). In highly connected networks of individuals, his populations reached poorer solutions than networks in which individuals were connected only moderately to one another.

2.3 CZIKSZENTMIHALYI'S SYSTEMS MODEL OF CREATIVITY

A widely accepted dynamic model of the process of creativity within a broader environment of other individuals is given by Czikszentmihalyi, Figure 1. This gives an account of the flow of ideas and interaction between a *person* (the creative individual), the *field* (the group of individuals that act as arbiters of creative output) and the *domain* (the collection of embodied work and symbolic representations deemed relevant by the field). (Czikszentmihalyi 1988)

Czikszentmihalyi's model is widely accepted as describing the social structure of the creative process, and the model proposed here will suggest that the activity in each section of the triangle takes place in one of three very different spaces, each of which can be mapped into the next as indicated by the arrows. As Czikszentmihalyi makes clear, the creative act is not an occurrence within the mind of an isolated individual, but an interaction with the domain and field, both of which are spaces outside the individual's private perception, and both of which may be shared by other individuals.

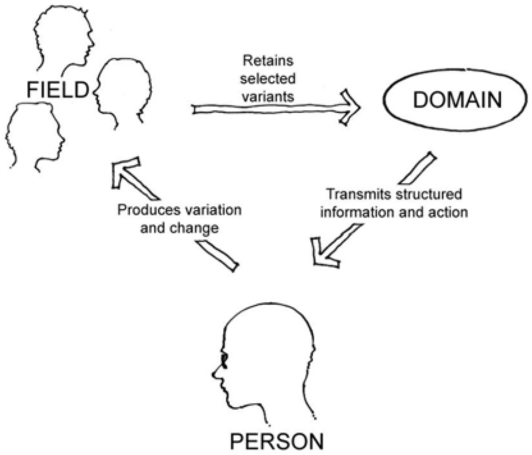


Figure 1. Czikszentmihalyi's systems model of creativity.

3 Building by an individual

3.1 ILLUSTRATION: A SAMPLE PROBLEM

A sample problem will be used to explain the proposed model with a real-world instance of collective design: that of the aggregation of buildings in towns built over time without a central plan. In this case the process is much like the swarm models introduced in Sec. 2.2.1, in that building is done by a number of people considering their own needs individually, yet a global order emerges from their effort.

Bill Hillier's analysis of hamlets in southern France is an exposition of this emergent order, in what he has termed the 'beady ring'. (Hillier and Hanson 1984) As settlements reach a certain size a regularity appears in the shape of a ring of joined spaces around a central clump of buildings facing outward, and several inward facing groups of buildings around the perimeter. While this pattern seems to appear in every one of the hamlets studied, it need not be the result of any kind of central planning, as a simplified model makes clear.

A grid is used to simplify the geometry, and two types of objects are represented in its squares: closed cells with an orientation defined by an entrance in one side, and open voids. The minimal building unit is made up then of two face-wise adjacent squares, with a closed cell facing on to an open space in front. The model allows these pairs to aggregate so that each new pair must join its open cell to at least one other open cell already placed, and the closed cell does not join another closed cell only at the vertex. Other than these two rules, the position and orientation of each new unit is completely random, but each time the model is run, the overall structure of the aggregation forms that of the beady ring settlements studied, with a chain of open spaces onto which inner and outer groups of buildings face.

As a basic framework for town generation this is enlightening, but creative design is far more than random search, and equally important are the specific differences between towns. In Hillier's own study he notes the differences between the beady rings of France, and their counterpart villages in England that tend toward a more linear arrangement. These cultural differences in global form are also a result of the same uncoordinated local actions over time, yet the particular nuances that lead to a circular or a linear arrangement seem somehow to have been instilled into the individual members of the culture that make each building. The overall structure of this grid model will be used below to show that such cultural norms can be learned by individuals.

3.2 DESIGN BY AFFORDANCES IN TWO CULTURES

Design is an act of continually making and then examining from a different point of view. Embodiment in the world allows this. The act of design by an individual agent in the above context is simply the selection from a set of possible alternatives: "which is the most like X?" But how do we know what X is?

Assuming every act of construction is selfish and uncoordinated, the motivation behind the decisions of building placement would be to maximise some particular qualities considered to be important, such as direct access to the public space of the town and the economy of sharing a wall with a neighbour in the rules above. Each of these is an affordance of particular vacant building sites available at any given time. Rather than predetermining which of these qualities are most desirable however, suppose they are relative and change from culture to culture. Each time a unit is built, the configuration of the surrounding neighbourhood relative to the cell pair gives an ideal example for an individual to follow, another example in the domain.

Two artificial cultural norms were established that were easily distinguishable from one another, and a simple algorithm written to aggregate open/closed pairs of units in the manner of each, Figure 2. The first is a strict arrangement of straight rows rather like highly planned settlements such as Manhattan, and the second is a completely random arrangement of units joined open cell to open cell. To learn the two ideals, a classification algorithm can be trained on the units as they are built. Each time a new pair is placed in the plan, the 7×7 cell square surrounding the open half of the doublet is taken as its neighbourhood, and oriented such that it is always seen by an agent looking from the open cell toward the closed. The 49 cells, each containing either a closed building (indicated by a filled cell, or 1), a public open space (a dot, or -1) or yet unbuilt (an empty cell, or 0) are used as an agent's sensory experience of that particular example in the domain.

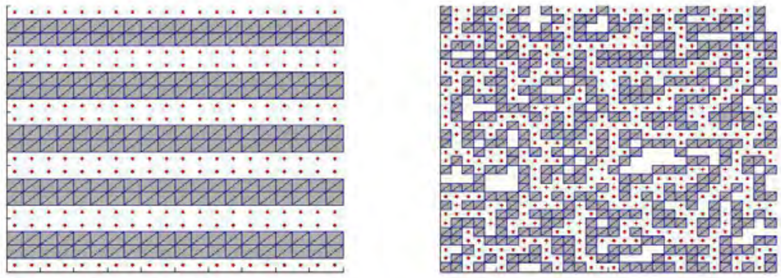


Figure 2. Building patterns of two cultures: strict rows and random aggregation.

The algorithm to build based on this is simple. The two swarm rules as applied to design say something like 'try to make something like what is accepted by your culture or group' (i.e. attraction toward the perceived mean) and 'try to distinguish yourself as far as possible from the other culture' (i.e. repulsion). Each building decision is an exercise in maximizing the qualities seen as desirable based on other examples in the domain. At every step a given number of positions and orientations are available to be built, and the decision is simply the act of choosing which one of these affordances best fits the ideal the agent has learned.

A support vector machine (SVM) was used as the agent's initial classifier due to its easily tuneable parameters. SVMs operate by finding a maximally separating hyperplane between the two labelled classes in a higher dimensional representation of the input, given in this case by a weighted sum of the non-linear Gaussian kernel function

$$\varphi(\boldsymbol{x}, \boldsymbol{\mu}) = \exp[\, - \| \boldsymbol{x} - \boldsymbol{\mu} \|^2 / \sigma^2 \,] \tag{2}$$

with a parameter σ^2 that can be adjusted – in this case the variance of the Gaussian. Figure 3 shows the results for $\sigma^2 = 5$, 15 and 25 respectively. The SVM output is plotted (left column) with the vertical axis indicating the output values, and 450 row examples followed by 450 random aggregation examples positioned along the horizontal axis. The resulting agents' construction over time is shown for each, with the agent's attempt at replicating the rows (centre) followed by the random aggregation (right). At each construction step, the possible construction sites and orientations are evaluated by the SVM, and the one closest the mean of either culture as learned is selected. It is evident from the results that as σ^2 increases there is both better separation between the two groups by the SVM, and also a clearer construction result – more obvious in the rows than in the random arrangement. But this separation is never quite enough, and the classifier can only be seen to produce really adequate rows with an artificially created set of 'perfect' examples of row neighbourhoods is used, all identical so that each is exactly perceived as the ideal mean, Figure 4.

Although there is a vast difference between the ability of the four agents above, their interaction with the environment always entails a similar kind of choice. It is this common environment that allows different agents to interact with one another, as investigated in the following section.

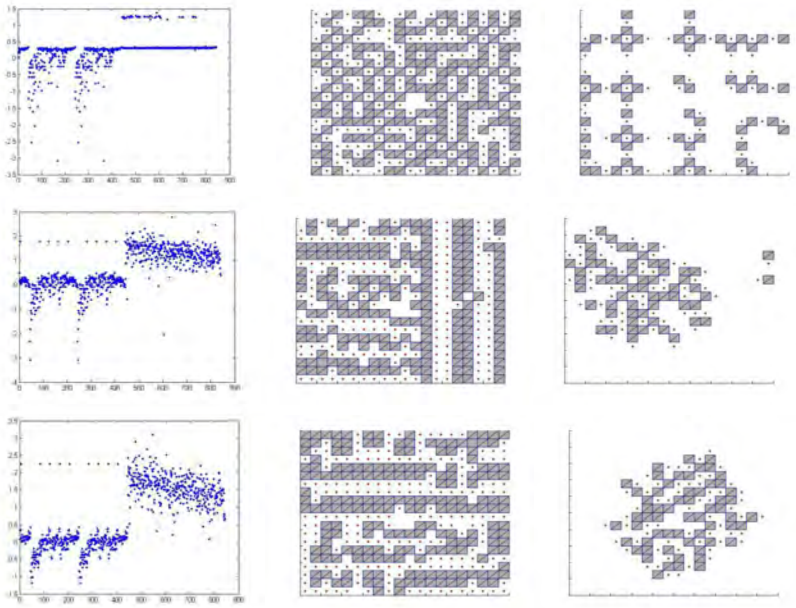


Figure 3. Building results for agents trained with a SVM: σ^2 = 5, 15 and 25. SVM output on 800 examples is shown at left, building patterns based on rows in centre, and building based on random aggregation at right.

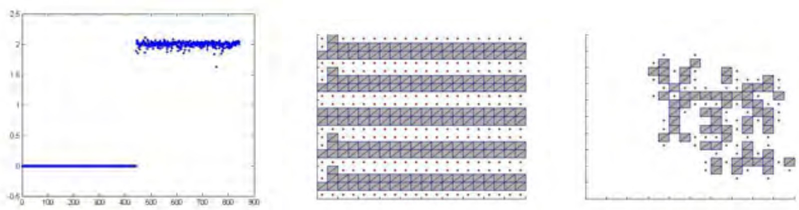


Figure 4. The same training on a set of 'ideal' examples.

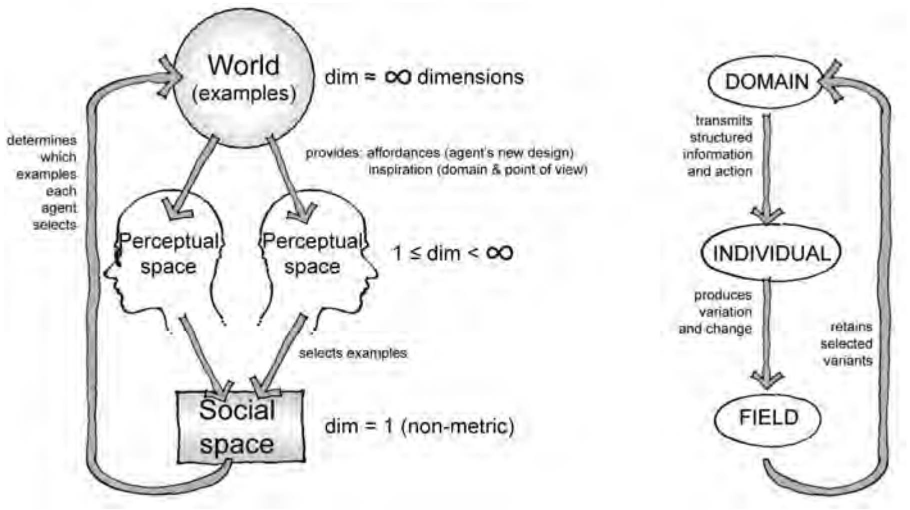


Figure 5. Three spaces of the model (left) paired with Czikszentmihalyi's (right).

4 Building by groups: a swarm in three spaces

4.1 STRUCTURE OF THE MODEL

Three distinct spaces form the arena for the collective swarm. The nature of these spaces and the way they are connected are the basis of this model, Figure 5. Creativity will not occur in any one of them, but in the cycle of mapping from one to the next. We can refer to these via Czikszentmihalyi's model, as they correspond roughly with its *domain, person* and *field,* and communication occurs between them in the same direction, but we will define the spaces somewhat more broadly in terms of what they can contain.

- *Space of the world*: Beginning with our shared, physical reality, this contains the set of embodied artefacts or events that can be experienced by all. These examples are available to any agent also embodied in the universe, and are anything that is objective, out there in the world, including even sounds and instances of symbols. This space includes any object or communication made by an individual, so it will be called the *world*, leaving *domain* to refer to selected sets within it.
- *Perceptual space*: Next, a subset of this reality is experienced by a given individual as subjective experience, in a second space of lower dimensionality we can call the *perceptual space*. This individual's perceptual space is unique, and therefore yields a unique picture of objective reality.

- *Social space*: The third space is the space in which the swarm dynamic can be seen: the social space of a shared culture. This is not necessarily a metric space, but can be represented as a graph of distances between individuals. The group of individuals closest to an agent would be that agent's *field*.

As communication occurs from one to the next, a point in one space can be mapped to the next space in the model. But due to the structure of the spaces, this can only occur in one direction. Most importantly, for one individual to communicate with another they must complete a full cycle, using the conventions of their social space to make an example in the world that the second individual can see with a different perceptual framework. Design as an act of selection from affordances as introduced in Sec. 3.2 allows this. This may seem a laborious process, but as with Steels' robots or in Czikszentmihalyi's model, it provides the framework for innovation.

4.2 SPACE OF THE WORLD

The example units placed in the above exercise constitute the domain in the space of the real world for our design agents, and a subset of all possible dimensions is used to represent the examples. Because the sensory input of each agent is an identical 49 square grid, each unique example can be represented by a point in a 49-dimensional space, a 2-d projection of which is shown in Figure 6. All example neighbourhoods are projected onto the first two principle components of the set: neighbourhoods of the straight rows are indicated by '×', and the random culture by '○' markers in the centre.

The choice of a 49-dimensional world for these examples is one of computational tractability, but in our own experience, each example from which a designer can be inspired can be represented as a point in a potentially infinite-dimensional space of physical reality.

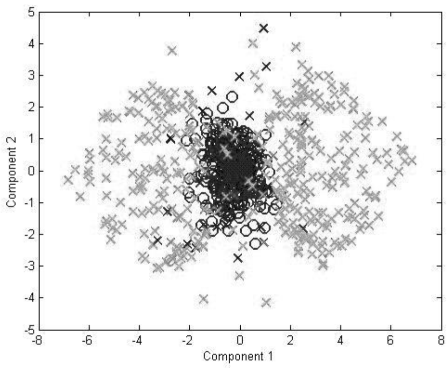


Figure 6. A projection of examples in a 49-dimensional world space.

The dimensionality chosen for the world is also, by necessity, higher than the agent's perceptual space. While the point that represents a given example has a potentially limitless set of qualities that may be experienced, our senses limit us to only a small set. But this inexhaustibility of dimensions is the chief advantage of being embodied in the world – an object in the domain such as a painting or sculpture can be revisited again and again and always be seen as something new, and the same is true of intangible arts such as music and literature.

The higher dimensionality of the space of the world compared to the structure of our perceptual space does not allow a thought to be uniquely mapped into reality. This might seem to pose a problem for designers, but not if the act of design is seen as the repeated selection from a set of affordances as they present themselves. The outline of design as given in section 3.2 requires only a choice from the possibilities as they appear in the agent's perceptual space.

4.3 PERCEPTUAL SPACE

Perceptual space, at any one time, is necessarily a lower-dimensional abstraction of the world space, which determines what we actually *see* in the world. In the case of the design agents in section 3.2, it is the one-dimensional output of the SVM. Any example in the real world can be mapped (via brain or learning algorithm) to a corresponding point in the space of an *individual's* perceptual space, which is different from every other individual's. Unlike the shared space if the world, this perception is completely private.

A perceptual space is represented in us by the state of our brain when experiencing the example. The nature of this space is like what has been termed *semantic space* by linguists. Semantic space research has shown that words and concepts can be mapped in a multidimensional space such that words with similar meanings are located near one another. Burgess and Lund (1988) have built a model of such a space based on the proximity of words to one another in Usenet discussions in which nouns such as 'dog' and 'cat' fall into one cluster, 'china' and 'america' together in another in a manner that coincides intuitively with many people's experience of the concept. This perceptual framework is the subjective counterpart to the space of external examples, the interior space of qualia or private meaning. A thing may exist in the world independently, but is actually experienced in the perceptual space of the mind.

Perception is an act of differentiation. Neurons react to *changes* in stimulus. It has long been known that the intensity of sensation is proportional to the frequency of neural activity, and that this decreases with time after the change (Adrian 1928). Thus white noise, or the hue and intensity of ambient light, etc. are only perceived against a contrasting other. When we see, we group the continuous spectrum of visible light into distinct colours, so perceptions of colours closer to green are seen as green, closer to blue as blue.

This act of perception is analogous to the two swarming rules in that perceptions shift closer to a perceived mean (e.g. green), and away from the other label (blue or yellow). This model proposes that the equivalent of agent movement in a traditional particle swarm occurs in this perceptual space, by changing the perceptual mapping. The swarm rules of attraction and repulsion are rooted here in the perceptual system of the individual simply to allow that individual to differentiate or classify effectively. In the SVM examples in section 3.2 it was seen that the most effective mappings present examples of one group closest to the ideal mean (attraction) and those of the other farther away (repulsion), resulting in greater differentiation between the two sets of examples, and a clearer reconstruction of that culture. The same was found of the neural networks used to map to this perceptual space.

4.3.1 Representing the individual's point of view

The behaviours of attraction and repulsion were implemented in the perceptual space via an artificial neural network. Training of the network serves to usefully illustrate this movement, as the function of every neuron:

$$\mathbf{y} = \mathbf{wx} + w_0, \tag{3}$$

is a simple linear function, and can be visualised as a hyperplane constantly moving in a high dimensional space in an attempt to separate the two classes of input examples. The agent's point of view can be pictured as aligned to this hyperplane and moving with it.

A three layer neural network was used to map to the agent's perceptual space, with 49 input nodes corresponding to the state of the neighbourhood, 50 nodes in the hidden layer, and a single, linear output that rates each example in a single dimension that represents the internal perception of the agent. Training was conducted by exposing the network to 450 examples from each of the two cultures and backpropagation of errors.

Several classification methods were tested. The typical error function

$$J = \tfrac{1}{2} \, \| \mathbf{t} - \mathbf{z} \|^2 \tag{4}$$

operates on the difference between the neural output $\mathbf{z}$ and a specified target $\mathbf{t}$, set at 0 for the domain examples and 1 for the others. Alternatively no target was set for examples outside the domain, and for these either the normal neural weight updates were subtracted rather than added, or the reciprocal $1/\mathbf{z}$ is used in (eq. 4), causing the error to fall as examples appear farther away. All three methods performed well; the results of the third are below, Figure 7.

Plotting the output of the trained neural network reveals how the agent sees the world. Each of the examples is shown as a single dot in the vertical axis corresponding to the value of the network's single node output, Figure 7, top. This agent was set in the culture of the straight row builders, as differentiated from the random aggregators, and as such has learned to see most of the first 450 examples along the horizontal axis (the row units) as 0, and most of the others (the random aggregations, to the right) as far away (note the extreme scale of the output axis). If this agent's neural network is used to place an aggregation of open and closed cells according to the algorithm described (Sec. 3.2), the result is one that very closely resembles that of the original rows in global arrangement, Figure 7, bottom.

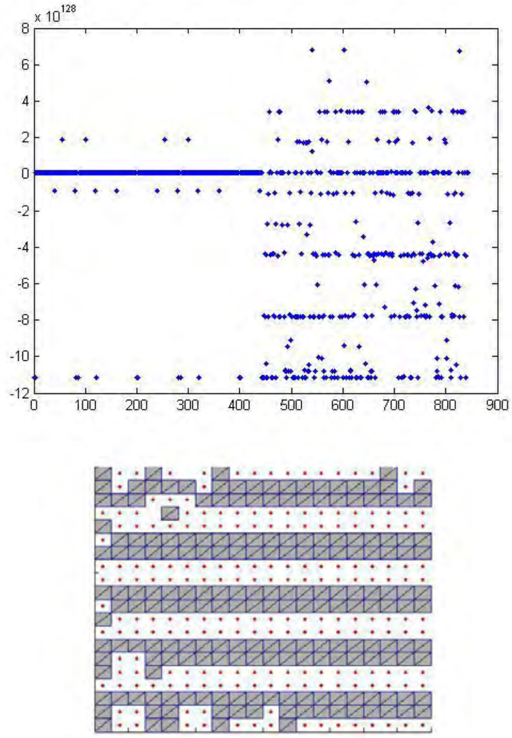


Figure 7. The agent's perceptual space (top), and its resulting building pattern.

Not every unit is placed perfectly, and not every example is seen by the network as clearly in its group, but every agent is different. In fact this difference will be crucial to the overall swarm dynamic when groups of agents interact. Various structures of network can be used representing different artificial minds, different numbers of internal connections or methods of measuring error, even learning algorithms that do not rely on neural networks. One of the main assertions of this paper is that differently constructed minds can share in the same overall process of social creativity. They are connected in the next space.

4.4 SOCIAL SPACE

The group of other agents with which one is associated, and which determines examples in the domain, constitutes the *field*. It is not a single, constant group of judges, but a fluid, changing collection of individuals selected based on the similarities of their perceptual mappings. To measure these connections between individuals the model proposes a third, *social space*, actually a simple one dimensional measure of distance between agents.

Its essential function is to enable communication between the otherwise private perceptual spaces of different agents. The similarity between two perceptual spaces can be measured by the degree of correspondence between how each sees the world. The perceptual spaces display a measure of distance between what the agent judges to be the current mean of its culture (0) and any given sample. After normalising these to have an identical variance of 1, the distance between any two agents' perceptions can be measured based on the mean of squared differences between each of the example points:

$$D(a_1, a_2) = \Sigma_{i = 1 : numExamples} [p_{a1}(ex_i) - p_{a2}(ex_i)]^2 / numExamples \qquad (5)$$

All learning algorithms that result in a perceptual mapping can be compared in this way, regardless of their internal workings. To illustrate, Figure 8 shows the result of several very different learning algorithms exposed to the same set of examples. Although each may differ in the details, each individual shares with the others the ability to perceive examples in the world. At the top is a neural network similar to the one in Figure 7, except that only a fixed number of examples closest to the mean are used in training. Below this, a different technique is used to train the network: errors from both groups are measured from the mean, but rather than adding the weight updates at each step for the examples of the random aggregation, they are subtracted. The last two examples are different algorithms entirely: a Kohonen self-organising feature map, and a support vector machine.

All of these different algorithms, when trained on the same examples, result in different outputs in their individual perceptual spaces (which may even have different numbers of dimensions) but each is alike in that the resulting perceptual framework allows the individual to make similar decisions about examples regarding their distance from the mean.

The group of other agents that each considers to be its *field* is determined by the distances measured as in (eq. 5), each selecting the agents perceived to be the closest. Table 1 shows the distances between the perceptual spaces of the four agents in Figure 8.

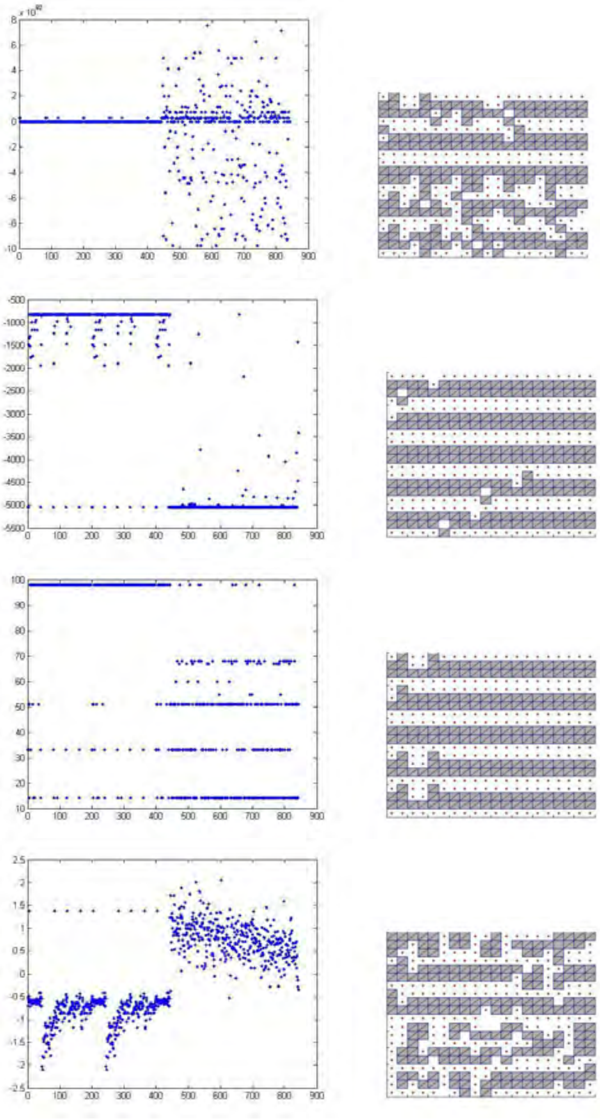


Figure 8. Agents trained with completely different algorithms (two three-layer neural networks, one Kohonen network and one SVM) have different perceptual spaces (left) but can make similar evaluations and similar constructions (right).

TABLE 1. Social space distances measured between the above perceptual spaces.

	neural net 1	neural net 2	Kohonen	SVM
neural net 1	-	1.47	1.54	1.62
neural net 2	1.47	-	0.44	1.95
Kohonen	1.54	0.44	-	1.90
SVM	1.62	1.95	1.90	-

Based on these distances, the second neural network agent and the Kohonen agent would each select the other as a member of their fields, being the closest of the possible choices. The similarity is also evident in the visual appearance of their construction outputs, Figure 8, right.

Kuhn (1962) emphasizes the role of a field's lexicon in both facilitating internal communication, and isolating it from outsiders. As the boundaries of a field are defined by shared examples that define it, we can actually speak of the field itself as having a perceptual framework of its own: the perceptual space that would be defined by those examples, Figure 9. Suppose we take a set of eight examples in the world. If you and I both select a set of six or seven as representative of our individual ideals we might each have one or two unique samples, but there is a general overlap in the remaining 5 which will define our shared field, and its agreed perceptual space. Also, because the field ignores examples outside those chosen, its distance to the perceptual spaces of each individual could be zero, even if these individuals would differ in mapping examples out of the field. This field's perceptual space therefore coincides to a fairly high degree with the perceptual spaces of each individual in the field, providing the common ground that makes communication and mutual understanding possible.

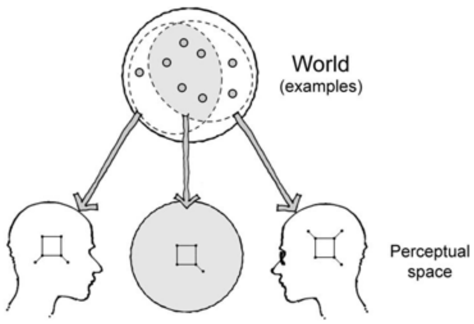


Figure 9. The field's shared perceptual space is defined by shared examples.

5 Completing the loop: putting agents together

At the macroscopic level, this model is concerned with both the changes in design over time, and the behaviour of large communities. The behaviour of a group of agents would therefore be expected to exhibit certain characteristics associated with creative social systems: innovation, local coalescence toward accepted ideals, and clique formation.

Innovation has two requirements, the most obvious being the generation of novelty in the world space of possibilities, a prerequisite for both P and H-creativity (Boden 1993). Over long spans of time, this inevitably results in a slow shift in cultural norms, fashions or styles, as an accumulation of many small innovations. If one imagines a theoretical space of 'all possible designs', illustrated schematically in Figure 10, then the artefacts thus far produced in the history of humanity would fill only a small cloud, leaving vast expanses of the space still unexplored. But that cloud is always expanding around its periphery, and over time the system should expand in the world space of possibilities, to explore it broadly.

The second requirement of creative innovation is that the results are not just new, but also unexpected or surprising (Boden 1993). Many swarm algorithms (Dorigo 1997; Kennedy and Eberhart 2001) and cultural simulations (Axelrod 1997; Saunders and Gero 2001; Sosa and Gero 2002) incorporate randomness to generate novelty, whereas others (Reynolds 1987; Wolfram 1994) produce a complex or chaotic overall behaviour from the interactions of deterministic agents. Because this model is proposing an emergent creativity in the interactions *between* groups rather than explicitly novelty-seeking agents, it follows the second approach. Although no stochastic algorithms are used for sampling or training, viewed over time the system should display apparent randomness and unpredictability, both in the examples chosen (or created) by each agent, and in changes of field in the social space.

Like the polarisations seen in Axelrod's and other swarming models, subgroups in a social system will be expected to coalesce toward some local consensus. This is the basic behaviour of swarm models. This swarming tendency among people is necessary because we are social – there is a biological need to coalesce and an intellectual need to understand one another.

Finally, cliquing tendencies also split us up, often causing the bitterest of disagreements between seemingly close individuals. Saunders and Gero (2001) demonstrate the influence of groups of artificially creative agents on one another in the creation of fractal art, showing that agents with similar desires for novelty tend to form cliques.

The effect is also revealed in genetic evidence: Bodmer and Cavalli-Sforza (1976) note that 93% of genetic differences occur within races, and the 7% genetic differences between them are weighted toward visible characteristics. These visible differences are explained by a sexual selection that penalizes traits identified in one's neighbours outside the group, thereby accentuating the visible differences of adjacent groups and increasing the cultural divide.

This divergent behaviour the creative social system should display is often pictured as a branching tree, such as that of languages, Figure 11 or the increasing specialisation of scientific disciplines from a common trunk of enlightenment natural philosophy, but there is also the possibility of merging branches. English, for instance, has had major contributions from neighbours on the Latin, Britannic and Northern Germanic branches as well as influence from many others, and there are the so called interdisciplinary fields like biochemistry, which combine major branches of science. Rather than the clearly defined branches of the diagram then, the whole is a diverging and converging collection of loosely connected individuals clustered around individual foci, and this is how a system of agents is expected to behave over time.

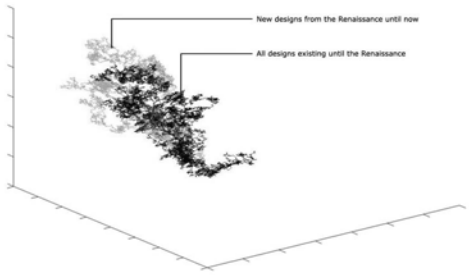


Figure 10. Examples in the space of all possible designs.

Figure 11. Indo-European languages. Image © 1990 Gamkrelidze and Ivanov

5.1 TESTING THE SWARM

Agents interact by sharing examples in a common world, and indicating their perceptions to others with whom they are close in the social space. The interaction of a group of agents is tested in this section. Each agent cycles through the following steps, one in each of the spaces mentioned:

1. Get a new set of n_d examples from the *world* that determine the agent's domain, and a set of n_o examples outside the domain.
2. Train the neural network so that it distinguishes the chosen n_d domain examples from the other n_o examples as the agent sees them. This adjusts the *perceptual space* of the agent. It can communicate its current position to all others by selecting an example from all available affordances in the world space nearest to what it perceives is its current ideal.
3. The similarity in the *social space* determines which agents communicate with one another. An agent selects the new set of samples for step 1 from the set pointed to by this group (the field), including the other agents' newest designs in its new domain.

The above steps accomplish the mapping between the three spaces as described in section 4: examples in the world are mapped to a lower-dimensional perceptual space, and distances between perceptual spaces are mapped to a single dimension in the social space. The cycle reiterates as proximity in the social space determines, or points to, high-dimensional examples in the world. This repeated process causes agents to constantly adjust their perceptual framework to accommodate new examples in the domain. The results of the model test indicate this motivates an overall cultural change, as represented by variation in the building output of a particular field of agents.

5.1.1 System behaviour: innovation and cliques

Figure 12 shows the result of a group's interaction over time according to the above rules. It plots an arbitrary (one-dimensional) projection of the domain means for each agent in their shared world on the vertical axis against time on the horizontal. The details of this appear quite different depending on the axis of projection chosen (just as they would appear different again in each agent's perceptual space), but the overall characteristics are the same. There is a gradual expansion from a common start, as agents' work explores the space of options.

One can see the same branching into cliques as occurs in Axelrod's model, and the trees of languages or disciplines, Figure 11, but in fact each is made up of many units produced by several agents. There is individual movement between them, and no strict definition of membership, but after 30 cycles two major groups appear, typified by agents 3 and 4. The building patterns produced by each of these agents in isolation at cycle 30 are shown in Figure 13. All agents in the clique represented by agent 3 display a tendency to build in a similar (but not identical) radial network, and those in the other clique in rough horizontal rows. An examination of the *fields* chosen by agents 3 and 4 also reveals that they are mutually exclusive, sharing no agents in common.

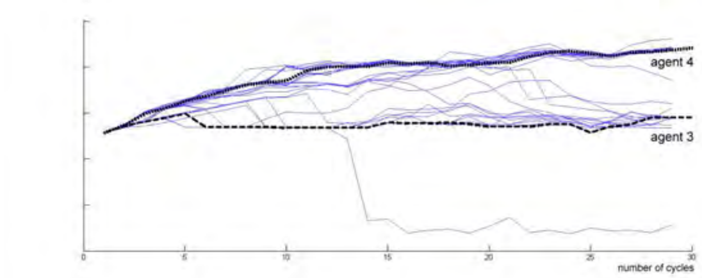


Figure 12. A projection of the agents' ideal means in the world space over time.

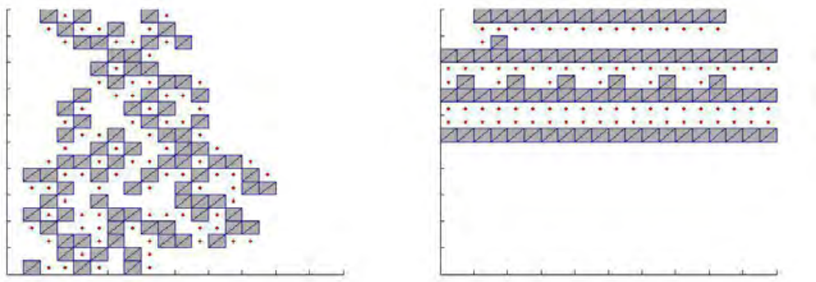


Figure 13. Examples of building patterns from two different cliques: agents 3 (left) and 4 (right).

Cultural change has occurred, in that the preferences dictated by the changing perceptual spaces of the agents cause them to build differently over time. At cycle 1 the building pattern of every agent is identical, but at cycle 30 neither of these building patterns is exactly like the others, or like the initial starting point.

5.1.2 The effect of different points of view

The hypothesis that different perceptual spaces, different ways of seeing the world, are responsible for the group's creativity was tested in the model in three different runs from the same initial domain. A simpler model was used, with only five dimensions in the world space and the agents' building affordances unrestricted (i.e. their output can be any point in this five-dimensional space), to look purely at the dynamics of the group over time.

Figure 14(a) shows the result of all agents locked to identical perceptual spaces. There is no difference to the way they see the world, and their ability as a society to explore a broad region of the world space is extremely low. (The ticks on the vertical axis in this case are actually single units rather than hundreds.) All agents have the same internal complexity as one another, and

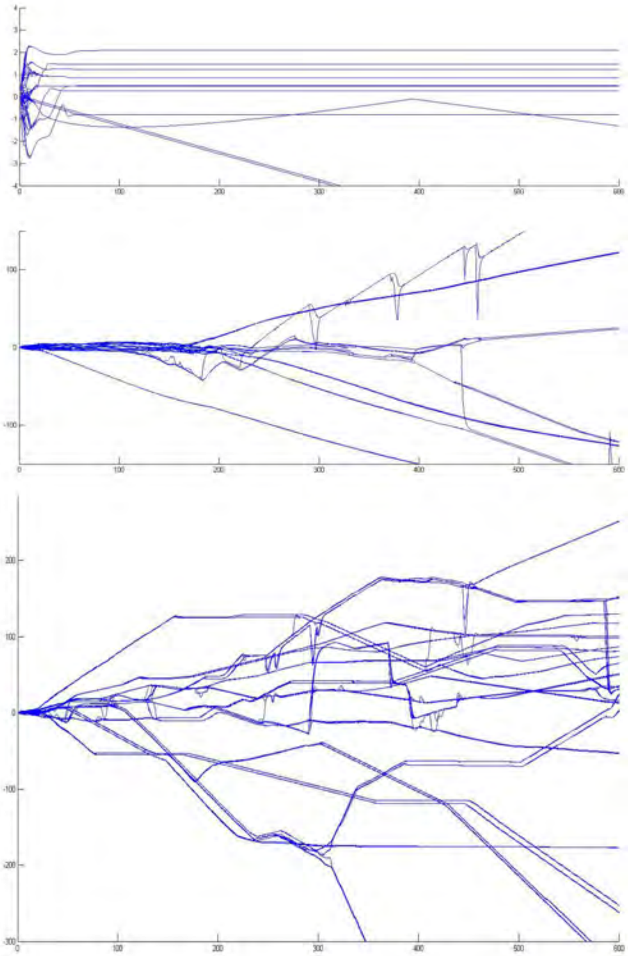


Figure 14. Agents' ideals in the real world (vertical) over time (horizontal):
a) (top) Identical perceptual framework in all agents,
b) (centre) Each agent with different perceptual frameworks,
c) (bottom) New agents added over time.

those in the other runs. The only difference in Figure 14(b) is the fact that the agents view the world differently from one another, but this produces both overall change and innovation of the group, and far more internal variation and complexity. The individual lines on the plots were found at any given time to contain between one and ten agents. Some can cross, particularly in the dense first 300 cycles. In doing so there is both a branching and merging of a loose collection of individuals. Even when these seem to be in clear fields an apparently interdisciplinary individual can be seen to cut across several branches by being near examples of both in its own perceptual space.

In Figure 14(c), the complexity is seen to further increase with the addition of new agents to the culture over time. Every ten time steps a new agent designer was added to the population. To avoid direct introduction of novelty, it was specifically placed in an existing field by being given a perceptual space and a domain of examples identical to an existing agent. Even with this initial similarity, there is a far greater branching and innovation of work than seen in the previous run. Fixed parameters of n_d and n_o ensure that a given field will eventually saturate when the number of examples exceeds their capacity to view, causing a split. This process occurs continuously, then, as long as the population increases.

5.2 THE INTERDISCIPLINARY INDIVIDUAL

An agent seen moving across fields only appears so from outside its own perceptual framework. It does not follow a middle line half-way between the two branches, because in some dimensions these two are very closely aligned. Such agents are found to include examples of both in a single domain, although they may look distinct from other agents' points of view.

This suggests that what we tend to call interdisciplinary work is often this same occurrence. Different disciplines have their own unique languages and customs that allow for ease of communication and rapid exchange within the community, but misunderstandings and general lack of exchange between groups. The more a discipline becomes 'specialised', the greater is its ability to make progress (movement in the swarm) on the problem at hand, but less its ability to communicate to outsiders. Interdisciplinary work results when individuals from different disciplines approach one another in dimensions that are not part of the general perceptual framework of either group. A multidisciplinary individual can bridge between the two groups not because of a *greater* breadth of understanding, but because of a *different* perceptual framework that includes the dimensions in which the two groups produce work of similar features. The work of a particular artist and a particular biologist can seem highly relevant to one another from this new point of view. Interdisciplinary work can itself sometimes develop into a new discipline as more individuals adopt similar views and form a new field.

5.3 SUBSTITUTES FOR RANDOMNESS, AND SOURCES OF INNOVATION

The behaviour of individuals within the creative system modelled appears unpredictable over time, but is not the result of a stochastic process. The outcome is completely deterministic given the initial conditions of domains and perceptual spaces. Instead, the apparent randomness appears to arise from two different processes.

The first is the act of design as a process of selection from affordances in the world. The details of the work are input to the agent, rather than output, and a constantly changing world (due to new building) affords different possibilities at each given point in time. Thus even an agent that maintains a constant state in terms of domain and perceptual space would produce different output at times t and t+1, and appear to be making random choices.

Even when the possibilities in the world are unrestricted however, as in section 5.1.2, there is still apparently random behaviour. The other source appears to be the cycle of mapping between the three different spaces of differing dimensionality. This introduces into the overall system a complex non-linearity like that seen in Reynolds' (1987) flocks or Wolfram's (1994) class 3 and 4 cellular automata.

6 Conclusion

In this work a computational model for creative design among agents was presented, in which domain and field change over time. These changes, which appear in real societies, seem to be an important part of the process. The simulation yielded global cultural innovation that occurs within several different abstract spaces. Their structure provides several advantages over a typical swarm model:

- The behaviours of attraction and repulsion that lead to swarm dynamics can arise out of the simple action of an agent classifying examples in the world with a learning algorithm.
- While agents in swarm algorithms are normally identical, differently constructed agents with different ways of learning can also swarm together, even while each exists in a different perceptual space. The point of view, sensory experience and even the dimensionality of perception may be different for every agent, but they can still form a common social dynamic by taking advantage of a shared world in which they act by selection of affordances.
- Even though the perceptual space of each individual is limited, the space in which they are able to swarm as a group is far greater in dimensionality. In this way it seems possible that a finite mind may explore any of the possibilities of an infinite-dimensional reality.

The model has been kept simple for clarity, and to show that individual innovation can result from such a structure. In particular, agents' behaviour has not been motivated by goals, either for utility or novelty for its own sake. Nonetheless, the model does produce the kind of behaviour expected of a swarm, and a seemingly random exploration through a space of possibilities, so it is likely that goals, in the form of a fitness evaluation, could be incorporated. Unlike stochastic particle swarm or optimisation algorithms however, random input would not be required.

Unusual for a model of creativity, this work proposes that the primary role of the mind is to take in, and make sense of the world, rather than stressing innovation for its own sake. But in making sense of what it takes in, it necessarily develops a new point of view that produces the innovation naturally. When two agents share the same examples in their domain, their perceptual frameworks become more aligned to one another by repeated exposure to those examples, but on examples outside the domain they may always disagree, as colleagues in work may disagree on politics or art. These variations in other dimensions continue to motivate the group, while the role of the group in this respect is to pull the individual along.

So where does individual creativity happen? Where does group creativity happen? These may not be separate questions. It may also be the case that creativity at a global level does not always come from an intentional effort on the part of the individual, but that novelty is sometimes a product of the interaction between the different parts of a creative system. Thus it is an emergent phenomenon that can happen at any level, among groups, neurons, agents or us.

Acknowledgements

I would like to thank Alan Penn for spatially related advice, and Peter Bentley for insights while developing the model presented in this paper.

References

Adrian ED: 1928, *The Basis of Sensation*. Christophers, London.

Axelrod R: 1997, The dissemination of culture: a model with local convergence and global polarization, *Journal of Conflict Resolution* **41(**2): 203-206.

Boden MA: 1990, *The Creative Mind: Myths and Mechanisms*. Weidenfeld and Nicolson, London.

Bodmer W and Cavalli-Sforza LL: 1976, *Genetics, Evolution and Man*. WH Freeman, San Francisco.

Brockman JB and Director SW: 1991, The Hercules task management system, *Procedings of the International Conference on Computer-Aided design.*

Burgess C: 1998, From simple associations to the building blocks of language: Modelling meaning in memory with the HAL model. *Behavior Research Methods, Instruments, and Computers* **30**: 188-198.

Czikszentmihalyi, M: 1988, Society, culture, and person: a systems view of creativity, *in* RJ Sternberg (ed.), *The Nature of Creativity: Contemporary Psychological Perspectives,* Cambridge University Press, Cambridge, pp. 325-339.

Dorigo M and Gambardella LM: 1997, Ant colony system: A cooperative learning approach to the traveling salesman problem. *IEEE Transactions on Evolutionary Computation* **1**(1): 53-66.

Dourish P: 2001, Where the *Action Is - The Foundations of Embodied Interaction*, MIT Press, Cambridge, MA.

Gamkrelidze TV and Ivanov VV: 1990, The early history of Indo-European languages. *Scientific American*, March: 110.

Gero JS: 1993, Towards a model of exploration in design, *in* JS Gero and F Sudweeks (eds) *Preprints Formal Design Methods for CAD,* Key Centre of Design Computing, University of Sydney, Sydney, IFIP, pp. 271-292.

Gibson JJ: 1979, *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.

Hillier B and Hanson J: 1984*, The Social Logic of Space*. Cambridge University Press.

Hutchins E: 1995, Cognition in the Wild. MIT Press. Cambridge, MA.

Kennedy J and Eberhart RC: 2001, *Swarm Intelligence*. Morgan Kaufmann, San Francisco.

Kuhn, Thomas S: 1962, *The Structure of Scientific Revolutions*, 3rd edition, University of Chicago Press.

Maher ML and Poon J: 1996, *Modelling Design Exploration as Co-evolution, Microcomputers in Civil Engineering* (Special Issues on Evolutionary Systems in Design).

Maturana HR and Varela FJ: 1987, *The Tree of Knowledge: The Biological Roots of Human Understanding*. Shambhala Publications Inc. Boston.

Nehaniv CL and Dautenhahn K: 1999, Of hummingbirds and helicopters: An algebraic framework for interdisciplinary studies of imitation and its applications, *in* J Demiris and A Birk, (eds), *Learning Robots: An Interdisciplinary Approach*, World Scientific Press, in press.

Norman DA: 1988, *The Psychology of Everyday Things*. New York: Basic Books.

Quick T, Dautenhahn K, Nehaniv CL and Roberts G: 1999, The essence of embodiment: A framework for understanding structural coupling between system and environment, *Proc Third International Conference on Computing Anticipatory Systems*, (CASYS, '99).

Reynolds CW: 1987, Flocks, herds and schools: A distributed behavioural model. *Computer Graphics* **21**: 25-34.

Rosenman, M: 1997, The generation of form using an evolutionary approach, *in* D Dasgupta and Z Michalewicz (eds), *Evolutionary Algorithms in Engineering Applications*, Springer-Verlag, pp. 69-86.

Saunders R and Gero JS: 2001, Artificial creativity: A synthetic approach to the study of creative behaviour, in JS Gero and ML Maher (eds), *Computational and Cognitive Models of Creative Design V*, Key Centre of Design Computing and Cognition, University of Sydney, Sydney, pp. 113-139.

Sosa R and Gero JS: 2002, Computational models of creative situations: Towards multiagent modelling of creativity and innovation in design, *in* JS Gero and FMT Brazier (eds) *Agents in Design 2002*, Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp. 165-180.

Steels L: 2000, The emergence of grammar in communicating autonomous robotic agents, in Horn W (ed.), *ECAI2000*. IOS Press, Amsterdam. pp 764-769.

Tang H-H and Gero J: 2001, Sketches as affordances of meanings in the design process, *in* JS Gero, B Tversky and T Purcell (eds), *Visual and Spatial Reasoning in Design II*, Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp. 271-282.

Wolfram S: 1994, *Cellular Automata and Complexity: Collected Papers*, Addison-Wesley, Reading MA.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 71-92

BEYOND BINARY CHOICES: UNDERSTANDING AND EXPLOITING TRADE-OFFS TO ENHANCE CREATIVITY

GERHARD FISCHER
University of Colorado, Boulder, USA

Abstract. Many research approaches are conceptualized as binary choices, representing endpoints of a spectrum (each of them providing important perspectives within their own discourses). Design and creativity are often conceptualized as being focused on one of these binary choices, thereby overlooking other possibilities. To better stimulate, enhance, and support creativity, our research has explored the middle ground between the endpoints defined by binary choices to identify "sweet spots" based on a careful trade-off analysis of specific goals, objectives, stakeholders, and socio-technical environments. This paper illustrates some of the major trade-offs related to design and creativity that we have explored in our research over the last ten years, including prescriptive and permissive environments, individual and social creativity, communities of practice and communities of interest, and consumer and active contributor cultures. It briefly describes some of the socio-technical environments that we have developed to enhance creativity in specific contexts.

1. Introduction

Our research over the last decade is grounded in *conceptual frameworks* and *system building* efforts characterized by the following global objectives:

- *empowering users rather than replacing or deskilling* them by emphasizing knowledge-based support environments from an intelligence augmentation perspective);
- advancing human-computer interaction to human problem-domain interaction, by *putting owners of problems in charge with domain-oriented design environment*s (Fischer 1994);
- transcending desktop-based computing by *integrating physical and computational environments* (Arias et al. 2000);
- supporting reflective practitioners with critiquing systems by *increasing the back-talk* of design artifacts and linking action and reflection spaces (Fischer et al. 1998; Schön 1983);

- creating open and evolvable systems grounded in the *seeding, evolutionary growth, reseeding process model* and supported by *meta-design* (Fischer et al. 2004a; Fischer et al. 2001); and
- understanding design as a *dialectical process between tradition and transcendence* by showing how the tension between old and new in computational artifacts can serve as a driving force of evolutionary developments. Emphasis on tradition reduces the impact of new media to "gift-wrapping," and ignorance of tradition leads to "techno-determinism" (Ehn 1988; Fischer 1998).

2. Binary Choices

Trade-offs are the most basic characteristics in design: they are, in fact, universal. There are no best solutions independent of goals and objectives (Simon 1996). Trade-offs are often characterized and conceptualized as *binary choices*. Binary choices represent the endpoints of a spectrum (each of them providing important perspectives within their own discourses). Exploring the middle ground between these endpoints, however, will help one to gain a deeper understanding of what stifles and hinders versus stimulates and enhances creativity. Identifying *"sweet spots"* as a combination of factors allowing for a particular suitable solution in a specific context and synergizing the best of the different approaches will enhance further progress. Csikszentmihalyi (Csikszentmihalyi, 1996) discusses personality characteristics of creative people who *"definitely know both extremes and experience both with equal intensity and without inner conflict."* Some examples described by Csikszentmihalyi are (1) being smart and naïve at the same time; (2) a combination of playfulness and discipline, or responsibility and irresponsibility; (3) an alternation between imagination at one end and a rooted sense of reality at the other; and (4) being rebellious and independent, but having internalized a domain of culture.

Creativity is a complex phenomenon, as indicated in part by the personality characteristics mentioned. Any socio-technical environment that supports and enhances creativity must therefore be based on a multi-dimensional framework and architecture. Table 1 provides an overview of some of the major binary choices that we have encountered and tried to overcome in our research (the trade-offs discussed in detail in sections 3.1 – 3.5 of this paper are highlighted in bold).

TABLE 1: Integrating Binary Choices and Finding Partial Resolutions

Choice-1	Choice-2	Choice-3 (Partial Resolution)
tool-based assistance	agent-based assistance	domain-oriented design environments (Shneiderman and Maes 1997)
generic ("Turing Tar Pit")	domain-oriented (over-specialized systems)	layered architectures (Fischer 1994)
tradition	transcendence	dialectical process between the two objectives (Ehn 1988)
descriptions, requirements	emergence, evolution	seeding, evolutionary growth, reseeding (Fischer et al. 2001)
serendipity	relevancy to the task at hand	provide both and let users choose (Roberts 1989)
extrinsic motivation	intrinsic motivation	social capital (Florida 2002)
novice/student/employee	expert/teacher/manager	collaborative advancement of knowledge (Rogoff et al. 1998)
physical	computational	augmented reality (Arias et al. 2000)
action	reflection	reflection-in-action (Schön 1983)
discipline	agility	risk-driven approach (Boehm and Turner 2004)
access (pull; passive critics)	delivery (push; active critics)	mixed-initiative (Horvitz 1999)
human support	computational support	socio-technical environments (Mumford 1987)
prescriptive	**permissive**	**guided discovery learning, contextualized tutoring (Mayer 2004)**
individual	**social**	**integration of individual and social (Fischer et al. 2005)**
communities of practice	**communities of interests**	**epistemological pluralism (Turkle and Papert, 1991)**
consumers (focused on use)	**active contributors (focused on design)**	**end-user development (Fischer 2002)**
closed systems	**open systems**	**meta-design (Lieberman et al. 2005)**

3. Examples of Trade-Offs

3.1. PRESCRIPTIVE VERSUS PERMISSIVE

Creativity is often associated with transcending the information given and exploring unknown territory. But transcending often implies that we acquire a deep understanding of what exists. People unfamiliar with domains will not develop creative extensions for them (Csikszentmihalyi 1996). The prescriptive/permissive trade-off can be explored in several interesting contexts, including: internal and external scripts (Schank and Abelson 1977); use of checklists in design environments (Lemke 1989); workflow systems in computer-supported collaborative work (CSCW) (Ellis et al. 1991); and the act of learning and learning environments, which will be used here for further illustration.

Self-directed Learning and Tutoring. One specific area in which the relationship between prescriptive and permissive approaches can be explored is learning. Here we contrast self-directed learning (being primarily permissive, often embedded in constructionist approaches) with tutoring (being primarily prescriptive, often embedded in instructionist approaches). The challenge is to identify a middle ground—learners need enough *freedom* to choose what to learn and how to learn it and enough *guidance* to explore and construct useful knowledge. If pursued independently, self-directed learning and tutoring suffer *shortcomings*. For example, self-directed learning, conceived as pure discovery learning, has the substantial weakness that learners are not exposed to coherent presentations of disciplinary knowledge, and thus remain stuck at suboptimal plateaus. Tutoring, without being contextualized, is not responsive to the real needs and interests of learners.

Tutoring and self-directed learning are grounded in contradictory educational approaches, TABLE 2:

- *Tutoring* is based on the assumptions that (1) the structure of a discipline is an accumulation of the fundamental ideas that enabled a scholar to proceed (Bruner 1960); (2) providing one-to-one instruction is effective (Mandl and Lesgold 1988); and (3) society can define a coherent body of knowledge that everyone should master (Hirsch 1996).
- *Self-directed learning* is based on the assumptions that (1) student interests are central (Dewey 1967); (2) people learn best when engrossed in a topic, or when motivated to seek out new knowledge and skills to solve a problem at hand (Csikszentmihalyi et al. 1993; Norman 1993); and (3) people in personally meaningful activities want to learn more and act as active contributors, not just as passive consumers (Fischer 2002).

What is needed but mostly lacking is moving *beyond binary choices***:** self-directed learning and tutoring are endpoints in a broad spectrum of possible approaches. Concepts such as *guided discovery learning* (Mayer 2004) and *community of learners* (Rogoff et al. 1998) illustrate different approaches and show that opportunities exist to exploit the best of both possible worlds.

TABLE 2: Distinctions and Complementary Nature of Tutoring and Self-Directed Learning

	Tutoring	Self-Directed Learning
characteristics	problem is given by the teacher or the systems; learning supported from the supply side; adult-run education; prescriptive	problem is based on the learner's needs and interest; learning supported from the demand side; child-run education; permissive
strengths	organized body of knowledge; pedagogically and cognitively structured presentations	real interests, personally meaningful tasks, high motivation
weaknesses	limited relevancy to the interests of the learner or the task at hand	coverage of important concepts may be missing; demand driven, unstructured learning episodes; lack of coherence
primary role of the teacher	sage on the stage — presents what he/she knows and is prepared for	guide on the side –answers and relevant information have to be culled from questions posed by others
planning versus situated responses	anticipating and planning of the learning goals and content	learning needs arise from the situational context
distribution over lifetime	*decreasing* in importance from school to university to lifelong learning	*increasing* in importance from school to university to lifelong learning
assessment	"standard" assessment instruments are applicable	"innovative" assessment instruments are needed
unique research challenges	presentation of an organized body of knowledge; responsiveness in the teacher-defined context to individual differences	task identification; context awareness; large repository of tutoring episodes

3.2. INDIVIDUAL VERSUS SOCIAL CREATIVITY

The Need for Multiple Voices in Design. Social creativity explores computer media and technologies to help people work together. It is relevant to design because collaboration plays an increasingly significant role in design projects that require expertise in a wide range of domains. Software design projects, for example, involve designers, programmers, human-computer interaction specialists, marketing people, and end-user participants (Greenbaum and Kyng 1991). Information technologies have reached such a level of sophistication, maturity, cost-effectiveness, and distribution that they are not restricted to only enhancing productivity—they also open up new creative possibilities (National Research Council 2003).

Design projects may take place over many years, with initial design followed by extended periods of evolution and redesign. In this sense, design artifacts are not designed once and for all, but instead they evolve over long periods of time (Fischer 2005) during which designers may extend or modify artifacts designed by people they have never met.

In extended and distributed design projects, specialists from many different domains must coordinate their efforts despite large separations of time and distance. In such projects, collaboration is crucial for success, yet it is difficult to achieve. Complexity arises from the need (1) to synthesize different perspectives, (2) to exploit collisions between concepts and ideas coming from different disciplines, (3) to manage large amounts of information potentially relevant to a design task, and (4) to understand the design decisions that have determined the long-term evolution of a designed artifact. Social creativity does not necessitate the development of environments in which the interests of the many inevitably supersede those of the individual. Appropriate socio-technical settings can amplify the outcome of a group of creative people by both augmenting individual creativities and multiplying rather than simply summing up individual creativities (Fischer et al. 2005).

Individual Creativity. Creative individuals, such as movie directors, leaders of sports teams, and leading scientists and politicians, can make a huge difference in exemplary cases. Individual creativity is grounded in the unique perspective that the individual brings to bear in the current problem or situation. It is the result of the life experience, culture, education, and background knowledge of the individual, as well as the individual's personal interest associated with a particular situation. Individual creativity, however, has limits. In today's society, the Leonardesque aspiration to have people who are competent in all of science has to fail because the individual human mind is limited (Campbell 2005; Shneiderman 2002).

Individuals may have the following concerns related to their voices being heard:

"Am I interested enough and am I willing to make the additional effort and time so my voice is heard?" —This relates to what motivates people to participate (e.g., to vote in an election, to engage in a neighborhood association). Participation is more likely in cases in which people are engaged in personally meaningful problems (Fischer 2002).

"Do I have something relevant to say?" — The local voices and unique expertise are often especially valuable in a global world; the incredible diversity of building styles, restaurants, food, and hotels that exist in different parts of the world are jeopardized and in some cases destroyed by the rise of tourism and the global marketplace (Friedman 2005).

"Am I able to express what I want to say?" — Owners of problems need to be independent of high-tech scribes; this requires literacy, and in the world today, where ideas and work products are documented with computers, it requires digital fluency (National Research Council 1999).

"Am I able and willing to express myself in a way that others can understand what I am saying?" — This is relevant in (1) participatory design processes in which people should express themselves with boundary objects (Star 2005) rather than with their own respective technical jargon, and (2) efforts so the public can understand the work of the scientists.

Social Creativity. Creative activity grows out of the relationship between an individual and the world of his or her work, as well as from the ties between an individual and other human beings. Much human creativity arises from activities that take place in a social context in which interaction with other people and the artifacts that embody group knowledge are important contributors to the process. Creativity happens not inside a person's head, but in the interaction between a person's thoughts and a socio-cultural context (Csikszentmihalyi 1996).

A group, community, or society is interested in hearing as many voices as possible for the following concerns:

"How can we encourage individuals to contribute to the good and progress of all of us?" — This is relevant in open source efforts, which rely on social capital and gift cultures (Fischer et al. 2004b).

"In order to stimulate and increase social creativity, how can we support and exploit cultural pluralism and epistemological pluralism as an advantage rather than as a disadvantage?" — Related questions include: Is the European multi-culturalism and its local and regional identities a strength or a weakness? Are we willing to accept the validity and the multiple ways of knowing and thinking, especially by including the voices of underrepresented and underprivileged groups (e.g., people with disabilities (Carmien et al. 2004))?

"How do we avoid the situation that voices get lost because there is too much information or their input does not get recorded?" — In other words, how do we create knowledge management environments that support the right

division between pull and push technologies and that have some context awareness?

"How do we avoid illegitimate voices?" — this includes information that is pushed at people without their consent (such as spam mail) or is made available against their will (such as violation of privacy).

"How do we avoid getting stuck in group think?" — This includes seeing controversy as an asset rather than as a limitation; *group think* (Janis 1972) is especially harmful if some groups believe that their way of thinking is on top, rather than on tap (Turkle and Papert 1991).

"How do we eliminate sources of exclusion?" — This includes not only rules that specifically exclude people (such as minorities, lay persons facing experts, or people with disabilities), but ways of thinking and organizing that make them reluctant to join in.

Integrating Individual and Social Creativity. Our work is grounded in the basic belief that there is an "and" and not a "versus" relationship between individual and social creativity (Fischer et al. 2005). Creativity occurs in the relationship between an individual and society, and between an individual and his or her technical environment. The mind, rather than driving on solitude, is clearly dependent upon the reflection, renewal, and trust inherent in sustained human relationships (John-Steiner 2000). We need to support this distributed fabric of interactions by integrating diversity, making all voices heard, increasing the back-talk of the situation, and providing systems that are open and transparent, so that people can be aware of and access each other's work, relate it to their own work, transcend the information given, and contribute the results back to the community. This process is illustrated (in part at least) by the *"location, comprehension, and modification"* cycle in software reuse (Ye and Fischer 2005), the *"collect/relate/create/donate"* model (Shneiderman 2002), and by the decentralized development process of open source communities (Scharff 2002).

Individual and social creativity can be integrated by means of proper *collaboration models* (Olson et al. 2001), appropriate *community structures* (Wenger 1998), *boundary objects* (Star 2005), *process models* in support of natural evolution of artifacts (Fischer et al. 2001), and *meta-design* (Fischer et al. 2004a). By integrating individual and social creativity, support will be provided not only for reflective practitioners but also for reflective communities. Even within disciplines, competence is not achieved in individual minds, but as a collective achievement made possible by the overlap of narrow specialties (Campbell 2005).

3.3. COMMUNITIES OF PRACTICE VERSUS COMMUNITIES OF INTEREST

"The clashing point of two subjects, two disciplines, two cultures ought to produce creative chaos." C.P. Snow (Snow 1993)

Design communities are increasingly characterized by a *division of labor* (Levy and Murnane 2004), comprising individuals who have unique experiences, varying interests, and different perspectives about problems, and who use different knowledge systems in their work (Bonifacio and Molani 2003). Shared understanding (Resnick et al. 1991) that supports collaborative learning and working requires the active construction of a knowledge system in which the meanings of concepts and objects can be debated and resolved. In heterogeneous design communities that form around large and complex design problems, the construction of shared understanding requires the interaction and synthesis of several separate knowledge systems (Turkle and Papert 1991).

Diversity is not only a constraint to deal with but an opportunity to generate new ideas, new insights, and new environments (Basalla 1988; National Research Council 2003). The challenge is often not to reduce heterogeneity and specialization, but to support it, manage it, and integrate it by finding ways to build bridges between local knowledge and by exploiting conceptual collisions and breakdowns as sources for innovation.

Communities of Practice (CoPs) (Fischer 2001b; Wenger 1998) are *homogeneous* design communities consisting of practitioners who work as a community in a certain domain undertaking similar work. Traditional learning and working environments (e.g., university departments and their respective curricula) are disciplinary. Throughout history, the use of disciplines and their associated development of a division of labor have proven to be powerful approaches. However, we know from all the attempts to support multidisciplinary work that "real" problems can only rarely be successfully approached by a lone discipline (Campbell 2005; Derry and Fischer 2005).

Communities of Interest (CoIs) (Fischer 2001a) are *heterogeneous* design communities bringing together stakeholders from different CoPs to solve a particular (design) problem of common concern. They can be thought of as "communities of communities" (Brown and Duguid 1991) or communities of representatives of communities. Examples of CoIs are (1) a team of software designers, marketing specialists, psychologists, and programmers interested in software development; or (2) a group of citizens and experts interested in urban planning, in particular, in implementing new transportation systems. CoIs are supported by the *Envisionment and Discovery Collaboratory* (Arias et al. 2000) (see section 4), an integrated physical and computational environment supporting informed participation through new forms of knowledge creation, integration, and dissemination. Fundamental challenges facing CoIs are found in building a *shared understanding* (Resnick et al. 1991) of the task at hand, which often does not exist at the beginning but is evolved incrementally and collaboratively and emerges in people's minds and in external artifacts. Members of CoIs must learn to communicate with and learn from others (Derry et al. 2005; Engeström 2001) who have different perspectives and perhaps different vocabularies to describe their ideas in order to establish a common ground (Clark and Brennan 1991).

Comparing CoPs and CoIs. Table 3 characterizes and differentiates CoPs and CoIs along a number of dimensions. The point of comparing and contrasting CoPs and CoIs is not to pigeonhole groups into either category, but rather to identify patterns of practice and helpful technologies. People can participate in more than one community, or one community can exhibit attributes of both a CoI and a CoP.

TABLE 3: Differentiating CoPs and CoIs

Dimensions	CoPs	CoIs
nature of problems	different tasks in the same domain	common task across multiple domains
knowledge development	refinement of one knowledge system; new ideas coming from within the practice	synthesis and mutual learning through the integration of multiple knowledge systems
major objectives	codified knowledge, domain coverage	shared understanding, making all voices heard
weaknesses	group-think	lack of a shared understanding
strengths	shared ontologies	social creativity; diversity; making all voices heard
people	beginners and experts; apprentices and masters	stakeholders (owners of problems) from different domains
learning	legitimate peripheral participation	informed participation

Our Center for LifeLong Learning and Design (L3D) is an example: it has many characteristics of a CoP (having developed its own stories, terminology, and artifacts), but by actively engaging with people from outside our community (e.g., other colleges on campus, people from industry, international visitors, and so forth), it also has many characteristics of a CoI. Design communities do not have to be strictly either CoPs or CoIs; they can integrate aspects of both forms of communities. The community type may shift over time, according to events outside the community, the objectives of its members, and the structure of the membership.

CoPs are biased toward communicating with the same people and taking advantage of a shared background. The existence of an accepted, well-established center of expertise and a clear path of learning toward this center allows the differentiation of members into novices, intermediates, and experts. It makes these attributes viable concepts associated with people and provides the foundation for legitimate peripheral participation as a workable learning strategy. Some limitations of CoPs are that *group-think* (Janis 1972) can suppress exposure to, and acceptance of, outside ideas; and the more someone is at home in a CoP, the more that person forgets the strange and contingent nature of its categories from the outside.

CoIs have a potential for creativity because different backgrounds and different perspectives can lead to new insights (Bennis and Biederman 1997). They can support pluralistic societies by coping with complexity, contradictions, and a willingness to allow for differences of opinion. A fundamental barrier for CoIs might be that the participants fail to create common ground and shared understanding. This barrier is particularly challenging because CoIs often are more temporary than CoPs; they come together in the context of a specific project and dissolve after the project has ended.

3.4. CONSUMER VERSUS PRODUCER CULTURES

The process of knowledge accumulation in society has undergone major changes. Initially, knowledge was accumulated in the heads of people and communicated by tales, stories, and myths. The *oral* tradition has been replaced by a *written* tradition that allows people to permanently record thoughts and widely distribute them (Ong 1982). *Information technologies* (Hippel 2005) have created fundamentally new opportunities, new challenges, and new problems for knowledge creation, integration, and dissemination, including *open source communities* (Fischer et al. 2004b; Raymond and Young 2001) and *collaboratively constructed online encyclopedias* such as Wikipedia (http://wikipedia.org/). The amount of available information and knowledge is exploding, and because information and knowledge consume attention, we all are suffering from it.

In our research we have developed a number of basic conceptual frameworks to support new ways to accumulate knowledge and selectively distribute it, including:

- the Seeding/Location/Comprehension/Modification/Sharing model instantiated by the Codebroker system (Ye and Fischer 2005);
- the Seeding/Evolutionary Growth/Reseeding model (Fischer et al. 2001); and

- the meta-design framework (Fischer et al. 2004a).

These approaches are related to: (1) the collect/relate/create/donate model of Shneiderman (Shneiderman 2002); (2) the basic assumption that information has a social life (Brown and Duguid 2000); and (3) the ideas of convivial tools and deprofessionalization (Illich 1973).

Professionally Dominated Cultures. A professionally dominated culture is characterized by a small number of experts and a large number of consumers (see Figure 1). Based on strong input filters (e.g., low acceptance rates for conferences and journals), relatively small information repositories are created. The advantage is the likelihood that the quality and trustworthiness of the accumulated information is high; thus, relatively weak output filters are required. The disadvantage of this model is that it greatly limits that "all voices can be heard," that most people are limited to accessing existing information, and that potentially relevant information (which may be of great value not at a global level but for the work of specific individuals) may not be incorporated into the information repository.

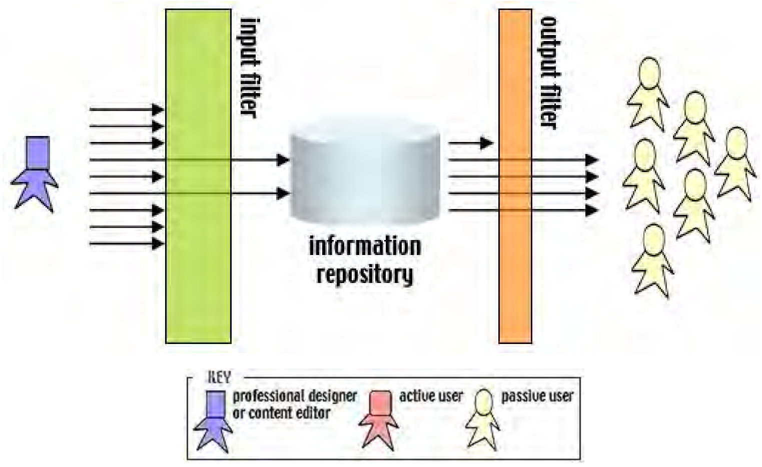


Figure 1: Producer/Consumer Relationships in a Professionally Dominated Culture

Design Cultures. Design cultures can be characterized by weak input filters, which allow users to not only access information but to become active contributors by engaging in *informed participation* (Brown et al. 1994). The resulting information repositories (see Figure 2) are much larger (the World Wide Web is the prime example of this approach). Major limitations of this model are the potentially reduced trust and reliability of the content of the information repositories. This requires powerful search mechanisms to find relevant information and strong new output filters to allow users to judge the reliability of the information.

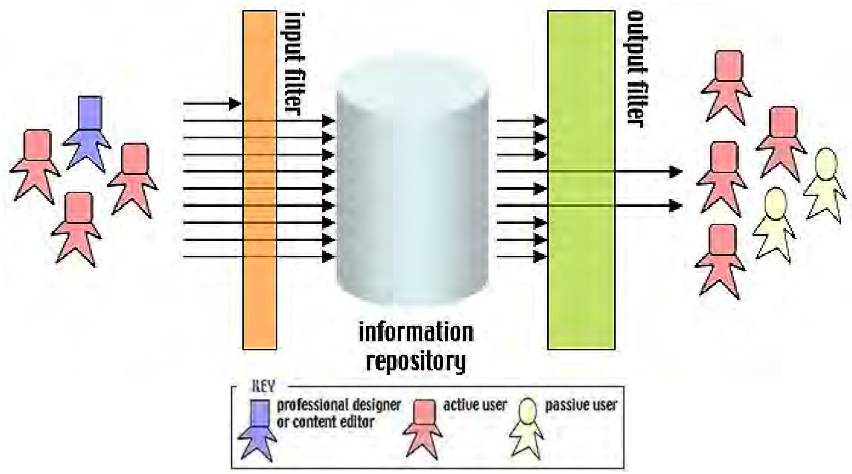


Figure 2: Producer/Consumer Relationships in a Design Culture

This brief characterization of the two models shows that both have strengths and weaknesses, and both serve as the guiding principles in different settings. Figure 3 illustrates how the proceedings of conferences—the CHI conference (white book) using strong input filters and the HCI International conference (dark books) using weak input filters—document their results in very different ways, depending on the basic criteria established by the respective meetings.

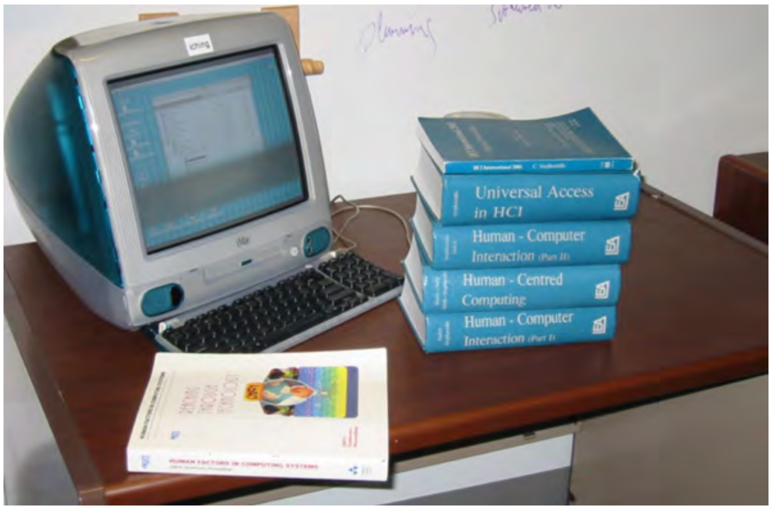


Figure 3: The Proceedings of Two Conferences

3.5. META-DESIGN: BEYOND CLOSED AND OPEN SYSTEMS

Meta-design (Fischer et al. 2004a) characterizes objectives, techniques, and processes to allow users to act as designers by creating new knowledge rather than restricting them to the consumption of existing knowledge. Meta-design allows creative and unplanned opportunism, supports reflective communities, and addresses one of the fundamental challenges of a knowledge society: to invent and design a culture in which all participants in a collaborative design process can express themselves and engage in personally meaningful activities (Hippel 2005).

The need for meta-design is founded on the observation that design requires open systems that users can modify and evolve. Because problems cannot be completely anticipated at design time when the system is developed, users at use time will encounter mismatches between their problems and the support that a system provides. These mismatches will lead to *breakdowns*, which serve as potential sources for new insights, new knowledge, and new understanding. Meta-design advocates a shift in focus from finished products or complete solutions to conditions for users to resolve mismatches and repair breakdowns when they are discovered during use.

Meta-design extends the traditional model of system development consisting of fixed stages to include an ongoing process in which stakeholders become *co-designers*—not only at design time but also throughout the whole existence of the system. A necessary, although not sufficient, condition for users to become co-designers is that software systems include advanced features (direct activation tools and design environments) that permit users to create complex customizations and extensions to existing systems. Rather than presenting users with closed systems, meta-design approaches provide them with opportunities, tools, and social reward structures to extend the system to fit their needs. Moreover, meta-design is a design methodology that involves multiple stakeholders. One of its objectives in its effort to overcome borders is to make all voices heard. An interesting challenge from this point of view is how to integrate the contributing voices originating from *individual and social perspectives*.

Meta-design covers the middle ground between general purpose programming languages (Turing Tar Pit) and over-specialized (turnkey) systems. Users need access to a middle ground of abstractions—lightweight but powerful tools and techniques that shorten the edit-compile-debug cycle of conventional programming. To modify a computer application, users should increase their knowledge only by an amount proportional to the complexity of the modification. This has been conceptualized as the "gentle slope" to programming, providing end-user developers with increasingly complex design environments for making changes.

Our evolving meta-design framework pays attention to motivation, specifically including the following aspects (Fischer et al. 2004b):

- making changes must seem possible for the skill and experience level of specific users (Scharff 2002);
- changes must be technically possible (a central objective of our meta-design approach) (Fischer and Giaccardi 2004);
- benefits must be perceived; that is, individuals must perceive a direct benefit in contributing that is large enough to outweigh the effort (Grudin 1987);
- the effort required to contribute must be minimal so that it will not interfere with getting the real work done (Carroll and Rosson 1987).

Social creativity needs the "synergy of many," and this kind of synergy is facilitated by meta-design. However, a tension exists between creativity and organization. A defining characteristic of social creativity is that it transcends individual creativity and thus requires some form of organization. On the one hand, elements of organization can and frequently do stifle creativity (Florida 2002). On the other hand are historical precedents that *too many voices* can be worse than having a few choices. As a prime example, the multiparty system that existed in the Weimar Republic in Germany after World War I created a less stable political system compared to countries with a limited number of political parties.

The open systems created by metadesign (a) promote the transcendence of the individual mind; (b) support the users' engagement in the collaborative construction and sharing of meaningful activities; and (c) enable the mutual adaptation and continuous evolution of users and systems by letting users modify the system at use time and adapt it to their dynamic practices.

4. Socio-Technical Environments: Exploiting Trade-Offs to Enhance Creativity

In the last decade, L3D has developed *socio-technical environments* to support the partial resolutions between the binary choices indicated in Table 1. Socio-technical environments can be characterized as follows: (1) They are needed because the deep and enduring changes of our ages are *not technological but are social and cultural, in their core substance.* Changes in complex environments are not primarily determined by technology, but are the result of incremental shifts in human behavior and social organization. (2) They are composed *not only* of computers, networks, and software, *but also* of people, processes, policies, laws, institutions, the flow of design materials and commodities, and many other aspects of a complex web of socio-cultural concerns. (3) They require a *co-design* of social and technical systems and use models and concepts that not only focus on the artifact, but exploit the social context in which the systems will be used. Meta-design is a critical component for socio-technical environments because it gives the users design power to modify and evolve the technical systems according to their needs. The following brief examples of socio-technical environments deal with specific binary choices and their respective solutions (in reference to Table 1).

Domain-oriented design environments (Fischer 1994) integrate construction and argumentation. They support CoPs by allowing them to interact at the level of the problem domain and not only at a computational level. They allow for efficient communication within the community at the expense of making communication and understanding difficult for outsiders. They integrate tool-based assistance (e.g., direct manipulation interfaces with objects grounded in the semantics of the problem domain) with agent-based assistance (e.g., critics and simulation components).

Computational critiquing mechanisms (Fischer et al. 1998) enrich the back-talk of situations, thereby increasing the users' understanding of problems by pointing out significant design situations and locating relevant information in large information spaces. Critics afford learning on demand by letting designers access new knowledge in the context of actual problem situations. Critics instantiate and transcend Schön's theory of design (Fischer and Nakakoji 1992); they support "reflection-in-action" and they increase the "back-talk" of the design situation, which in Schön's framework is determined by the designers' skill, experience, and attention (Schön 1983). Critics explore and support the trade-offs between (1) serendipity and relevance to the task at hand, (2) information access and information delivery, and (3) new collaboration models between human and computational support.

The Envisionment and Discovery Collaboratory (Arias et al. 2000) supports CoIs with an environment in which participants collaboratively solve problems of mutual interest. The problem contexts explored in the collaboratory, such as urban transportation planning, flood mitigation, and building design, are all examples of open-ended design problems. The socio-technical environment empowers users to act as designers in problem-solving activities by supporting face-to-face collaboration (see Figure 4). It allows users to engage in complex design tasks by supporting them to incrementally articulate their ideas and negotiate with each other to create mutually agreeable design plans. With the Envisionment and Discovery Collaboratory, new relationships between individual and social creativity (Fischer et al. 2005) can be explored.

Figure 4: The Envisionment and Discovery Collaboratory

CodeBroker (Ye 2001) (a reuse support system specifically addressing temporal distance) creates awareness of each other's work so that efforts are not wasted and people can focus on what has not been done before. CodeBroker monitors software developers' programming activities, infers their immediate programming task by analyzing semantic and syntactic information contained in their working products, and actively delivers task-relevant and personalized reusable parts (Fischer et al. 1998) from a reuse repository created by decomposing existing software systems. CodeBroker will be further developed as an open source software system (Raymond and Young 2001) to support the collaboration of a large number of developers. CodeBroker explores our integrated approaches of reflection-in-action, mixed-initiative interactions, and socio-technical environments.

Courses-as-Seeds (dePaula et al. 2001) is an educational model with the goal to create a culture of informed participation that is situated in the context of university courses and yet extends beyond the temporal boundaries of semester-based classes. Courses are conceptualized as seeds, rather than as finished products, and students are encouraged and supported as knowledge workers who play an active role in defining what they will learn. From the courses-as-seeds standpoint, the role of technology is to form and sustain active communities of learners who can make their voices heard by contributing ideas from their own unique viewpoints and to connect them in new ways. From this perspective, mere access to existing information and knowledge (e.g., seeing courses as finished products, either in the classroom or on the Web) is a very limiting concept. The courses-as-seeds framework explores issues and challenges associated with meta-design, the trade-offs between consumer and producer cultures (see Figure 1 and Figure 2), and the synergy between individual and social creativity.

5. Conclusions

Creativity is a multi-faceted concept. Creative people often combine personality traits that are in conflict with each other (Csikszentmihalyi 1996). Socio-technical environments enhancing creativity must support not only one end of the spectrum of binary choices, but also—depending on the domain, tasks, and objectives of the people—must exploit trade-offs in a situated fashion to come as close as possible to the "sweet-spot" for a particular situation. This paper has described some of the trade-offs that we have explored in our research over the last decade and the systems that we have built to gain a deeper understanding of creativity and to support creative people.

Acknowledgments

The author thanks the members of the Center for LifeLong Learning and Design (L3D) at the University of Colorado, who have made major contributions to the ideas, frameworks, and systems discussed in this paper. The reviewers of this paper have provided valuable feedback leading to this final version. The research was supported by (1) the National Science Foundation, grants (a) REC-0106976 'Social Creativity and Meta-Design in Lifelong Learning Communities,' and (b) CCR-0204277 'A Social-Technical Approach to the Evolutionary Construction of Reusable Software Component Repositories'; (2) SRA Key Technology Laboratory, Inc., Tokyo, Japan; and (3) the Coleman Institute, University of Colorado, Boulder.

References

Arias, EG, Eden, H, Fischer, G, Gorman, A and Scharff, E: 2000, Transcending the individual human mind—Creating shared understanding through collaborative design, *ACM Transactions on Computer Human-Interaction* **7**(1): 84-113.

Basalla, G: 1988, *The Evolution of Technology,* Cambridge University Press, New York.

Bennis, W and Biederman, PW: 1997 *Organizing Genius: The Secrets of Creative Collaboration,* Perseus Books, Cambridge, MA.

Bobrow, DG: 1991, Dimensions of interaction, *AI Magazine* **12**(3): 64-80.

Boehm, B and Turner, R: 2004, *Balancing Agility and Discipline,* Addison Wesley, Boston.

Bonifacio, M and Molani, A: 2003, The richness of diversity in knowledge creation: An interdisciplinary overview, *Proceedings of I-KNOW'03*, Graz, Austria, pp. 379-388.

Brown, JS and Duguid, P: 1991, Organizational learning and communities-of-practice: Toward a unified view of working, learning, and innovation, *Organization Science* **2**(1): 40-57.

Brown, JS, and Duguid, P: 2000, *The Social Life of Information,* Harvard Business School Press, Boston, MA.

Brown, JS, Duguid, P and Haviland, S: 1994, Toward Informed Participation: Six Scenarios in Search of Democracy in the Information Age, *The Aspen Institute Quarterly* **6**(4): 49-73.

Bruner, J: 1960, *The Process of Education,* Random House, New York.

Campbell, DT: 2005, Ethnocentrism of disciplines and the fish-scale model of omniscience, *in* Derry, SJ, Schunn, CD and Gernsbacher, MA (eds), *Interdisciplinary Collaboration — An Emerging Cognitive Science,* Lawrence Erlbaum Associates, Mahwah, NJ, pp. 3-21.

Carmien, S, Dawe, M, Fischer, G, Gorman, A, Kintsch, A and Sullivan, JF: 2004, Socio-technical environments supporting people with cognitive disabilities using public transportation, *in Transactions on Human-Computer Interaction (ToCHI)*, (in press).

Carroll, JM and Rosson, MB: 1987, Paradox of the active user, *in* JM Carroll (ed.), *Interfacing Thought: Cognitive Aspects of Human-Computer Interaction,* The MIT Press, Cambridge, MA, pp. 80-111.

Clark, HH and Brennan, SE: 1991, Grounding in communication, *in* Resnick, LB, Levine, JM and Teasley, SD (eds), *Perspectives on Socially Shared Cognition,* American Psychological Association, pp. 127-149.

Csikszentmihalyi, M: 1996, *Creativity — Flow and the Psychology of Discovery and Invention,* Harper Collins Publishers, New York, NY.

Csikszentmihalyi, M, Rathunde, K, and Whalen, S: 1993, *Talented Teenagers: The Roots of Success and Failure,* Cambridge University Press, New York.

dePaula, R, Fischer, G, and Ostwald, J: 2001, Courses as seeds: Expectations and realities, *Proceedings of the Second European Conference on Computer-Supported Collaborative Learning (Euro-CSCL' 2001)*, Maastricht, Netherlands, pp. 494-501.

Derry, S, and Fischer, G: 2005, *Toward a model and theory for transdisciplinary graduate education,* Available at http://l3d.cs.colorado.edu/~gerhard/papers/2005/aera-montreal.pdf

Derry, SJ, Schunn, C, and Gernsbacher, MA (eds): 2005, *Interdisciplinary Collaboration: An Emerging Cognitive Science,* Lawrence Erlbaum Associates, Mahwah, NJ.

Dewey, J: 1967, *The School and Society,* University of Chicago Press, Chicago, IL.

Ehn, P: 1988, *Work-Oriented Design of Computer Artifacts,* (2nd ed.), Arbetslivscentrum, Stockholm.

Ellis, CA, Gibbs, SJ, and Rein, GL: 1991, Groupware: Some issues and experiences, *Communications of the ACM* **34**(1): 38-58.

Engeström, Y: 2001, Expansive learning at work: Toward an activity theoretical reconceptualization, *Journal of Education and Work* **14**(1): 133-156.

Fischer, G: 1994, Domain-oriented design environments, *Automated Software Engineering* **1**(2): 177-203.

Fischer, G: 1998, Making learning a part of life—Beyond the 'gift-wrapping' approach of technology, *in* P Alheit, and E Kammler (eds), *Lifelong Learning and Its Impact on Social and Regional Development,* Donat Verlag, Bremen, pp. 435-462.

Fischer, G: 2001a, External and sharable artifacts as sources for social creativity in communities of interest, *in* JS Gero, and ML Maher (eds), *Computational and Cognitive Models of Creative Design V,* Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp. 67-89.

Fischer, G: 2001b, External and shareable artifacts as opportunities for social creativity in communities of interest, *Proceedings of the Fifth International Conference on*

Computational and Cognitive Models of Creative Design, University of Sydney, Australia, pp. 67-89.

Fischer, G: 2002, Beyond 'couch potatoes': From consumers to designers and active contributors, *in FirstMonday (Peer-Reviewed Journal on the Internet),* Available at http://firstmonday.org/issues/issue7_12/fischer/.

Fischer, G: 2005, Distances and diversity: Sources for social creativity, *Proceedings of Creativity and Cognition*, London, April, pp. 128-136.

Fischer, G, and Giaccardi, E: 2004, Meta-Design: A framework for the future of end user development, *in* H Lieberman, F Paternò, and V Wulf (eds), *End User Development — Empowering People to Flexibly Employ Advanced Information and Communication Technology,* Kluwer Academic Publishers, Dordrecht, The Netherlands.

Fischer, G, Giaccardi, E, Eden, H, Sugimoto, M, and Ye, Y: 2005, Beyond binary choices: integrating individual and social creativity, *International Journal of Human-Computer Studies (IJHCS) Special Issue on Computer Support for Creativity,* EA Edmonds and L Candy (eds), **63**(4-5): 482-512.

Fischer, G, Giaccardi, E, Ye, Y, Sutcliffe, AG, and Mehandjiev, N: 2004a, Meta-Design: A manifesto for end-user development, *Communications of the ACM,* **47**(9): 33-37.

Fischer, G, Grudin, J, McCall, R, Ostwald, J, Redmiles, D, Reeves, B, and Shipman, F: 2001, Seeding, evolutionary growth and reseeding: The incremental development of collaborative design environments, *in* GM Olson, TW Malone, and JB Smith (eds), *Coordination Theory and Collaboration Technology,* Lawrence Erlbaum Associates, Mahwah, NJ, pp. 447-472.

Fischer, G, and Nakakoji, K: 1992, Beyond the macho approach of artificial intelligence: empower human designers - do not replace them, *Knowledge-Based Systems Journal, Special Issue on AI in Design* **5**(1): 15-30.

Fischer, G, Nakakoji, K, Ostwald, J, Stahl, G, and Sumner, T: 1998, Embedding critics in design environments, *in* MT Maybury and W Wahlster (eds), *Readings in Intelligent User Interfaces,* Morgan Kaufmann, San Francisco, pp. 537-559.

Fischer, G, Scharff, E, and Ye, Y: 2004b, Fostering social creativity by increasing social capital, *in* M Huysman and V Wulf (eds), *Social Capital and Information Technology,* MIT Press, Cambridge, MA, pp. 355-399.

Florida, R: 2002, *The Rise of the Creative Class and How It's Transforming Work, Leisure, Community and Everyday Life,* Basic Books, New York.

Friedman, TL: 2005, *The World is Flat: A Brief History of the Twenty-First Century,* Farrar, Straus and Giroux, New York.

Greenbaum, J, and Kyng, M (eds): 1991, *Design at Work: Cooperative Design of Computer Systems,* Lawrence Erlbaum Associates, Hillsdale, NJ.

Grudin, J: 1987, Social evaluation of the user interface: Who does the work and who gets the benefit? *in* H Bullinger and B Shackel (eds), *Proceedings of INTERACT'87, 2nd IFIP Conference on Human-Computer Interaction (Stuttgart, FRG),* North-Holland, Amsterdam, pp. 805-811.

Hippel, EV: 2005, *Democratizing Innovation,* MIT Press, Cambridge, MA.

Hirsch, ED: 1996, *The Schools We Need And Why We Don't Have Them,* Doubleday, New York.

Horvitz, E: 1999, Principles of mixed-initiative user interfaces, *in Human Factors in Computing Systems, CHI'99 (Pittsburgh, PA),* ACM, New York, pp. 159-166.

Illich, I: 1973, *Tools for Conviviality,* Harper and Row, New York.

Janis, I: 1972, *Victims of Groupthink,* Houghton Mifflin, Boston.

John-Steiner, V: 2000, *Creative Collaboration,* Oxford University Press, Oxford, UK.

Lemke, AC: 1989, *Design Environments for High-Functionality Computer Systems*, Ph.D. Dissertation, University of Colorado at Boulder.

Levy, F and Murnane, RJ: 2004, *The New Division of Labor: How Computers are Creating the Next Job Market,* Princeton University Press, Princeton, NJ.

Lieberman, H, Paterno, F, and Wulf, V (eds): 2005, *End User Development - Empowering People to Flexibly Employ Advanced Information and Communcation Technology,* Kluwer Publishers, Dordrecht, The Netherlands.

Mandl, H, and Lesgold, A: 1988, *Learning Issues for Intelligent Tutoring Systems,* Springer-Verlag, New York.

Mayer, RE: 2004, Should there be a three-strikes rule against pure discovery learning? — The case for guided methods of instruction, *American Psychologist,* **59**(1): 14-19.

Mumford, E: 1987, Sociotechnical systems design: Evolving theory and practice, *in* G Bjerknes, P Ehn and M Kyng (eds), *Computers and Democracy,* Avebury, Brookfield, VT, pp. 59-77.

National-Research-Council: 1999, *Being Fluent with Information Technology,* National Academy Press, Washington, DC.

National-Research-Council: 2003, *Beyond Productivity: Information Technology, Innovation, and Creativity,* National Academy Press, Washington, DC.

Norman, DA: 1993, *Things That Make Us Smart,* Addison-Wesley Publishing Company, Reading, MA.

Olson, GM, Malone, TW and Smith, JB (eds): 2001, *Coordination Theory and Collaboration Technology,* Lawrence Erlbaum Associates, Mahwah, NJ.

Ong, WJ: 1982, *Orality and Literacy,* Routledge, London.

Raymond, ES and Young, B: 2001, *The Cathedral and the Bazaar: Musings on Linux and Open Source by an Accidental Revolutionary,* O'Reilly and Associates, Sebastopol, CA.

Resnick, LB, Levine, JM and Teasley, SD (eds): 1991, *Perspectives on Socially Shared Cognition,* American Psychological Association, Washington, DC.

Roberts, RM: 1989, *Serendipity: Accidental Discoveries in Science,* John Wiley and Sons, New York.

Rogoff, B, Matsuov, E and White, C: 1998, Models of teaching and learning: Participation in a community of learners, *in* DR Olsen and N Torrance (eds), *The Handbook of Education and Human Development — New Models of Learning, Teaching and Schooling,* Blackwell, Oxford, UK, pp. 388-414.

Schank, RC and Abelson, RP: 1977, *Scripts, Plans, Goals, and Understanding,* Lawrence Erlbaum Associates, Hillsdale, NJ.

Scharff, E: 2002, *Open Source Software, a Conceptual Framework for Collaborative Artifact and Knowledge Construction*, Ph.D. Dissertation, University of Colorado at Boulder.

Schön, DA: 1983, *The Reflective Practitioner: How Professionals Think in Action,* Basic Books, New York.

Shneiderman, B: 2002, *Leonardo's Laptop — Human Needs and the New Computing Technologies,* MIT Press, Cambridge, MA.

Shneiderman, B and Maes, P: 1997, Direct Manipulation vs. Interface Agents, *Interactions (ACM)* **4**(6 (Nov)): 42 - 61.

Simon, HA: 1996, *The Sciences of the Artificial,* (third ed.), The MIT Press, Cambridge, MA.

Snow, CP:1993, *The Two Cultures,* Cambridge University Press, Cambridge, UK.

Star, SL: 2005, Categories and cognition: Material and conceptual aspects of large-scale category systems, *in* SJ Derry, CD Schunn and MA Gernsbacher (eds), *Interdisciplinary Collaboration — An Emerging Cognitive Science,* Lawrence Erlbaum Associates, Mahwah, NJ, pp. 167-186.

Turkle, S and Papert, S: 1991, Epistemological pluralism and the revaluation of the concrete , *in* I Harel and S Papert (eds), *Constructionism,* Ablex Publishing Corporation, Norwood, NJ, pp. 161-191.

Wenger, E: 1998, *Communities of Practice — Learning, Meaning, and Identity,* Cambridge University Press, Cambridge, UK.

Ye, Y: 2001, *Supporting Component-Based Software Development with Active Component Repository Systems*, Ph.D. Dissertation, University of Colorado at Boulder.

Ye, Y and Fischer, G: 2005, Reuse-conducive development environments, *International Journal Automated Software Engineering,* Kluwer Academic Publishers, Dordrecht, Netherlands **12**(2): 199-235.

COMPUTATIONAL CREATIVITY

Creativity as disruptive adaption: A computational case study
Tapio Takala

Can designs themselves be creative?
Mary Lou Maher, Kathryn Merrick and Owen Macindoe

Towards understanding human-computer c-creativity
Oliver Hoffman

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 95-110

CREATIVITY AS DISRUPTIVE ADAPTATION – A COMPUTATIONAL CASE STUDY

TAPIO TAKALA
Helsinki University of Technology, Finland

Abstract. The article studies what creativity means when broken down to the very essential elements. Creative design is assumed to be a process that brings up new and useful products in a surprising way, i.e. against expectations but using a pattern instead of random search. These features are further analyzed with a case study of geometric packing problems. A computational problem solving agent is built that uses a small number of different strategies to place bottles in a case. Its adaptive control mechanism, based on reinforcement learning, leads to fixation of strategy and into a conflict when the strategy does not work. Relaxation of expectations allows it to (re)invent a novel strategy, which in favorable circumstances becomes a new fixation, an innovation. These circumstances are analyzed with respect to the problem domain and the order in which problems are presented to the agent, concluding that creative moments appear when entering the boundary of a subdomain where a different problem solving strategy must be applied.

1. Introduction

Creativity is a fundamental question in current AI research, but still far from being fully understood. Often it is considered to be a human trait alone, even a mystery.

In a review article, Buchanan (2001) treats the issue from psychological and computational points of view. Quoting him, *there is no consensus, just considerable ambiguity, about what we call creative behavior or what is involved in this behavior*. However, referring to Minsky, he concludes that *defining the criteria for acting creatively assures us that a computer can be creative.*

One reason why creativity evades definition is that it is contextual. In the larger context, referring to great inventors or artists, people talk about "big-C" Creativity, whereas similar behavior in mundane everyday activities is "small-c" creativity. In many of her articles, Boden (e.g. 1995) emphasizes the contextuality by distinguishing personal (P) creativity from historical (H) creativity. She also points out that creativity is to act against the rules by dropping or transforming the prevailing constraints. Mere novelty is not enough to define a product as being creative.

As long as we observe creativity in an open world, its definition remains contextual. In order to make a computational model we need a closed world that includes both a potentially creative subsystem (G) and the evaluating criteria (E) for it. Obviously the closed world would be smaller than the real society, or even a single person, Figure 1.

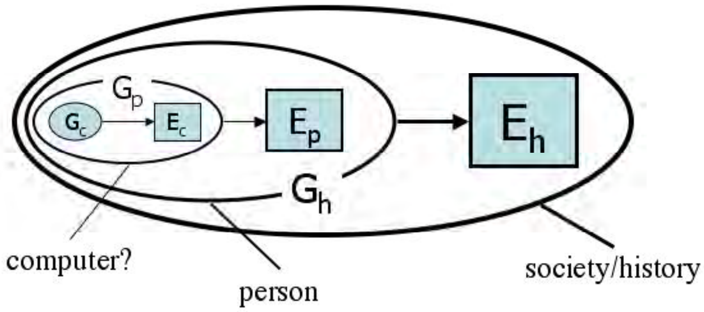


Figure 1. Context defines the expectations (E) against which the creativity of a generative process (G) is evaluated.

Because creativity is anyway contextual, there cannot be any objective definition based alone on the results or products of a creative process. We need to model the recognition of creativity as well. A major point in this article is, that the recognition process actually is more important than the generative part. If a person invents something by accident (i.e. starts using a novel solution), but doesn't understand that it was a great invention, would he be called creative? Probably not. On the other hand, if an artist accidentally finds, for example, a beautiful piece of wood, and puts it in frames in an exhibition, is she then called creative? Yes, much more probably at least than the dumb inventor.

Researchers in artificial life (Langton 1989) have tried to extract the smallest set of common features to all living things (metabolism, homeostasis, reproduction, etc.), and to make a theoretical definition, based on which any artificial construction can be evaluated if it is alive (or more accurately "a-live"). Our approach is analogous to that, trying to find the minimal definition that applies to all creativity.

The aim of this article is to see what would be a minimal set of requirements for creative behavior, i.e. the smallest possible "c" that still could be called creativity. Based on that it may be possible to start working with theoretical and computational models of creativity, that are free from human subjectivity.

1.1 ESSENTIAL ELEMENTS OF CREATIVITY

Creativity is often defined as a process producing something new and useful. As such this is not enough, because then even a slightest modification of an existing product would make it creative, which is not how we usually understand the word. Instead of just novel, a creative product should be unexpected, or surprising (Boden 1995).

Breaking the rules

But what makes it surprising? In order to know if something is creative, we ought to know the prevailing expectations, or the current habits of designing, against which a new approach can be compared. We need to model not only the agent that generates (more or less creative) products, but also the recognizing agent assessing when the product appears to be creative.

Often creativity is characterized as breaking the rules. However, there are different kinds of rules and different ways of breaking them. Simple ignorance of rules alone leads to anarchy. It may be useful for demonstrating social power (as Alexander the Great did when opening the Gordian knot with a sword), but otherwise it may be just absurd (for example, when breaking valuable objects while packing them in a small space by brute force). Instead of just breaking the existing rules, creativity brings up new rules that appear to be useful.

Creativity does not break such rules that keep the problem setting consistent. However, it breaks the illusory rules that are not actually given in the onset, but are only mentally built by the subject based on what has been useful in past situations (Takala 1999). Recognizing that these expectations are unnecessary leads to the “a-ha” moment of enlightment.

Relative novelty

If the context society does not know the proposed solution at the moment it is presented, it will be considered novel. This may mean that the invention is novel in the historical sense, but may also be caused by the society not having heard about it, or having known it but forgotten.

This brings us to the concept of situated (S) creativity (Gero 2002). Novelty is determined by comparing against the prevailing knowledge, actually against the expected rules only. This is emphasized by examples where a solution is immediately found to be self-evident but still creative: “Why didn’t I come to think about that?”

Gero (2002) also classifies designs as *routine*, if the same set of rules can be used throughout. By definition, if creativity is breaking the rules, this cannot be creative. Non-routine design is further divided into *innovative* and *creative*, the former only extending the ranges of variables in the rules, whereas the latter introduces new variables and thus makes more substantial changes in the design space. Although this classification was presented in the context of productive design act, it can be interpreted within recognition as well. When looking at a design, one may think of it in routine ways, or introduce innovative/creative viewpoints. They do not change the design itself but the way one thinks about it. With this interpretation, the classification conforms with the observations made above.

Illumination and other emotional reactions

Yet another important point in creativity is *reflection*: in order to be creative, a system must be able to observe its own behavior, and recognize the creative moment when rules are broken and a novelty appears. This feeling of illumination may be strong and it has a positive feedback, resulting in pleasure and *satisfaction*.

Satisfaction with past experiences may be the reason, why people tend to use familiar concepts rather than try out new ones, a behavior called *fixation* in this paper. Design fixation is a particular example of this, denoting a designer's premature commitment to a familiar solution, which then prevents considering other alternatives (Purcell and Gero 1996). The term is used here in a similar, though more general sense. Fixation is a necessary component in creativity, as it delimits the ways one will think, causing some ways to be more probable. These expected ways of thought are the rules to be broken in a creative act.

When a person is faced with a problem that does not get solved with the expected rules, a *conflict* appears. This is also important for creativity, as it triggers the need to think differently (Killander and Sushkov 1995). What typically happens in a creative process then is that the person, after trying to solve the problem persistently but in vain, runs into *frustration* and temporarily gives up. That starts the incubation period, during which the subconscious mind continues an opportunistic search with *relaxation* of constraints, and possibly comes out with an alternative, creative solution.

A creative mind does not freeze after a solution is found, but continues to face new situations, some of which may call for creative behavior. The satisfaction after a success may again be the underlying reason for *curiosity*, a behavior seeking for interesting problems to be solved, i.e. those potentially leading to novelties (Saunders 2001). Thus the creative personality continuously runs the cycle from fixation to conflict to illumination and to new fixation again.

The following list summarizes the set of features typical in creative behavior as described above. Tentatively these are proposed to be necessary requirements forming a definition of creative processes.

- rules/constraints for generating designs or interpreting them

- expectations, i.e. fixation to a set of rules
- problem triggering a conflict
- frustration, relaxation and opportunistic search
- reflection: recognition of novel rules
- positive emotional feedback (creative moment)
- curiosity

The practical research question now is: Can we computationally simulate the process and its essential features? If so, we have formulated them clearly enough to be represented in an artificial world. Experiments there may then confirm if the definition was right, i.e. if the chosen principles result in enough creative-like behaviors.

2. The case study

As a simulated world cannot contain many different aspects of real life, we need an illustrative case where the essential features of creativity can be demonstrated in an extremely simplified form. The core issues to be considered here are:

- a well-defined problem with a small number of parameters, in order to be simulated easily
- enough problem variability to span a domain of interesting, non-trivial problems

Geometrical packing problems appear to be a fruitful domain for our case study. They are important in practice, as even a small improvement in efficiency may mean huge savings in logistics industry. They are also non-trivial, as can be seen from the vast number of cases without a proof of optimality. They are easy to represent computationally, but often appear to be NP-complete, i.e. there is no better algorithm for finding a guaranteed optimum solution than an exhaustive search, or even worse: because the variables are continuous, a discrete exhaustive search is impossible. Of course, however, there are many heuristic strategies that work better in the average and that can find good approximate solutions.

Generally the task in a packing problem is to design a configuration of geometric objects, such that they fit inside a given constrained space. Often they are expressed as optimization tasks, to minimize the container size for a given number of objects to be packed, for example. There are various different classes of problems, depending on the shapes of objects and the given constraints, (see e.g. Friedman 2005).

2.1 PROBLEM DEFINITION

In this study the particular problem was to pack a given number of bottles in a case. Assuming the bottles are upright in a box, the problem becomes two-dimensional packing of circles inside a rectangle. Placing one bottle into the case reduces to finding a point for the circle center that is at least the amount of its radius away from the box boundaries and from the other circles.

Depending on the number of bottles and size of the box, there may be an infinite number of solutions, a singular unique configuration, or the problem may be impossible to solve.

Figure 2(a) shows a typical commercial case, the six-pack, which appears to be the smallest configuration of six bottles. However, in large cases the rectangular placement is not optimal, as the best packing approaches the hexagonal (honeycomb) grid of Figure 2(b) when the number of bottles increases. As will be seen below, neither of these well-organized patterns is always the best. Either one, or even a more irregular configuration may be optimal in a specific case.

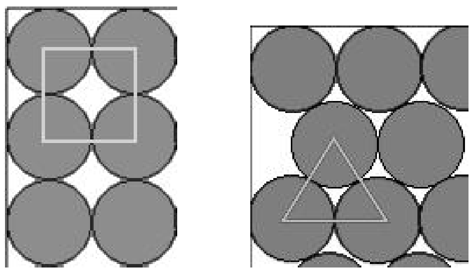


Figure 2. The (a) rectangular grid (six-pack) and the (b) hexagonal grid.

For this study, the bottle size and number of bottles for each case was fixed. On the other hand, size of the case was variable in order to generate a number of different problems. The overall problem setting thus was to make different six-packs, i.e. try to fit six bottles of same size into a rectangular case of given dimensions.

At first sight the problem may seem trivial. However, it is not easy to prove that a particular configuration is optimal, neither is it easy to find a rule for creating a satisficing design for a tight box. And if generalized to larger numbers of bottles, the problem becomes more complex with sometimes very irregular or even surprising optimal solutions.

2.2 THE METHOD

Our system is a simulated software agent that takes one bottle at a time and places it into the case of given size. If all six bottles fit in, the problem is successfully solved.

Potentially there is a huge number of possible approaches to the problem. To make it tractable, only three predefined strategies for placing a single bottle were used. Two of these are based on the rectangular and hexagonal grids of Figure 3. The third strategy is simply a random placement.

Technically, the available places in a case are checked by drawing circles and box boundaries extruded by the circle radius, as in Figure 4. This shows the occupied area where a new bottle center cannot be placed. Out of the remaining points inside the box, a position is selected using one of the three alternative strategies:

- seek a horizontally or vertically closest position to a previously placed circle. This always results in a rectangular grid, although not necessarily with an even length of rows.
- take the highest available point (and the leftmost if there are several equally high). This usually results in a hexagonal grid which is known to be optimal for infinite spaces, but also in specific cases generates many different variations.
- place the circle at a random free position. This does not usually make regular or dense arrays but, if we are lucky, it may in some cases result in better designs than either of the rules above..

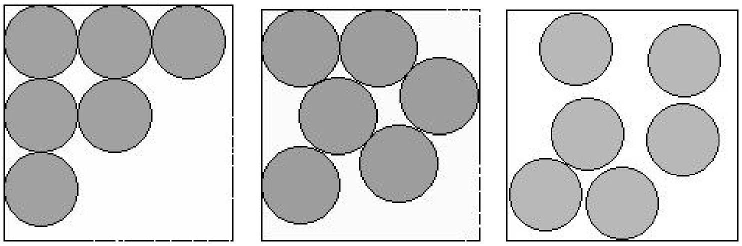


Figure 3: Sample configurations with each strategy:
(a) rectangular, (b) hexagonal and (c) random

If a placement strategy does not immediately succeed, a retrial is allowed for at most a given number of times (this particularly applies to random placement, where the trials are substantially different – the other algorithmic strategies result in the same configuration again).

In the retrials, another strategy may also be randomly chosen, based on probabilities assigned to each strategy. The probabilities are controlled by reinforcement learning, i.e. in case a strategy succeeds, its probability increases, whereas with a failure it decreases (the other probabilities are tuned accordingly to keep there sum as one). Every time a new problem is faced, the strategy with highest probability is tried first. This adaptive learning makes a positive feedback, causing the system to show persistence and to fixate in a recently successful strategy, even if others might do as well. If the dominant strategy does not work out, its probability decreases with retrials until another one becomes highest. Then the fixation ends and another strategy is tried out.

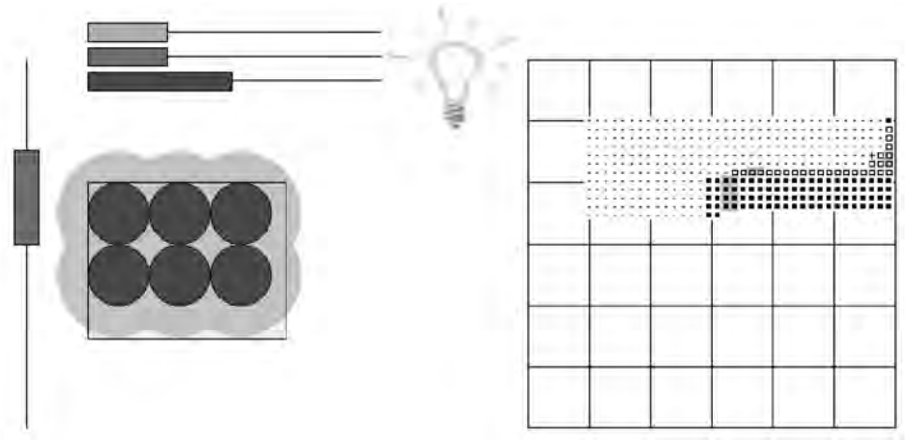


Figure 4. Snapshot of the program at the moment of enlightment, displaying the current problem (box with circles), probabilities for each strategy (bars above the box), the solution space (to the right), and a satisfaction indicator (to the left). The lighting bulb indicates that the system has just found a new applicable strategy.

Positive feedback from a successful solution is also separately cumulated as a “feeling of satisfaction”, which raises quickly, just like the probability of the successful strategy does. With a failing trial the satisfaction decreases, though slower than it raises. From changes in this emotional indicator one may recognize features belonging to a creative process: trials with a bad strategy fail and lead to dissatisfaction. But when a better strategy (accidentally) is found and used a few times, then satisfaction increases quickly. This sudden rise of satisfaction, corresponds to the “a-ha” experience. The system knows that it has found a new solution method, which consistently applies to those problems it has been trying to solve. In the figures 4-7 these cases are indicated with grey color. Figure 4 shows how the concepts discussed above are visualized for tghe observer.

Note that anthropomorphic terms, such as “fixation”, “frustration”, “creative moment” and “curiosity”, are purposely used throughout this article in order to point out the proposed analogies of the system’s behavior to creativity in real life. They are not to be taken literally, but in a metaphorical sense.

3. Results from test cases

When given a problem, the agent tries to solve it by placing circles in the case. It may try several times with different strategies, but eventually it either reports a solution or gives up after a limited number of trials. In order to study its dynamic behavior, another agent was programmed that serves the first one continuously with new problems. In the test runs I used different strategies to scan the problem space. Interesting phenomena were encountered, that are reported below in more detail.

The results are visualized with a diagram displaying the two-dimensional problem domain with width and height of the rectangular case as its axes. Each point represents a particular problem defined by the corresponding box dimensions. The origin is at the top-left corner and the grid markers are at units of one circle diameter. Thus, for example, the box fitting a conventional six-pack would be at points (2,3) and (3,2), as shown by the circles in Figure 5. The marker symbol tells the strategy used to solve the problem at each point.

3.1 FIXATION OF STRATEGY

Generally the problem solving agent easily gets fixated to a particular strategy after a small number of successful trials. This is demonstrated in figure 5, where each horizontal row is a left-to-right scan of problems, i.e. the width of the box is increased in small increments while keeping the height constant. At the left end there is an impossible problem (too small box to fit six circles), shown with a (-) sign. During the scan the agent tries the three different strategies more or less randomly. When a problem becomes solved, the strategy successfully used is tried again for the next problem. As this is an easier one (a larger box), the agent succeeds again and then the same strategy is used throughout, resulting in a row with one repeating symbol only.

3.2 CREATIVE BEHAVIOR

A more interesting phenomenon happens when the agent surprises itself by reinventing a strategy it has forgotten (i.e. has not used for some time). This is demonstrated in Figure 6, which is the same as Figure 5, except that ordering of problems goes from right to left, i.e. from a trivial problem towards an impossible one. In the beginning of a row any strategy will do, and it becomes immediately fixated. Thus the right part of each line consists of similar symbols, which may randomly be any one of the three alternatives. Following the scan towards left, the same strategy may continue until the problem becomes intractable. However, in some places it appears that first the agent has given up (-) but then another symbol appears along the row, indicating that a new strategy has been chosen and used consistently until the problem becomes really impossible.

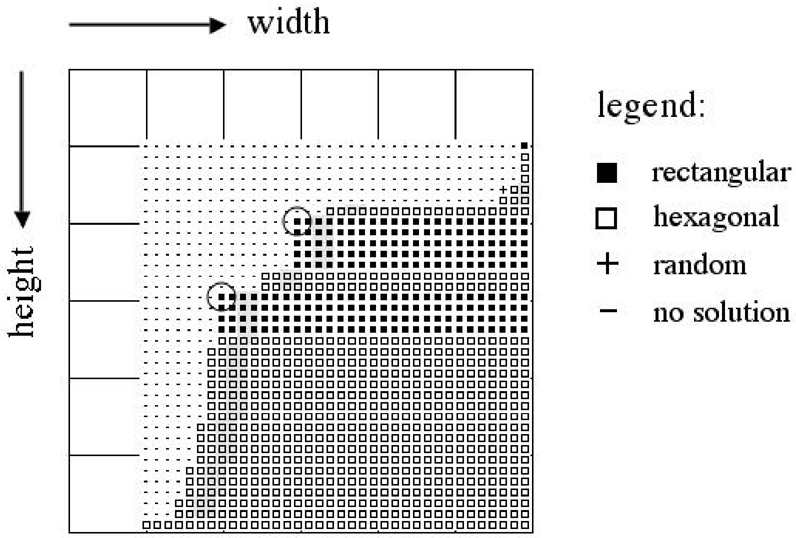


Figure 5. Fixation of strategy during a left-to-right scan of problems. Conventional six-box is marked with circles.

This is a simulated creative moment that can be distinguished as a disruptive behavior: after successfully solving a number of problems with the same strategy, the system runs into a situation where the usual strategy doesn't work. With repeated unsuccessful trials it becomes frustrated, possibly giving up. However, deeming the problem impossible may be only seemingly right, and actually it is solvable by another strategy. This strategy is found after relaxation, i.e. by giving up the usual strategy and (more or less randomly) trying something else. When a new strategy succeeds, it is tried again in another situation and, if reinforced, becomes the new fixation. This overall behavior can be seen to resemble creativity as it contains the essential features listed in section 1.1.

From this experiment it seems that the interesting creative behavior appears near the border of impossible problems. Thus a further question is: where are these cases exactly and why?

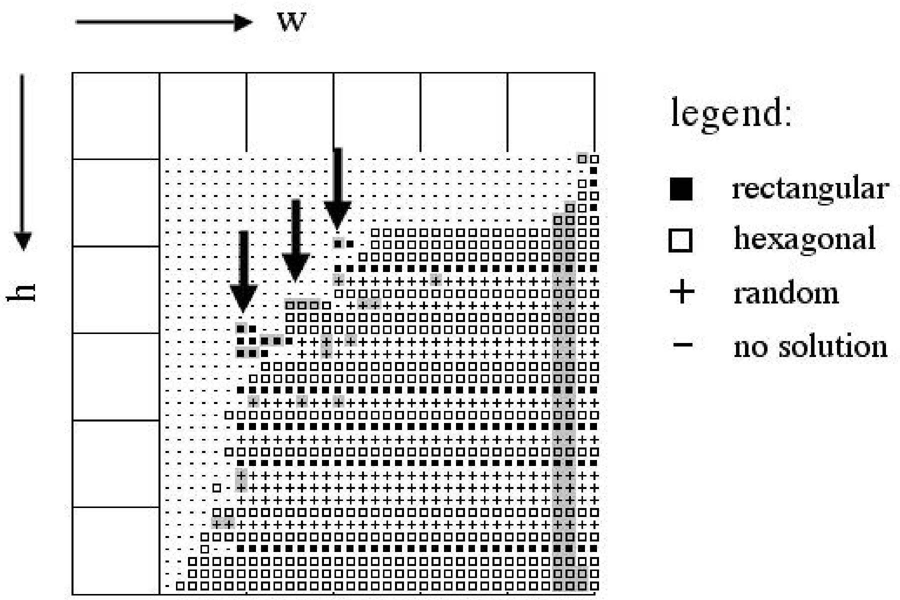


Figure 6. Creative moments appearing as grey spots in right-to-left scan of problems.

3.3 RANDOM WALK THROUGH THE DOMAIN OF INTERESTING PROBLEMS

An ordered scan of the problem domain gives an overall view of it. However, the results depend on the order of scans, as seen by comparing Figures 5 and 6. Also a complete scan runs through the boring areas of impossible (towards top-left corner) and trivial (towards right-bottom) problems.

In order to explore the most interesting part inbetween, I made a feedback loop of both agents, or combined them into a double-agent. The problem domain is scanned with a random walk method controlled by curiosity that seeks interesting problems. Each time a new problem is given, it is taken from a point nearby the previous one, and on the opposite side to the point before that, but with small random variation. This makes a continuous randomly turning path. In order to keep it in the area of interest, a bias was added, turning the path towards the top-left corner (i.e. more difficult problems) whenever a case has been solved, and to the opposite direction if the trial fails. Some results are shown in Figure 7. The path keeps in a rather narrow area, with the strategy symbol alternating here and there. Most consistently marked areas are the three "corners" near the center of the figure. In each of these only a single strategy seems to be applicable.

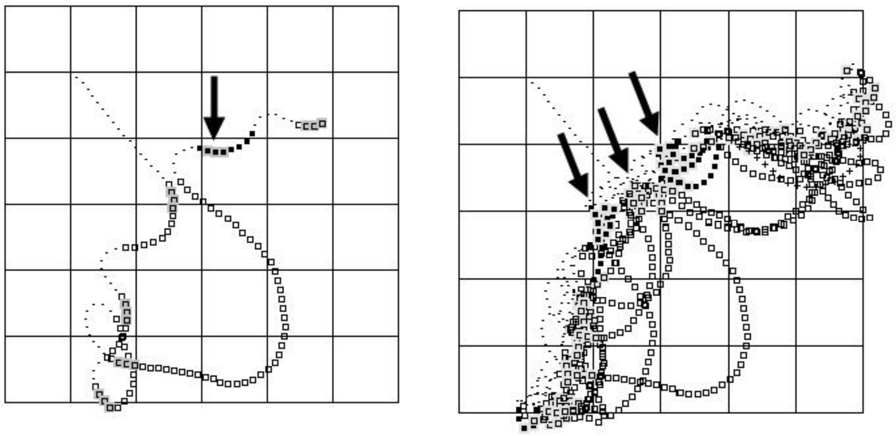


Figure 7. Controlled random walk in the area of interesting problems. Arrow in the left part indicates a point, where a new strategy was found. Arrows in the right part indicate areas where a single strategy seems to be applicable.

4. Discussion – analysis of the problem domain

To get a better understanding of the phenomenon, I explored the problem domain by regular scan with each single strategy in turn.

The subdomains where rectangular or hexagonal grids are applicable strategies are shown with dark grey in Figures 8(a) and 8(b), respectively. The trials not solved are depicted with light grey. Figure 8(c) shows the subdomain of rather trivial problems, as it was produced with the random strategy with at most five trials for each case.

Strictly impossible cases with width or height less than one diameter unit are not considered at all. Other impossible cases are difficult to find for sure, because we do not know all possible configurations, some of which might be better than those produced by simple strategies. Extensive statistical trials would give an impressions of this subdomain.

Most interesting are the non-trivial solvable cases, particularly those solvable by one strategy only. These are found by comparing the maps in figure 8. Most obviously the upper left corners of each subdomain are singular. Located in the points (2, 3) and (3, 2) for rectangular strategy are the conventional six-packs. At points (2.5, 2.73) and (1.86, 3.5) / (3.5 1.86) are the hexagonal dense packages, as depicted in Figure 9.

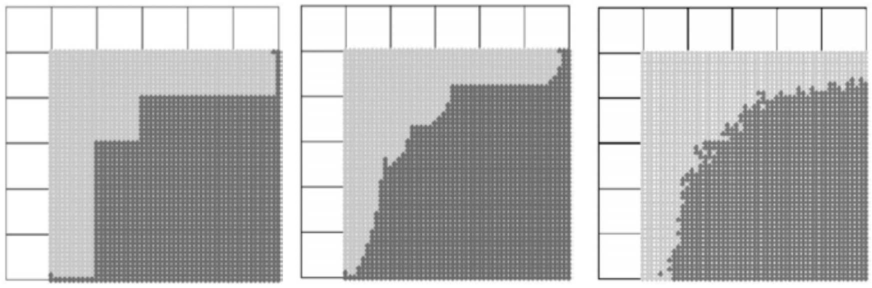


Figure 8. Subdomains for each strategy:
(a) rectangular, (b) hexagonal and (c) random

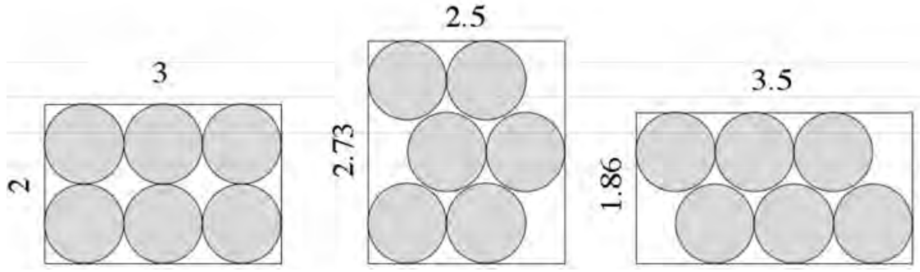


Figure 9. Optimally dense six-packs in rectangular and hexagonal form.

These are qualitatively different cases where another configuration would not work. A continuous deformation could be imagined leading from one to another, but none of our strategies would produce it. This incontinuity in solutions causes a disruptive leap in strategy if the succession of problems goes from one subdomain to another. The disruptive change can be understood as a creative moment.

4.1 IS THIS CREATIVITY?

One might ask how close to real creativity these experiments actually are. They demonstrate such features as producing novel and useful designs (though in a relatively small world), expectations based on experience rather than given constraints (fixation to a strategy), conflicting situations (the fixed strategy does not work), unexpected solutions with enlightment after relaxation of rules (based on random selection), and finally fixation of new rules (if application of the new strategy is successful).

What can be considered missing here are, for example, associative thinking for finding new solutions, sense of humor and aesthetics, recognition of patterns from random configurations, and inductive formation of rules from experiences. These are all found to be typical traits of creative people. Compared to human life, one has to keep in mind that the computer's capabilities are still extremely low. Taking that into account, I think that some new steps towards computational creativity have been taken despite of the missing parts.

One might also ask whether an extensive random search might work out better results than the strategies applied here. Even though this might be true, I think that it would be not as creative as a process. An individual solution alone lacks the pattern that can be applied more generally and that starts a new strategy. In a historical context someone might later recognize a pattern in it and then call the solution creative. In that case, creativity should be attributed to the later inventor.

5. Conclusions and future work

This work aims at demystifying the concept of creativity by demonstrating that it can appear even in very primitive situations in simulated environments, if we accept a minimalistic definition of creativity. Many characteristic features of creativity, as listed in the introduction, have been demonstrated in a simple setting.

Perhaps the most important point is that a model of creativity should include not only a generative element but also one with a partial selection of all potential rules, which forms the situational expectations, against which the generated constructs can be compared for novelty (as the "computer" part in Figure 1). Other observations spawning from this are that fixation, conflicts and frustration, which normally are considered harmful for thinking, are also necessary elements in creativity. Yet another element is reflection about the process itself, whether it has broken its own rules. And in order to keep creativity running as a continuous process, positive feedback (satisfaction) and curiosity are also needed. The features listed above are suggested to form the minimalistic definition of creativity.

Potential for creative solutions depends on the problem domain, particularly on the structure of the subdomains of solutions with different strategies. If a single strategy (a pattern or a rule) covers all possible solutions, there is no place for surprises, everything happens as expected. That would be a domain of routine designing.

Creative moments appear at changes of subdomain, thus their realization depends on the order the problems are presented. Fixation to a default strategy is necessary in order to develop expectations, which are necessary for a surprise.

In case of continuous wandering in the problem space, creativity appears at subdomain boundaries. A typical situation is when approaching from more trivial (several strategies apply) towards more difficult area in problem space. If done in reverse order, the first applicable strategy becomes a fixation that is applied all over, and no conflict appears.

An important part missing here, as compared to real world creativity, is autonomous formation of strategic rules. In the case study all the strategies were predefined, and novelty is only relative but appropriate when situated: reinventing the wheel is a creative act, if one has already forgotten the existence of the wheel. In the future we should add inductive learning mechanisms for recognizing new patterns in random experiments and for representing them as formal configuration rules.

In a closed world like the case example here, we may take for granted a fixed number of patterns, each of which may be "reinvented" as new after being forgotten. In a more realistic situation, the inventions are cumulated as history, and new patterns compared to that ought to be invented.

Assuming that we still are in a closed world and there is no mystical creative source, the new patterns can only be formed by combinatorial processes. A future task is to study different possible forms of them. Known approaches are, for example, analogues, associative pattern matching, abductive logic, etc. Collectively these might be characterized as "layered search heuristics" (Buchanan 2001).

In this article I have challenged those previously widely accepted definitions of creativity that look at the generative process and its rule formation alone, without considering the rules as expectations to be broken. In doing so, I have tried to look from a different viewpoint the question, what creativity is. I have presented a set of features that are suggested to be essential to creativity. It remains open to discussion, which of these features are considered necessary, and if the set is sufficient to define creativity. To me, the process has contained several moments of personal creativity, bringing delight. If this approach will be wider accepted in the historical sense, I will be even happier.

In conclusion, the paper points out that creativity may be defined as a process adapting to new situations in a disruptive way, such that prevailing expected rules are suddenly changed. The detailed problems being solved, and the particular strategies to solve them, are not so important. As Buchanan (2001) puts it: *key to creativity is at the metalevel*.

Acknowledgements

I'd like to thank the reviewers for constructive comments that helped to make the point in this article clearer.

References

Boden, M: 1995, Creativity and unpredictability, *Stanford [Electronic] Humanities Review*, *Constructions of the Mind* **4**(2) www.stanford.edu/group/SHR/4-2/text/boden.html

Buchanan, B: 2001, Creativity at the metalevel – AAAI-2000 Presidential Address. *AI Magazine* **22**(3): 13-28.

Friedman E: 2005 (cited), Erich's Packing Center, www.stetson.edu/~efriedma/packing.html

Gero, JS: 2002, Computational models of creative designing based on situated cognition, *in* T Hewett and T Kavanagh (eds), *Creativity and Cognition* 2002, ACM Press, pp. 3-10.

Killander AJ and Sushkov VV: 1995, Conflict oriented model of creative design, in JS Gero, ML Maher and F Sudweeks (eds), *Preprints Computational Models of Creative Design* (3rd Heron Island conference), pp.369-396.

Langton, C: 1989, Artificial life, *in* CG Langton (ed.), *Artificial Life*, SFI Studies in the Sciences of Complexity VI, Addison-Wesley, pp. 1-47.

Purcell, TA. and Gero, JS: 1996, Design and other types of fixation, *Design Studies* **17**(4): 363-383.

Saunders, R: 2001, *Curious Design Agents and Artificial Creativity*, Ph.D. Thesis, Faculty of Architecture, The University of Sydney.

Takala, T: 1999, Simplistic jokes and drawings as a guide towards computational creativity, *in* JS Gero and ML Maher (eds), *Computational Models of Creative Design IV*. University of Sydney, pp. 33-46.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 111-135

CAN DESIGNS THEMSELVES BE CREATIVE?

MARY LOU MAHER, KATHRYN MERRICK
University of Sydney, Australia and
National ICT, Australia

and

OWEN MACINDOE
University of Sydney, Australia

Abstract. Studies of design and creativity usually investigate the processes that result in a design product that is distinguished as being a creative product. The focus of these studies comprises the definition and recognition of creativity and the development of cognitive and computational models of creative design. We consider these studies in light of the development of a design that is itself creative. If some of the characteristics associated with creative design or a creative product can be used to describe the behaviour of a product, then we assert that the design is itself creative. We embed a computational model of curiosity within the design of specific product in order to ascribe the characteristics of creativity to the product. We illustrate this concept with the design of a curious place.

1. Introduction

We introduce the concept of a product that has an embedded computational process capable of being creative. Our implementation of these ideas is grounded in the concept of an intelligent room. In our intelligent room, the room learns new behaviours by looking for novel events and creating goals to learn more about how to predict and achieve those events with the purpose of aiding the human activities within the room. We propose that the resulting room is creative, in the sense that it is able to detect novelty and to adapt its behaviour in response to a novel event.

When we consider computational or cognitive models of creative design, we study or develop processes and mechanisms that lead to creative designs. This assumes a common understanding of the difference between creative design and routine design as well as a distinction between a creative process and a creative product.

It is important in a discussion on computational models of creative design to distinguish creative design from other kinds of design. This is necessary or all models of design are models of creative design. The qualifier “creative” makes reference to something novel or unexpected. The idea of novelty is relative. A specific product may be familiar to one person, and therefore not considered creative, while to another person the same product may be novel and considered creative. Boden (1994) talks about two types of creativity: one is psychological (P-creativity), "that is the creative idea is apparent to the person in whose mind it arises", and the other is historical (H-creativity), "that is the creative idea is P-creative and no one else, in all human history, has had it before". She states more strongly that "many creative ideas [are interesting] as they concern novel ideas that not only *did not* happen before, ... but that *could not* have happened before".

Dasgupta (1994) expands this notion in terms of psychological novel (PN-creative), psychological original (PO-creative), historical novel (HN-creative) and historical original (HO-creative). His Computational Theory of Scientific Creativity (CTSC) attempts to encompass agents A and cognitive processes P for which PO-creativity and HO-creativity is possible respectively for the domain and the community. This *explains* rather than predicts P conducted by A in terms of a knowledge level process P(KL) to transform a scientific goal into a solution. This distinction between novel and original, or personal and historical, is important when developing a model for a creative design. In our model, we focus on personal creativity and novelty, where the design is embedded with an agency that acts and learns to respond to novel events with no consideration for a social construct of novelty or evaluation.

Gero and Maher (1993) distinguish between routine, innovative, and novel design using the concept of design variables to make the distinction. In a routine design, the variables and the values associated with the design are known in advance. In innovative design, the variables are known but some of the values for the variables fall outside the known range. In novel design, the designer introduces new variables, defining a new kind of design that was not part of the original search space. In our model, we have a reasoning process in which the agent generates it own goals and behaviours, and therefore appeals to Gero and Maher’s definition of novel design.

Finally, the distinction between a creative process and a creative product indicates what is being evaluated. A creative process is one in which the process that generates the design is novel, and a creative product is when we evaluate the result of the design process as being novel. In our model, we consider a process as part of a product. The product has agency, and that agency produces creative behaviours. Therefore, the product is creative because it has creative behaviours.

There are numerous other characteristics associated with creative design beyond novelty. These include aesthetic appeal, quality, unexpectedness, uncommonness, peer-recognition, influence, intelligence, learning, and popularity (Runco and Pritzker 1999). This more broadly defines creative design as being more than just novel, and including judgements related to its appeal and usefulness. In our model we focus on novelty, and although we don't preclude the other characteristics in an evaluation of our product, we do not incorporate them in the computational model.

In this paper, we consider a computational model of curiosity as a basis for developing a product whose behaviour is creative. Our approach starts with the basic concept of an agent model, extended to include motivation driven by curiosity to learn new behaviours. In this paper we include a review of motivation theories as a basis to inform a computational model of motivation and provoke discussion related to models of creativity. We associate a motivated agent with a design product, giving the product behaviours that include curiosity. We propose that the integration of curiosity with agent models as a reasoning component of a design results in a design that responds and adapts to its use.

2. Adaptable Designs by Incorporating Agents into the Design Product

We have been designing, implementing, and inhabiting virtual worlds for education and collaborative design activities using various agent models to give aspects of the world agency (Smith et al 2004; Gu and Maher 2004; Clark and Maher 2005; Rosenman et al 2005). These 3D networked virtual environments provide a sense of place in which each object in the place comprises a 3D model with location in the 3D world and a computational model that describes the behaviour of the object. Such environments provide a good platform for studying computational models of design because they are a closed world in terms of the objects in the world being knowable by querying the virtual world server, and are open worlds because people can inhabit and interact with the world in unpredictable ways similar to the physical world. By associating objects in the 3D virtual world with an agent model, we can study computational models of design in which the design itself is able to design and adapt to its use.

There is no universal definition for the term agent. However in the context of computer science, agents as intentional systems operate independently and rationally, seeking to achieve goals by interacting with their environment (Wooldridge and Jennings 1995). An agent has the ability to operate usefully by itself, however the increasing interconnection and networking of computers is making this situation rare. Typically, the agent interacts with other agents (Huhns and Stephens 1999). Hence the concept of multi-agent system is introduced with the applications of distributed artificial intelligence.

In object-oriented systems, objects are defined as computational entities that encapsulate some states, are able to perform actions, or methods on this state, and communicate by message passing. There are similarities between agents and objects, but there are also significant differences (Wooldridge 1999). Agents embody a stronger notion of autonomy than objects, and in particular, they decide for themselves whether or not to perform an action on request from another agent. In addition, agents are capable of flexible (reflexive, reactive, reflective/proactive and social) behaviours, and the standard object model has nothing to say about such types of behaviours.

In Figure 1 we show what these virtual worlds look like, and what we mean by an agent model. The left side image shows the 3D virtual world as a place that is inhabited by people represented as avatars. The 3D world is made up of individual objects, each associated with a 3D model and a computational model. The right side of the figure shows an agent model. Each agent has sensors that are able to sense information about its environment, in this case the 3D world, and effectors that are able to change their environment. This combination of virtual worlds and agent models allows us to develop and study designs in which the components of the design have agency. Once we can associate agents with the objects in the design, we can consider whether a design can be creative itself.

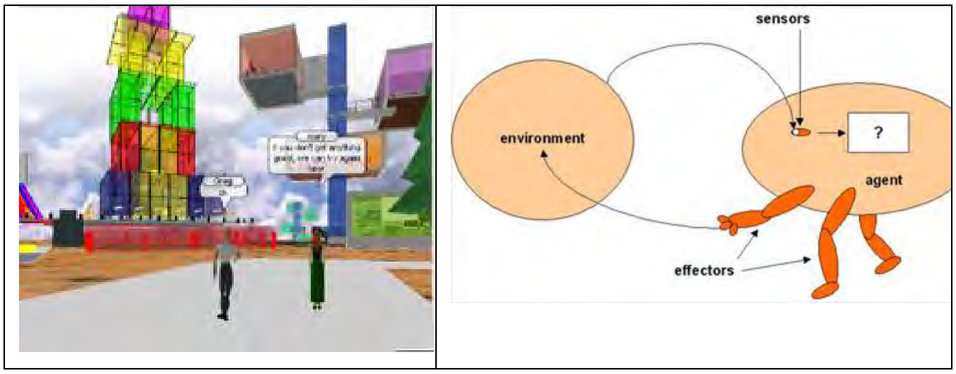


Figure 1. Virtual worlds and agents.

Maher and Gero (2002) developed a multi-agent system as the core of a 3D multi-user virtual world. Each object in the world is an agent in a multi-agent system. The agent model provides a common vocabulary for describing, representing, and implementing agent knowledge and communication. The agent can sense its own environment and can generate or modify the spatial infrastructure needed for a specific activity for the users of the world. The common agent model is illustrated in Figure 2, where each agent has five kinds of reasoning: sensation, perception, conception, hypothesizer, and action.

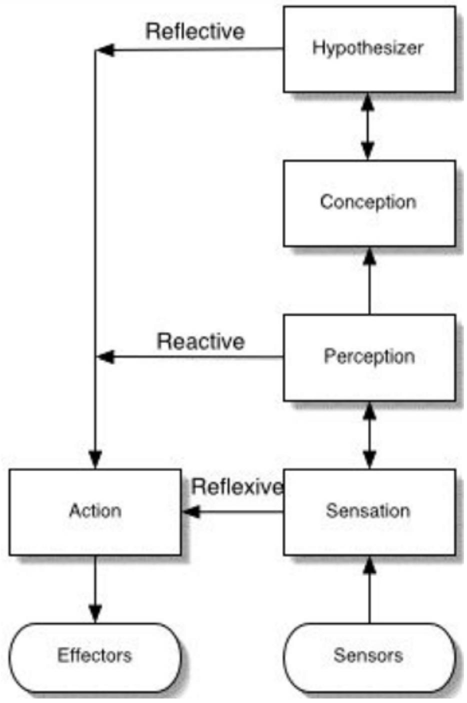


Figure 2. Agent model showing levels of reasoning (Maher and Gero 2002).

Sensors receive information about the state of the world at any time t. This includes the objects and their properties including location, the avatars and their properties, and itself as an object in the world. **Sensation** transforms raw input from the Sensors into structures more appropriate for reasoning and learning. **Perception** transforms sense-data into the percepts, or perceptual objects, that are used both to interpret interactions and as the units with which concepts are constructed. Percepts are grounded patterns of invariance over interactive experiences, and are constructed by clustering like patterns into equivalence classes so as to partition the sensory representation space. Perception is driven both by concepts and by the sense-data. **Conception** learns and uses concepts about the world to reinforce or modify the agent's beliefs and goals. Concepts are abstractions of experience that confer a predictive ability for new situations. The concept of a meeting, for example, is a representation of the activities of the agent with which meetings are involved, and its various realizations are predictions of possible interaction. **Hypothesizer** identifies mismatches between the current and desired states of the world, and reasons about which goal should be achieved in order to reduce or eliminate that mismatch. It identifies possible actions which when executed will change the world to meet those goals. **Action** reasons about which sequence of operations on the world, when executed, can achieve a specific goal. **Effectors** are the means by which actions are achieved by making changes to the 3D virtual world.

This model was extended by Gu and Maher (2004) to develop a Generative Design Agent (GDA). The GDA responds to its environment by designing places for the avatars needs. In addition to the computational processes in the Maher and Gero model, the GDA includes a design process that is essentially a design grammar. While this grammar is able to add new objects to the world and remove them as determined by a set of intended functions for the virtual world, the process does not specifically address novelty or computational models of creativity.

The agent approach to virtual worlds provides for new kinds of interaction among the elements of the virtual world and between people and the virtual world that makes both the virtual environment and interactions with it dynamic.

3. Motivated Agents

The reasoning process used in the design of adaptable virtual worlds is based on a cognitive agent model. The model describes the levels of reasoning and provides a framework for the knowledge the agent needs in order to respond to changes in the virtual world. However, the agent model assumes that the agent has all of the knowledge needed to respond to the world when the agent is designed and implemented. An alternative is to define an agent model that includes the ability to change its knowledge over time in response to its observation and interaction in the world. Various theories of motivation and motivated learning agents inform a more general computational model of motivated agents.

3.1. MOTIVATION THEORIES

Motivation is the cause of action (Mook 1987). When we ask the question: “Why did he or she do that?” we are inquiring about an individual’s motivation. Motivation is though to have three primary functions: a directing function that steers an individual’s behaviour towards or away from specific goals, an activating function that energises action in pursuit of goals and an organising function that influences the combination of behavioural components into coherent, goal-oriented behavioural sequences (Green et al 1984; Kandel et al 1995).

Psychological study of motivation searches for theories that describe the functions of motivation in natural systems such as humans and animals. Motivation theorists do not agree on a unified causal explanation of the behaviour of natural systems. Rather, causation has been attributed to such factors as the environment, physiology, the psyche or social forces with early researchers tending to focus on one or the other of these views. Various attempts have been made to either classify (Green et al 1984; Mook 1987) or synthesise (Alderfer 1972; Maslow 1954) the large body of research related to psychological motivation.

While some computational models of motivation have been closely informed by psychological research, others introduce new ideas specifically tailored to artificial systems. In an effort to classify motivation theories in a manner that is relevant for both natural and artificial systems and which does not encroach on the terms used by psychological motivation theorists, we have used three broad categories: biological motivation theories, motivation theories of the mind and social motivation theories.

3.2. MOTIVATION THEORIES FOR NATURAL SYSTEMS

3.2.1. Biological Motivation Theories

Biological motivation theories attempt to explain the motivation processes that work within the biological system of a behaving organism. The **drive theory** of motivation holds that homeostatic requirements drive an individual to restore some optimal biological condition when stimulus input is not congruous with that condition. For example, high body temperature might drive an individual to sweat in order to restore its optimal body temperature. Drive theory was developed in its most elaborate and systematic way by Hull (1943; 1952) as a central part of his theory of behaviour. Hull's theory postulates that behaviour is a response both to a motivational factor called drive and to habits that are reinforced during an individual's lifetime. The more often a response is reinforced, the more habitual it becomes in a particular situation and the more likely it is to be repeated when the conditions are the same as those in which it was reinforced. When a response has become a habit through frequent reinforcement it comes to be performed more intensely under conditions of high drive. Hull modelled the relationship between habit, drive and a behavioural response as multiplicative based on the assumption that both habit and drive are necessary for behaviour.

In recent years there has been a tendency to drop the concept of drive, in particular because it is no longer believed that drives can be considered as unitary variables (McFarland 1995). The notion of high or low hunger, for example, is a misnomer. Hunger is more accurately described in terms of a number of variables such as fat, protein and carbohydrates. As an alternative to drive theory, McFarland proposed the idea of a **motivational state**. An individual's motivational state can be represented by a point in a motivational space. The axes of the space are important motivational stimuli such as fat or protein levels or the strength of some external stimulus. The major difference between the state-space approach to motivation and the drive concept is that the state-space approach makes no assumption that different motivational factors are multiplicative or about the relationship between motivation and behaviour.

In both drive and motivational state theories, a total absence of homeostatic drives such as hunger or thirst should produce an individual that does, and seeks to do, nothing. However, studies of sensory deprivation and isolation in the early 1950s showed that low levels of stimulation, which should produce little drive and hence be attractive according to drive theory, are in fact unattractive and produce a tendency to seek out stimulus complexity. **Arousal theory** offers an alternative to drive theory's explanation of the intensive aspects of behaviour by stating that we seek from our environment, not a universally minimal amount of stimulation, but rather a moderate or optimal level of stimulation so there is an inverted U-shaped relationship between the intensity of a stimulus and its pleasantness (Wundt 1910). A general model for the conditions that produce arousal assumes that arousal is a response to a change in the level of stimulation to which a person is exposed between an existing condition of stimulation and a new and different condition (Green et al 1984). Implicit in the idea of an existing state is the assumption that individuals tend to establish a baseline level of stimulation through constant adjustments and adaptations to their environment. Over time a loss of sensitivity accrues with prolonged exposure to a particular stimulus.

3.2.2 Motivation Theories of the Mind

The view of hunger and thirst as homeostatic drives or optimal arousal theory imply that feeding, drinking or exploration are initiated as a result of monitored changes in physiological state. However, in addition to occurring in response to physiological changes, behaviours such as feeding and drinking often occur in anticipation of such changes (McFarland 1995). In recognition of this, cognitive motivation theories focus on questions such as what determines the consequences of behaviour, how do consequences influence behaviour and to what extent do individuals account for the probable consequences of future behaviour in terms of the costs and benefits of different courses of actions.

The **operant theory** of motivation recognises that individuals are not only driven by deprivations and needs but may be guided to important goals by perceptions and cognitions. When an individual does something that is rewarded, for example, they are not influenced by any real or imagined loss of drive but by the idea of being rewarded. A voluntary response emitted by an individual in order to achieve some reward is called an operant. Skinner's law of conditioning for operants (1938) states that if the occurrence of an operant is followed by the presentation of a reinforcing stimulus, the strength of the operant will be increased. The converse law, the law of extinction, states that if the occurrence of an operant already strengthened through conditioning is not followed by the reinforcing stimulus, the strength is decreased. A reinforcing stimulus, or reward, is not assigned any specific properties other than that it follows an operant. For example, it may be a pleasant, internal feeling of satisfaction, the receipt of money from an external source, an unpleasant, internal feeling of boredom or an electric shock from an external source.

Successful acquisition of reward triggers the formation of mental associations between acts and the rewards that follow them. This association generates an expectancy that if the act is repeated it will be rewarded again. The expectancy of being rewarded after some responses forms the basis of incentive. The **expectancy-value theory** of incentive defines incentive as a multiple of the expectancy of receiving a reward and the value of that reward to the individual.

The notion of the value of a reward to an individual was approached by Atkinson et al (1966; 1974) in their theory of **achievement oriented motivation**. Atkinson defines the value of a reward to an individual in terms of the tendency of that individual to either approach success or avoid failure. If an individual is motivated by a tendency to approach success, Atkinson proposes that they will evaluate the potential reward of a situation in terms of their probability of success so that success on a difficult task is more valuable than success on a simple one.

Some individuals, rather than being motivated to approach success, are motivated simply to avoid failure. If an individual is motivated by a tendency to avoid failure they will evaluate the potential reward of a situation differently to an individual motivated by a tendency to approach success. In an individual motivated to avoid failure, the higher the probability of achieving a task, the greater the negative incentive associated with failure at that task. Thus, individuals motivated to avoid failure tend to choose either easy tasks at which they are likely to succeed or difficult tasks for which there is a clear reason for failure.

While expectancies and values together determine an individual's orientation toward future behaviour, theories such as the expectancy-value theory of incentive do not explain how expectancies and values are formed. Rather an individual's cognitive representation of the environment and their role in it is simply assumed to exist. **Attribution theory** seeks to provide this explanation. A causal attribution is an inference about why some event has taken place. An attribution may be about one's own behaviour or about another's behaviour. Heider (1958) introduced the idea that people follow specifiable rules in interpreting the causes of behaviour. Attribution theory attempts to specify the processes that are involved when an individual develops an explanation the behaviour of others or themselves. Heider used attribution theory to develop his **naïve analysis of action theory** which describes the cause of behaviour in terms of the average person's commonsense analysis of behaviour. Central to Heider's theory was the idea that, along with professional psychologists, naïve perceivers share the belief that there are two classes of causes: personal forces and environmental forces. Heider further subdivided each of these forces into two categories: ability and trying, task difficulty and luck respectively. He proposed that the relationship between ability and task difficulty is additive. That is, environmental forces could oppose or support the personal force and thus increase or reduce its effectiveness. Further he proposed that the personal force, trying, is made up of two components, intention and exertion, and that successful action depends on the presence of both.

Attribution theory can produce an explanation for some behaviours in terms of personal forces such as physiological drives "because they are hungry" and environmental forces such as extrinsic rewards "to earn money". However there are other behaviours that are inexplicable to the average observer. For example, some people make a pastime of skydiving "for fun" or climb mountains "because they are there". These behaviours involve exploration, seeking novelty, curiosity or meeting a challenge. To this extent they are all intrinsically motivating. White (1959) first argued for the existence of what he called **effectance motivation** or competence motivation. He proposed that individuals are motivated to engage in behaviours that can satisfy the desire to feel self-determining and competent. Effectance motivation is the desire to deal effectively with ones environment. White believes that effectence motivation is always present but is only manifested when other more basic needs are satisfied. Specifically, behaviours such as exploratory play, curiosity and stimulation seeking would be expected to appear only when an individual is otherwise homeostatically balanced. White also proposed that effectance motivation is undifferentiated, meaning that the satisfaction of the effectance motive is not tied specifically to any given behaviour. Rather any behaviour that allows an individual to deal effectively with its surroundings can satisfy the motive. In their theory of **intrinsic motivation**, Deci and Ryan (1985) extended the theory of competence motivation to define the types of behaviours that will permit an individual to gain a sense of competence and self-determination. They proposed that individuals are involved in an ongoing, cyclical process of seeking out or creating optimally challenging situations and then attempting to conquer those challenges. A feeling of competence emerges from situations in which an individual is optimally challenged. Optimal challenging situations are based on an individual's unique complement of skills. The situations that are most intrinsically motivating are those that contain information relevant to structures already stored and mastered but that are discrepant enough to call forth adaptive modifications. Overly familiar or excessively repetitive tasks and tasks that greatly exceed existing capacities will trigger boredom and distress respectively (Hunt 1975). In other words, individuals will orient themselves towards an activity in some domain of behaviour where they are required to learn or stretch their abilities by a small amount, that is, tasks that are neither too difficult nor too easy.

3.2.3. Social Motivation Theories

Where biological motivation theories and motivation theories of the mind are concerned with the individual, social motivation theories are concerned with what causes individuals to act when they are in contact with one another. One of the earliest theories that offers an explanation for motivation in social situations is Charles Darwin's **theory of evolution** (Darwin 1859). Darwin's idea was that animals have the structural and behavioural characteristics required to survive and breed within their habitats. His theory has three key components. Firstly, animals vary from one another within a species. Secondly, animals pass on their characteristics to their offspring. Thirdly, variation within a species means that some members of the species are better adapted than other to the ecology in which they live. Those better adapted are more likely to have offspring and pass on their structural and behavioural characteristics. Those that are poorly adapted will have fewer offspring so their characteristics will diminish over successive generations. Thus the cause of an individual's behaviour can be thought of as influenced by generations of the individual's ancestors and by the selection pressure by the environment in which the species lives.

Alternative social theories of motivation constrain the influence on an individual's behaviour to that individual's social contemporaries rather than their ancestors or environment. In his **theory of cultural effect**, Mook holds that the culture of the society in which an individual lives affects action in two ways (Mook 1987). Firstly he writes that it determines what skills, thoughts and schemata are cognitively available to an individual in a particular situation. For example an individual from western society lost in a forest may not have the notion of eating ants cognitively available as a means of satiating hunger. Secondly, Mook notes that cultural values affect what selections an individual will make from those that are cognitively available. For example suppose someone informed the lost individual that ants are a good source of protein. The individual might still balk at eating them based on their cultural perception of ants as dirty or ugly.

Similar to the theory of cultural effect but confined to even smaller social groups is the notion of **conformity**. The term conformity refers to behaviour that an individual engages in because of a real or imagined group pressure. It must be different from what the individual might have done were the pressure not exerted. Research has shown that conformity pressures can be powerful and effective motivators in both small and large groups.

3.3. MOTIVATION THEORIES FOR ARTIFICIAL SYSTEMS

Motivation theories for artificial systems have been produced by researchers from the artificial life and artificial intelligence communities either to gain insight into the causes of action in living organisms or to construct new artificial systems that have some computational advantage when solving complex problems. Much of the research concerned with creating artificial systems that mimic the biological, cognitive and social properties of systems found in nature is based on the concept of an agent. While some computational models of motivation have been informed by biological and psychological research, others introduce new ideas specifically tailored to artificial systems.

3.3.1. Motivation Theories Derived from Biological Systems

The term artificial life is used to describe research into human-made systems that possess some of the essential properties of life. As a result, artificial life researchers concerned with motivation theories tend to base their models on biological motivation theories. In fact, motivations, according to artificial life researchers (Avila-Garcia and Canamero 2002; Gershenson 2001), constitute urges to action based on internal bodily needs related to self sufficiency and survival. As a result, the computational models of motivation emerging from the artificial life community tend to implement a homeostatic process to maintain essential physiological variables within certain ranges.

Action selection architectures for autonomous agents make decisions about what behaviours to execute in order to satisfy internal goals and guarantee survival in a given environment and situation. A computational model of the drive theory of motivation is one approach to building an action selection architecture (Canamero 1997; Gershenson 2001). Motivations in computational models of drive theory are characterised by a set of controlled essential physiological variables, a set of drives to increase or decrease the level of the various controlled variables, a set of external incentive stimuli that can increase a motivation’s intensity and a behavioural tendency of approach or avoidance towards these stimuli. A feedback detector generates an error signal, the drive, when the value of a physiological variable departs from its set-point. This triggers the execution of inhibitory and excitatory behaviours to adjust the variable in the appropriate direction. Each motivation receiving an error signal from its feedback detector receives an intensity or activation level proportional to the magnitude of the error.

3.3.2. Motivation Theories Derived from Theories of the Mind

Artificial intelligence is the science and engineering of making intelligent machines, especially intelligent computer programs. Artificial intelligence researchers seek to achieve a scientific understanding of the mechanisms underlying thought and intelligent behaviour and their embodiment in machines. As a result they tend to base their models on cognitive motivation theories. Sloman and Croucher (1981) introduced the need for a "store of 'springs of action' (motives)" as part of a computational architecture of the mind. They presented a broad model of two-tiered control in which motives occupy the top level and provide the drive or urge to produce lower level goals that specify the behaviour of an agent. In a departure from theories of motivation in natural systems, Sloman and Croucher hypothesised that motives would need to incorporate structural descriptions of states to be achieved, preserved or avoided. Many subsequent models of motivation have used motives of this form to trigger goal creation (Aylett et al 2000; Luck and d'Inverno 1998; Norman and Long 1995; Schmill and Cohen 2002).

Norman and Long (1995) proposed a model for **motivated goal creation** that enables agents to create goals both reactively and pro-actively. In their model, the state of the environment and the agent are monitored by a set of motives. Motives are domain specific so, for example, in a warehouse domain motives might include satisfying orders in a timely manner, keeping the warehouse tidy and maintaining security. A change in state may trigger a response from the agent if the strength of the motive exceeds a certain threshold. The strength of a motive is calculated from the state of the domain and the internal state of the agent. This mechanism ensures that the agent will only respond to and reason about changes if they are sufficiently important. A motivational response creates a goal to consider the primary reasons for the trigger of attention. If further activity is required a goal is created that will, if satisfied, cause the mitigation of the stimuli that triggered the motivation. This mitigation takes the form of planned actions in the agent's domain. Because these agents can predict their future beliefs they are able to create proactive goals.

The notion of domain specific goals is a departure from many of the motivation theories from natural systems which seek to find general principles to describe the causation of action. Practically speaking, the implementation effort required to create agents for new domains is high as new motives must be defined for each new domain. In a more domain independent approach, Saunders and Gero created agents motivated by **curiosity** by extending the social force model (Helbing and Molnar 1995) with a fifth force, a desire to move towards potentially interesting physical locations. Various general theories of what is interesting have been developed. For example, Lenat's AM (1976) included 43 heuristics designed to assess what is interesting. Schmidhuber (1997) defined something to be interesting if it is 'similar-yet-different' to previously experienced situations. Saunders and Gero (2002; 2004) drew on these examples to develop computational models of novelty, interest and curiosity. Saunders defined the novelty of environmental stimuli to be inversely proportional to how often stimuli are experienced, how similar stimuli are to each other and how recently stimuli have been experienced. He implemented a novelty detector using the classification error from unsupervised neural networks. Like Schmidhuber, Saunders and Gero believe that novelty is not the only determinant of interest. Interest in a situation is also related to how well an agent can learn the information gained from novel experiences. Consequently, the most interesting experiences are often those that are 'similar-yet-different' to previously encountered experiences. Saunders and Gero in their curious agent, model this phenomonen using the arousal theory of motivation (Berlyne 1960).

While curious agents incorporate a domain independent model of interest, and are able to learn an underlying model of the situations they encounter in their environment, they are unable to learn new behavioural sequences to manipulate their environment. One well known model for learning such behavioural sequences is the **reinforcement learning** algorithm (Sutton and Barto 2000). Reinforcement learning uses rewards to guide agents to learn a function which represents the value of taking a given action in a given state with respect to some task. An agent is connected to its environment via perception and action. On each step of interaction with the environment, the agent receives an input that contains some indication of the current state of the environment. The agent then chooses an action as output. The action changes the state of the environment and the value of this state transition is communicated to the agent through a scalar reinforcement signal. The agent's behaviour should choose actions that tend to increase the long-run sum of values of the reinforcement signal. This behaviour is learnt over time by systematic trial and error. Reinforcement learning parallels operant theory with the additional assumption that reinforcement stimuli are always provided from a source external to the agent.

In an effort to produce agents that are able to bootstrap a broad range of competencies in a wider range of domains, Singh et al (2005) developed a model of **intrinsically motivated reinforcement learning**. In this model, agents are hardwired to identify changes in light and sound intensity as salient (interesting) events. Each first encounter with a salient event initiates the learning of an option and an option-model (Precup et al 1998) for that salient event. An intrinsic reward is generated each time the salient event is encountered that is proportional to the error in the prediction of the salient event according to the learned option-model for that event. When the agent encounters an unpredicted salient event a few times, its updated action-value function drives it to repeatedly attempt to achieve that salient event. The agent acts on the environment according to an e-greedy policy with respect to an action-value function that is learned using a mix of Q-learning and SMDP planning. As the agent moves around the world, all the options and their models initiated so far are simultaneously updated using intra-option learning algorithms. Initially only the primitive actions in the environment are available to the agent. Over time, the agent identifies and learns skills represented by options and option models. These then become available to the agent as action choices. As the agent tries to repeatedly achieve salient events, learning improves both in its policy for doing so and its option-model that predicts the salient event. As the option policy and option model improve, the intrinsic reward diminishes and the agent becomes bored with the associated salient event and moves on.

3.3.3. Motivation Theories Derived from Social Interaction Theories

Social motivation theories have been pursued by researchers in artificial life and artificial intelligence alike and frequently inform the development of multi-agent systems. One such example from the artificial life community experiments with the **evolution of purposeful behaviour** in multi-agent systems. Gusarev et al (2001) experimented with a population of motivated agents capable of reproducing. Their simulation consisted of a population of agents with two basic needs, the need for energy and the need to reproduce. The population evolves in an environment where patches of food grow. Agents can move, eat grass and mate with each other. Mating results in a new agent that inherits the characteristics of its parents according to some simple genetic rules. Their simulation demonstrated that simple hierarchical control systems in which simple reflexes are controlled by motivations, can emerge from evolutionary processes. They showed that this hierarchical system is more effective compared to behavioural control governed by means of simple reflexes only.

In another example from artificial intelligence literature, Martindale (1990) presented an extensive investigation into the role that the search for novelty plays in literature, music, visual arts and architecture. He concluded that the search for novelty exerts a powerful influence on creative activity. Saunders and Gero (2001) produced a computational model of creativity that captures the search for **novelty within a social context**. In his model, agents can communicate particularly interesting artworks to others as well as reward other agents for finding interesting artworks. He shows that both an individual's need for novelty and the collective experience of a group of agents are responsible for creating a consensus as to what is creative.

4. Intelligent Rooms

We take the concept of cognitive agents as a component of elements of a virtual world, extend the agent model to include motivation and curiosity, and move the agent from being associated with an element of a virtual world to being associated with a physical place. This extends recent work in intelligent rooms.

The idea of rooms with embedded computing power has been a subject of research in computer science since at least the late 1960s. Krueger's work on rooms that users can interact with such as VIDEOPLACE (Krueger 1985) and the work of MIT's Architecture Machine Group on novel user interfaces for rooms using gesture and speech recognition systems such as in "Put-That-There" (Bolt, 1980) laid the groundwork for current research.

More recently, in their papers on Intelligent Environment (IE) design, Brookes et al (1997) and Coen (1998) argued that a key design goal for developing IEs is to enable them to adapt to, and be useful for, everyday activities. They also adopted the stance shared by Ubiquitous Computing researchers that the computing power embedded in IEs ought to be invisible and integrate naturally with everyday activities (Weiser 1991), in contrast with earlier systems which often required users to be familiar with special interface devices in order to interact with computer-enhanced rooms. Since these papers were published the focus in IEs has been on multi-layer system architectures and sensor hardware appropriate for the IE computational models rather than incorporating creative adaptive capabilities. In addition, Brookes and Coen's group at MIT found that configuring new sensor and effector systems to allow their IEs to produce useful behaviours was time consuming and labour intensive. If an IE could creatively adapt its behaviour from its patterns of usage and learn for itself how to manipulate its sensors and effectors usefully both of these issues could be addressed.

An agent controlled IE that is a physical space for living or working can bring embedded computational power to bear in a manner that helps users of the environment perform their daily tasks. The term Intelligent Environment has not been universally adopted and IEs also go under other names such as Jeng's (2004) Ubiquitous Smart Spaces. An IE would necessarily need to be able to sense what is happening inside of it and respond to it with effectors - whether lights, projectors, or doors - in order to exhibit intelligent behaviour and help users. The agent that makes the environment intelligent is in the layer of software between low-level hardware management and higher-level application management, able to receive input from the room's sensor systems and to utilize effectors and direct applications.

IEs have several specific design requirements. In addition to adapting to, and being useful for, everyday activities as mentioned above, Brooks et al and Coen have argued that IEs should have a high degree of interactivity and should be able to understand the context in which people are trying to use them and behave appropriately. An IE is essentially, as Kulkarni (2002) suggests, an immobile robot, but its design requirements differ from those of normal robots, in that it ought to be oriented towards maintaining its internal space rather than exploring or manipulating its environment.

MIT's intelligent room prototype e21, shown in Figure 3, attempts to facilitate everyday activities via a system called ReBa, described by Hassens et al (2002) which is the context handling component of the room. ReBa observes a user's actions via the reports of other agents connected to sensors in the room's multi-agent-society and uses them to build a higher level representation of the user's activity. Each activity, such as watching a movie or giving a presentation, has an associated software agent, called a behaviour agent which responds to user action and performs a reaction, such as turning on the lights when a user enters the room. Behaviours can then layer on top of one another based on the order of user actions, acknowledging differences in context such as showing a presentation in a lecture setting versus a showing one in an informal meeting. Although ReBa can infer context in this way, it cannot adapt to new ways of using the room. In order for an entirely new context to be created, ReBa's behaviour agents are programmed to recognize the actions of the user and take an appropriate action. It does not creatively adapt to new usage patterns. Furthermore, when new sensors are added to the room, the existing rules are modified manually if they are to take advantage of the new sensor information. Our model, by contrast, uses a mechanism driven by a motivation model to creatively adapt its behaviours rather than having the behaviours predefined as part of the agent.

Other researchers have taken approaches to designing environments that are not explicitly agent-based. Both the University of Illinois' Gaia (Roman et al 2002) and Stanford University's Interactive Workspace Project (Hanssens et al 2002) have taken a more OS-based approach, developing Active Spaces and Interactive Workspaces respectively, which focus on the space's role as a platform for running applications and de-emphasizing the role of the room as a pro-active facilitator. The onus for prompting action from the space in these systems is placed upon the user and the applications developer, and although Gaia's context service provides the tools for applications developers to create agent-based facilitating applications, their overall model is not inherently reactive or adaptive. Georgia Tech's Aware Home Research Initiative plans on incorporating an infrastructure for developing context-aware applications (Kidd et al 1999). Our model focuses on the adaptive behaviour of the IE rather than on the hardware/software infrastructure of the sensors and effectors.

Figure 3. MIT's Intelligent Room Project (Hassens et al 2002)

5. An Example of a Design that is Creative: A Curious Place

The requirement for creative adaptability in an IE suggests the need to focus the agent's attention on novel events in the agent's environment in order to develop new behaviours from observations of patterns in these events. From the literature on motivation as a mechanism for focusing attention discussed in the previous section, we present a model driven by intrinsic motivation, effectance motivation, and arousal. From Sing et al's work on a computational model for intrinsic motivation comes the idea of an agent being self-motivated to learn about novel events. Combining these structures with a frequency-based model of curiosity and learning and action components creates a model of a motivated learning agent for an IE, based on a more general model presented by Kasmarik et al (2005), that creatively adapts its own behaviours in response to the recognition of curious events that it senses.

Our curious place model, shown in Figure 4, assumes two significant entities: the world and the agent. The world is described at any point in time by the data that can be sensed by the curious place. The agent has sensors to sense the state of the world, effectors to change certain aspects of the state of the world, a memory of world states and events, and a reasoning process that includes motivation, action, and learning.

5.1. THE WORLD STATE

The curious place exists within a specific world available through its sensors. The state of the world is the basis for agent's interaction with the world; therefore it becomes the basis for configuring sensors and effectors and creatively adapting to new behaviour patterns of its users. The world state at time t, $W(t)$, is characterised as a partitioned tuple of sensor inputs, which are in turn represented as attribute-value pairs such as PRESSURE_PAD=ON. One side of the partition represents inputs from sensors without associated effectors, such as a pressure pad in the floor. The state of a pressure pad in the floor can only be changed by a person moving on or off the pressure pad, and therefore, cannot be directly changed by the agent. The other side of the partition represents inputs from sensors that do have associated effectors, such as a sensor attached to a light switch which can be changed by a person or by the agent. A world state at time t, is sense data represented in the following form:

W(T) ::= (<senseOnly> | <senseEffect>)

And an example of such a state is:

(PRESSURE_PAD=ON | LIGHT _INTENSITY=0.5, DESK_LAMP=ON)

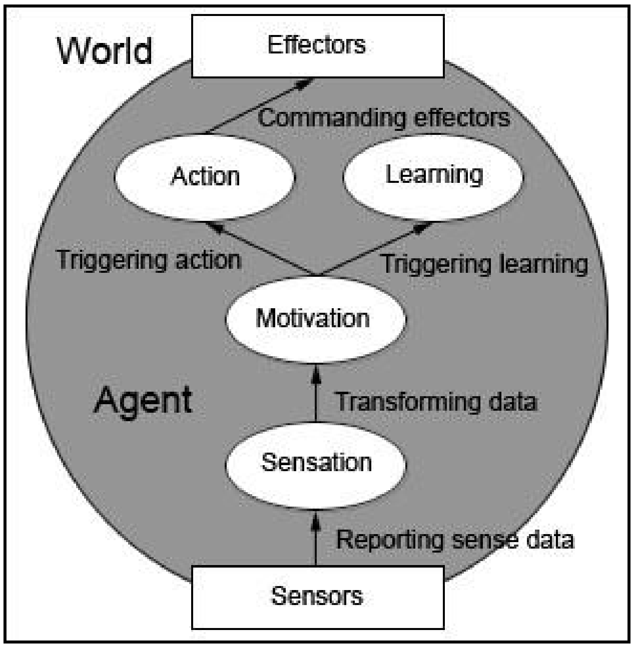


Figure 4. The curious place model.

This distinction is relevant because the agent should only be motivated to learn to repeat events over which it has control. For example, the change in the state of the pressure pads can only be made by humans moving themselves or objects in the room, so an event that includes only a change in the state of the pressure pads cannot be affected by the agent. In contrast, an event that includes a change in the state of the data projectors can be affected by the agent.

5.2. SENSATION

In the sensation process, sensor input from the world is converted into a form suitable for performing reasoning and learning. The new world state *W(t)* is compared with the previous world state *W(t-1)* to extract events. An event is represented as *Delta(t)*, the changes in sensor inputs between *W(t)* and *W(t-1)*. These changes are central to the arousal model of the motivated learning agent, since arousal is a response to a change in stimulus levels. *Delta(t)* takes the same form as *W(t)*, a partitioned tuple, but the values of the tuple represent the changes in sense data values between *W(t)* and *W(t-1)* with numeric values being calculated as normalized differences and nominal elements being 0 if no change occurred and 1 if one did occur. For example:

W(0) = (PRESSURE_PAD=ON | LIGHT_INTENSITY=0.5, DESK_LAMP=ON)

W(1) = (PRESSURE_PAD=OFF | LIGHT_INTENSITY=0.8, DESK_LAMP=ON)

Delta(1) = (PRESSURE_PAD=1 |LIGHT_INTENSITY=0.3, DESK_LAMP=0)

5.3. MOTIVATION

The motivation component serves to focus the attention of the agent on novel events and guide it to infer new behaviours from interesting patterns in its history of states. Identifying novel events is governed in this model by a motivational model of curiosity. While a novel event is considered curious to the agent and therefore motivates it to learn new behaviours, the event can't be so novel that there is insufficient data about the world states occurring before the event for the agent to adapt or learn new behaviours. We considered two models that capture this idea of "different, but not too different": the self organising maps used by Saunders and Gero in their curious agent, and the novelty detector based on event frequency clusters used by Kasmarik et al in their motivated agent.

We are currently working with the novelty detector based on event frequency clusters. Events are divided into groups using unsupervised clustering of event frequencies. Each group is defined to be novel or not novel based on their frequencies of occurrence. The novel events are then further clustered into groups of increasing rarity so that the agent can be motivated to learn about more common or 'easier' events that are more likely to have sufficient patterns in the agent's memory.

Clustering is performed by first sorting events in order of ascending frequency where frequency is calculated as the number of times the event has occurred divided by the size of the agent's lifetime. This produces an ordering $(e_1, f_1), (e_2, f_2) \ldots (e_n, f_n)$ with differences $d_1, d_2 \ldots d_n$ where $d_k = f_k - f_{k-1}$. K-means clustering with $k=2$ and initial centroids 0 and d_{max} where $d_{max} = \max_j d_j$ produces two groups g_1 and g_2 with average distances to centroids a_1 and a_2. g_i has the minimum average a_i then events can be clustered as follows: Place f_1 in a new cluster. For $f_2, f_3 \ldots f_n$, place f_k in the same cluster as f_{k-1} if $d_k \in g_i$ or in a new cluster otherwise. We say that an event e_i is novel if its frequency f_i falls in the same cluster as f_1.

5.4. LEARNING

The learning component is at the core of the agent's creative adaptability. Because it is inappropriate for an intelligent room to experiment with changes in the state of the room as a reinforcement learning agent might, learning must rely upon drawing inferences from previously experienced world states via data mining techniques without being able to affect the environment during the learning process. The aim of the learning component of the agent model is to infer a set R of behavioural rules from the set of stored world data S and then store R in memory for the action component to utilize. Such behavioural rules will be of the form:

Rule ::= IF SENSE = <window> THEN EFFECT = <action>

Where <window> is a delta combined with hashes of recently activated behaviours and <action> is a tuple of attribute-value pairs consisting only of sensor data that can be affected. Such rules are formed by considering the changes in world state within a given time window and constructing rules to enact equivalent changes when sufficient support and confidence levels exist for such a rule to be derived. Techniques based on Generalised Sequential Pattern Mining (Agrawal and Srikant 1995; Srikant and Agrawal 1996) or the MINEPI algorithm (Manilla et al 1997) can then be used to find these rules from the memory of world state tuples. The more that a mined rule seems like correct behaviour to the agent in terms of support and confidence, the more strongly the agent feels motivated to follow the rule, mirroring a kind of effectance motivation. This effectance motivation is represented by a priority associated with each mined rule that is a function of the support and confidence assigned to the rule by the data mining algorithm.

5.5. ACTION

The action component of the agent model maps the most recently sensed world state $W(t)$ and previous world states within a given time window to a rule from the set of behavioural rules R to be executed by the agent's effectors. This is done via a rule engine that supports rule prioritisation. Behavioural rules that generate more effectance motivation are favoured over those that produce lower effectance motivation as reflected in the rule's priority. It then sends the appropriate commands to the agent's effectors to enact the changes in the world dictated by the rule selected.

5.6. MEMORY

The motivation, learning, and action components all require information about earlier states of the world, and the sensation and learning components update that information. This necessitates a memory component for storing deltas and behavioural rules. The various kinds of interactions with memory are outlined in the sections on the specific components and Figure 5 provides a diagrammatic summary.

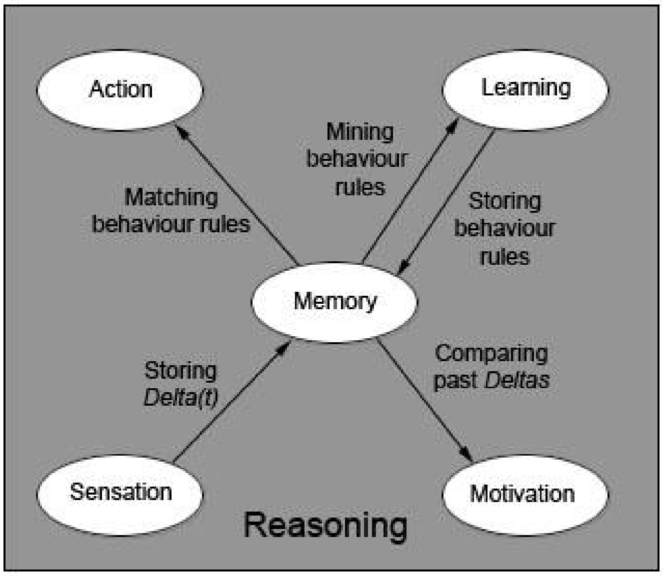


Figure 5. Interactions between the reasoning and memory components of the model.

6. Conclusions

Computational models of creative design are usually considered as tools that assist a human designer while designing. In this paper we reconsider this assumption and look at computational models of creative design as a component of a design product. The situations in which this is relevant are scenarios in which a design product operates in an unpredictable and changing environment, for example, a virtual or physical room that supports a broad range of changing human activities.

We have examined the key characteristics of models of creative design and focussed on a review of motivation theories. Our objective is to establish a theoretical basis for a design product capable of exhibiting creative design behaviour, and specifically a computational model of a curious place. The core of our model is a computational model of motivation that drives an agent for a room to learn new behaviours. The model that we present is currently being implemented and tested in The Sentient, a multipurpose room for seminars, design cognition experiments, and immersive interactive displays.

Our model for a creative design differs from other models of interactive designs by comprising: a model of motivation to trigger learning, a learning component that can use its previous experiences as a basis for developing new behaviours, and an action model that can determine which known behaviour to apply to change the environment in response to a change in the state of the world.

7. References

Agrawal, R, Srikant, R: 1995, Mining sequential patterns, *in Proc. of the Int'l Conference on Data Engineering (ICDE)*, Taipei, Taiwan, March 1995.

Alderfer, C: 1972, *Existence Relatedness and Growth*, Free Press, New York.

Atkinson, JW and Feather, NT: 1966, *A Theory of Achievement Motivation*, Wiley, New York.

Atkinson, JW and Raynor, JO: 1974, *Motivation and Achievement*, VH Winston, Washington DC.

Avila-Garcia, O and Canamero, L: 2002, Comparison of behaviour selection architectures using viability indicators, *The EPSRC/BBSRC International Workshop on Biologically Inspired Robotics: The Legacy of W Grey Walter*, HP Labs, Bristol, UK, pp. 86-93.

Berlyne, DE: 1960, *Conflict, Arousal and Curiosity*, McGraw-Hill, New York.

Berlyne, DE: 1970, Novelty, complexity and hedonic value, *Perception and Psychophysics* **8**: 279-286.

Berlyne, DE: 1971, *Aesthetics and Psychobiology*, Prentice-Hall, Englewood Cliffs, NJ.

Boden, M: 1994. What is creativity? *in* Margaret Boden (ed.) *Dimensions of Creativity,* MIT Press.

Bolt, RA: 1981, Put-That-There: Voice and gesture at the graphics interface, *in Proceedings of the 7th Annual Conference on Computer Graphics and Interactive Techniques*, Seattle, US, pp. 262-270.

Brooks, RA: 1997, with contributions from M Coen, D Dang, J DeBonet, J Kramer, T Lozano-Perez, J Mellor, P Pook, C Stauffer, L Stein, M Torrance and M Wessler. The Intelligent Room Project, *in Proceedings of the Second International Cognitive Technology Conference (CT'97)*, Aizu, Japan, pp. 271-279.

Canamero, L: 1997, Modelling motivations and emotions as a basis for intelligent behaviour. *in* WL Johnson (ed.), *The First International Symposium on Autonomous Agents*, ACM Press, New York, NY, pp. 148-155.

Clark, S and Maher, ML: 2005, Learning and designing in a virtual place: Investigating the role of place in a virtual design studio, *Proceedings of eCAADe 2005*, Lisbon Portugal, pp.

Coen, MH: 1998, Design principles for intelligent environments, *in Proceedings of the Fifteenth National / Tenth Conference on Artificial Intelligence / Innovative Applications of Artificial Intelligence,* Madison, Wisconsin, United States pp. 547 – 554.

Darwin, C: 1859, *The Origin of Species*.

Dasgupta, S: 1994, *Creativity in Invention and Design: Computational and Cognitive Explorations of Technological Originality*, Cambridge University Press.

Deci, E and Ryan, R: 1985, *Intrinsic Motivation and Self-Determination in Human Behaviour*, Plenum Press, New York.

Gero, J and Maher, ML: 1993, Preface *in* JS Gero and ML Maher (eds) *Modellng Creativity and Knowledge-Based Creative Design*, Lawrence Erlbaum and Assoc. pp. 106.

Gershenson, C: 2001, *Artificial Societies of Intelligent Agents,* BEng Thesis, Fundacion Arturo Rosenblueth, Mexico.

Green, RG, Beatty, WW and Arkin, RM: 1984, *Human Motivation: Physiological, Behavioural and Social Approaches*, Allyn and Bacon, Inc, Massachussets.

Gu, N and Maher, ML: 2004, A grammar for the dynamic design of virtual architecture using rational agents, *International Journal of Architectural Computing* **4**(1): 489-501.

Gusarev, RV, Burtsev, MS and Red'ko, VG: 2001, A life model of evolutionary emergence of purposeful adaptive behaviour, *European Conference on Artificial Life*.

Hanssens, N, Kulkarni, A, Tuchinda, R, Horton, T: 2002, Building agent-based intelligent workspaces, *in Proceedings of the 3rd International Conference on Internet Computing,*pp. 675-681

Heider, F: 1958, *The Psychology of Interpersonal Relations*, Wiley, New York.

Helbing, D and Molnar, P: 1995, Social force model for pedestrian dynamics, *Physical Review* **51**: 4282-4286.

Horner, MS: 1974, The measurement and behavioural implications of fear of success in women, *Motivation and Achievement* 91-117.

Huhns, MN and Stephen, L: 1999, Multiagent systems and society of agents, *in* Weiss, G. (ed.), *Multiagent Systems, A Modern Approach to Distributed Artificial Intelligence*, MIT Press, MA, pp.79-120.

Hull, CL: 1943, *Principles of Behaviour*. Appleton-Century-Crofts, New York.

Hull, CL: 1952, *A Behaviour System: An Introduction to Behaviour Theory Concerning the Individual Organism*. Yale University Press, New Haven.

Jeng, T: 2004, Designing a ubiquitous smart space of the future: The principle of mapping, *in* JS Gero (ed.) *Design Computing and Cognition '04*, Kluwer Academic Publishers, The Netherlands, pp. 579 – 592.

Kandel, ER, Schwarz, JH and Jessell, TM: 1995, *Essentials of Neural Science and Behaviour*, Appleton and Lang, Norwalk.

Kasmarik, K, Uther, W, Maher, ML: 2005, Motivated agents, *The 19th International Joint Conference on Artificial Intelligence*, Edinburgh, Scotland, pp. 1505-1506

Kidd, C, Orr, R, Abowd, G, Atkeson, C, Essa, I, MacIntyre, B, Mynatt, E, Starner, T, Newstetter, W: 1999, The aware home: A living laboratory for ubiquitous computing research, *in Proceedings of the Second International Workshop on Cooperative Buildings*, Pittsburgh, PA

Kreuger, MW: 1985, VIDEOPLACE--An artificial reality, *in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, San Francisco, US, pp. 35-40s

Kulkarni, A: 2002, Design principles of a reactive behavioral system for the intelligent room, *in Bitstream: The MIT Journal of EECS Student Research*, April 2002 Edition. Cambridge, MA, pp. 1-5

Lenat, D: 1976, AM: An artificial intelligence approach to discovery in mathematics. PhD Thesis, Stanford University.

Martindale, C: 1990, *The Clockwork Muse*. Basic Books, New York.

Maher, ML and Gero, JS: 2002, Agent models of virtual worlds, *Proceedings of ACADIA 2002*, Pamona, CA.

Maslow, A: 1954, *Motivation and Personality*, Harper, New York.

McFarland, D: 1995, *Animal Behaviour*, Longman, England.

Mannila, H, Toivonen, H, Verkamo, AI: 1997, Discovery of frequent episodes in event sequences. *Data Mining and Knowledge Discovery* **1**:259-289.

Mook, DG: 1987*, Motivation: The Organisation of Action*, WW Norton and Company, Inc, New York.

Norman, TJ and Long, D: 1995, Goal creation in motivated agents, *Intelligent agents: theories, architectures and languages*. Springer-Verlag, pp. 277-290.

Román, M, Hess, CK, Cerqueira, R, Ranganathan, A, Campbell, RH, Nahrstedt, KN, Gaia A: 2002, Middleware infrastructure to enable active spaces, *in IEEE Pervasive Computing* Oct-Dec (2002) pp. 74-83

Rosenman MA, Smith G, Ding L, Marchant D and Maher ML: 2005, Multidisciplinary design in virtual worlds, in *CAADFutures 2005*, Vienna, Austria.

Runco, M and Pritzker, S eds. 1999, *Encyclopedia of Creativity*, San Diego, CA: Academic Press.

Saunders, R and Gero, JS: 2001, The digital clockwork muse: A computational model of aesthetic evolution, *The AISB'01 Symposium on AI and Creativity in Arts and Science*, SSAISB.

Saunders, R and Gero, JS: 2002, Curious agents and situated design evaluations, *in* JS Gero and FMT Brazier (eds), *Agents In Design*. Key Centre of Design Computing and Cognition, University of Sydney, pp. 133-149.

Saunders, R and Gero, JS: 2004, *Situated Design Simulations Using Curious Agents.* AIEDAM.

Schmidhuber, J: 1997, *What's Interesting,* TR-35-97, Lugano, Switzerland.

Singh, S, Barto, AG, and Chentanex, N: 2005, Intrinsically motivated reinforcement learning, *Advances in Neural Information Processing Systems* **17:***(NIPS)* (to appear).

Skinner, BF: 1938, *Behaviour of Organisms*, Appleton-Century-Crofts, New York.

Sloman, A and Croucher, M: 1981, Why robots will have emotions, *The 7th International Joint Conference on Artificial Intelligence*, Vancouver, Canada, pp. 197-202.

Smith, G, Maher, ML and Gero, JS: 2004, Towards designing in adaptive worlds, *Computer-Aided Design and Applications* **1**(1-4): 701-708.

Srikant, R, Agrawal, R: 1996, Mining sequential patterns: Generalizations and performance improvements, to appear in *Proc. of the Fifth Int'l Conference on Extending Database Technology (EDBT)*, Avignon, France, March 1996.

Sutton, RS and Barto, AG: 2000, *Reinforcement Learning: An Introduction*, The MIT Press.

Tolman, EC: 1932, *Purposive Behaviour in Animals and Men*, Century, New York.

Weiser, M: 1991, The computer for the 21st Century, *in Scientific American* **265**(3): 94-104.

White, RW: 1959, Motivation reconsidered: The concept of competence, *Psychological Review* **66**: 297-333.

Woodworth, RS: 1918, *Dynamic Psychology*, Columbia University Press, New York.

Wooldridge, M.: 1999, Intelligent agents, *in* G Weiss (ed.), *Multiagent Systems, A Modern Approach to Distributed Artificial Intelligence*, MIT Press, MA, pp.27-78.

Wooldridge, M and Jennings, NR: 1995, Intelligent agents: Theory and practice*, Knowledge Engineering Review* **10**(2): 115–152.

Wundt, W: 1910, *Principles of Physiological Psychology*. Macmillan, New York.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 137-151

ON UNDERSTANDING HUMAN-COMPUTER CO-CREATIVE DESIGNING

Identifying obstacles for synthesising diverse research sources

OLIVER HOFFMANN
University of South Australia, Australia

Abstract. Can a model of Human-Computer Co-Creative Designing (HC 3D) be obtained by combining criteria for computer supported human creativity with computer engineering models? These sources are based on different notions, reflect different implicit priorities, and different implicit world views. Combining results is therefore challenging, but also promises to yield insights applicable in the more general areas of computing and creativity research.

1. Introduction

How can computer systems and human users be creative together? This question can easily be confused with two related topics. First, supporting creativity is different from increasing productivity. Rather than making our routine activities more efficient, information technology can extend our creative potential, help us to "reframe and redirect the expenditure of human effort, generating unanticipated payoffs of exceptionally high value" (Committee on Information Technology and Creativity 2004). And second, arriving at enhanced human-computer co-creativity is different from either increased human or increased computer potential in itself. From a systems perspective, human-computer creative interaction would have to be more or at least different than the sum of its parts.

Certain aspects of HC 3D have been addressed by different scientific communities, but complete models are scant. Information technology and it's contribution to creativity has received considerable scientific attention, but the majority of such work focuses on (computer) enhanced human creativity or enhanced computing power (modelling creative design processes), much less attention was given to understanding the added benefit of human-computer co-operation. Human-Computer Interaction (HCI) is a significant research area in itself, of course, but it focuses on issues of interaction such as the computer interface, with the goal of adapting computer systems to user needs. The main difference to a systems view of HC 3D lies in what is considered means and what is considered ends: In HCI, satisfying human needs is the end, and adapting computer systems the means. For understanding enhanced HC 3D, creative designing is the end, and appropriate combinations of human and computing contributions the means.

Can scientific results describing divers aspects of HC 3D be combined in the same way that human and computing contributions are? The method of integrating previous research results for obtaining new knowledge is called research synthesis, and like all scientific methods has its strengths and weaknesses. As Suri (2004) argues, “A synthesist can adapt several philosophical and theoretical ideas from the literature on primary research methods to the process of a research synthesis”, and thus might have to challenge implicit views from one or several of the contributing approaches or fields, Figure 1. The goal of this article is to address some of the potential obstacles for synthesising a complete model of HC 3D from primary research fields such as HCI and design computing.

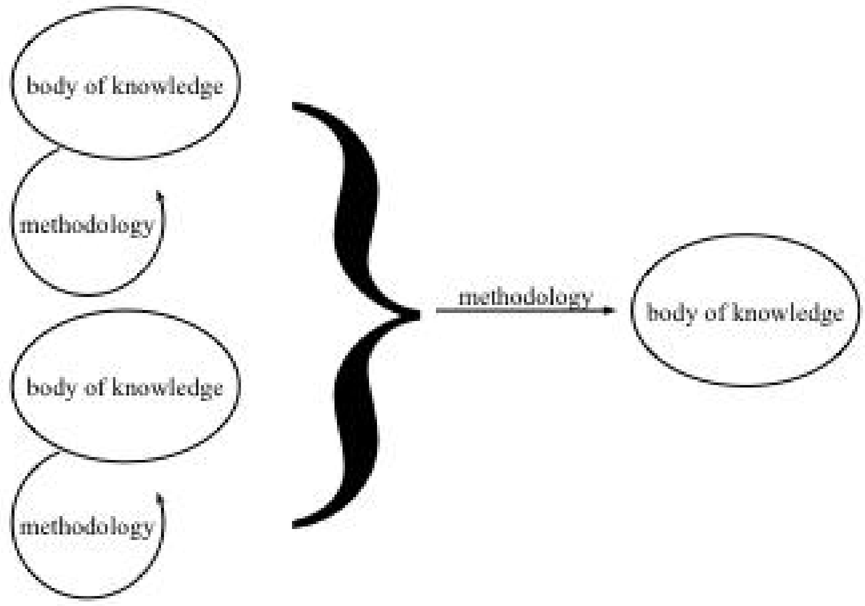


Figure 1: trans-disciplinary research synthesis

It is important to note that the analysis presented here is different from a stand alone critique of claims in the primary research fields. One prominent example of the latter is Searle’s critique of artificial intelligence. His Chinese room (Searle 1980) argument was directed against the claim that computer systems would “possess” knowledge. The analysis here does not attempt to question the absolute validity of primary research approaches or results, it attempts to clarify the relative role of these contributions for a research synthesis.

2. Enhanced Human Abilities

Humans and computer systems are substantially different, and so are the settings for examining them. In approaches aiming for enhancing human abilities or “augmenting human intellect” (Engelbart 1962) with computing power, computer systems are expected to perform a service role towards their human masters. Lubart (2005) portrays creative HCI as “ways that computers can contribute to people’s creativity”. “Real partnership, in which humans and computers work hand in hand”, on the other hand is treated as a sort of utopia, an “ambitious vision of HCI”.

That might depend on how one defines real partnership, or on whether working hand in hand is seen as a specific type of interaction, or as a specific view on interaction. To turn the question around: What kind of creative process would involve both humans and computer systems, but not constitute a real partnership between them? If either humans or computers do not contribute any added value to a process, why involve them both? In this case, either one might be better off doing it alone.

Lubart has of course good reason to use real partnership as a distinguishing feature, separating such kinds of human computer interaction from those where the computer performs a nanny, pen-pal or coach role. But his classification illustrates that complex HCI with emergent features gets less scientific attention than in could.

What do creative users expect from computer systems? Any information system user can be creative. But for some, like artists, creative designers, scientists developing a new theory, or engineers working on innovative solutions, creativity is an essential goal. Like a magnifying glass, these groups of users expose the role of information systems in creative processes. In some ways, these users expect the same basic services as all users: computation, storage, and communication. “Tasks for helping people be more creative more of the time” Shneiderman (2002) can be classified according to the services they depend on (Shneiderman’s tasks in italics):

Information system service for creative users 1: modelling. The ability to compute on existing information can serve as the basis for various kinds of models, which can be used for visualisations of objects and processes, **exploration** of scenarios and of complete works from various fragments.
Information system service for creative users 2: book keeping. Not surprisingly, the ability to store information is one of the key reasons to use

an information system, including for creative purposes. This service helps with tasks such as **reviewing** previous steps in a process and **searching** for compatible material.

Information system service for creative users 3: communication. Human creativity frequently (some argue always) involves some sort of collaborative effort, and information systems can provide means for **relating** to others or **disseminating** results.

Some creative computer users are also computer experts, but most are not. Subsequently, most see the computer as a black box, and are not interested in intricate system performance details, only in overall system behaviour towards them. From this perspective, behaviourist criteria for the needs of creative users can be formulated, for instance those compiled by Candy and Edmonds (1997): The system must enable the user to

IS behaviour criterion 1: adopt an holistic perspective on the task or problem To achieve this, the user should have access, for example, to overviews, multiple views and alternative representation of the data in respect of the developing solution

IS behaviour criterion 2: keep several channels of exploration open in parallel To achieve this, the user should be able to alternate between tasks freely, fluently and quickly. This implies having simultaneous access to different forms of visual data and methods for knowledge interaction

IS behaviour criterion 3: explore and evaluate existing design knowledge in relation to other heterogeneous knowledge sources, generate and evaluate new concepts and apply constraints as appropriate

Candy and Edmonds derive these criteria from studies on what they call creative knowledge work, primarily on scientists' use of computer systems for analysis and theory development. Hewett (2005) uses the term creative problem solving environments for computer system supporting such work.

When Shneiderman's list of expected services and Candy and Edmonds's criteria for overall behaviour are combined, one can see that they are pointing in opposite directions. While it is important that computer system help with modelling (information system service for creative users 1), it is also important that the choice of model and representation is always left to the user, enabling a holistic overview (IS behaviour criterion 1). So with every new computer system capability, ways of maintaining a holistic user perspective has to be provided. Which is partly contradictory. If information systems are to perform their basic services reliably, information system engineers would have to make sure that the appropriate knowledge representation is used for modelling, and not any knowledge representation. It is tempting to delegate this issue to the task of designing appropriate user interfaces, but an interface can only present what is internally represented, interfaces can only hide information, they can not add functionality (else they are not interfaces any more). At system design time, engineers have to anticipate user choice consequences. Unlimited user choice would require unlimited system power to maintain all sorts of models associated with these representations. At some point, engineers will have to make choices for users, in order to ensure system performance stays intact. Engineers would also have to ensure that information systems have enough control over the process to complete their services reliably, placing constraints on users options for changing between tasks freely.

In other words: For information system services to be delivered reliably, information systembehavioural criteria will have to suffer. This tension reflects the dual nature of creativity: As Mayer (1999) demonstrates, "the majority [of authors] endorse the idea that creativity involves the creation of an original and useful product". In the case of computer enhanced human creativity, these two aspects are split between the different sets of research results: Usefulness/reliability is stressed in Shneiderman's tasks, but originality/novelty is stressed by Candy and Edmonds' criteria. Both describe requirements for the computer role in enhancing human creativity, but Shneiderman describes what the computer should do, while Candy and Edmonds describe what the computer should enable. Thus, in summary, enhancing human creativity would require splitting the dual nature of creativity between computer system and human partner, with the computer being required to assure reliability and at the same time enable novelty.

3. Enhanced Computing Power

The tension between novelty and reliability effects mutual user and engineers responsibilities and expectations, and it has an even more visible effect on engineers understanding of their own creativity and of creativity in general. There is a conflict of interest between the expression of user creativity and the expression of engineering creativity. "Technology is the manifestation of engineering creativity" (Burghardt 1995), the products of engineering creativity are physical objects, complex systems, or processes in the sense of a service, technique or method.

Of course novelty is a desired property for these products. However, it is not sufficient on its own. In artistic creativity or any form of non-functional creativity, novelty alone may be regarded as automatically being effective, or effectiveness may be judged according to purely aesthetic or expressive criteria. In the case of engineers, however, effectiveness means, in the first instance: “Will it work?”. The consequences of generating novelty that lacks effectiveness are quite different for information system engineers and information system users. For an artist or author, for instance, it might mean embarrassment, damage to the reputation, or loss of income, although it might also mean praise for being avant garde. For engineers in general, however, it might well mean bankruptcy for a firm, endless lawsuits, or even a disaster causing great loss of life. Thus (as has been argued in greater detail in Hoffmann et al 2005), in engineering creativity reliability takes precedence over novelty. Cropley and Cropley (2005) refer to creativity possessing this particular property as functional creativity, Burghardt (1995) calls it “creativity with a purpose”.

Thus more engineering creativity might not always be beneficial to more user creativity. While creative users expect to be supported in their non-algorithmic, divergent thinking and nuanced judgement (Guilford 1950; Resnick 1987), engineers try to contain system behaviour, apply as much convergent thinking as possible in order to attain convergent system behaviour, and thus indirectly restrict user options for holistic overviews.

This issue has an influence on the relationship between computer system engineering creativity and computer system user creativity in general, and it also effects the relative roles of research approaches based on the computing paradigm and research approaches based on different paradigms. Design computing approaches such as (Saunders 2002) and artificial creativity approaches such as (Machado and Cardoso 2002) are all based on engineering views, and their results have to be adjusted prior being synthesised with other sources.

One significant example of how results from these engineering approaches have to be re-interpreted in order to link them with contributions from the arts or humanities is their understanding of the knowledge notion. This can be demonstrated by analysing the limits of certain research approaches within the engineering paradigm.

One example are perspective based models of creative design, like those of Haymaker et al (2002), Figure 2, and Hoffmann et al (2001). These models aim for allowing greater user flexibility by isolating hard engineering requirements within what is at times called aspects, views, or perspectives. Views/perspectives incorporate various models, and they are loosely linked through filters/translators, giving users more freedom in changing between different forms of representation. Then reliability requirements could be satisfied within views/perspectives, and novelty requirements via filters/translators. But how would engineering the filters/translators fit within computing paradigms? Every view/perspective incorporates some specific knowledge, and if the information system as a whole is to perform reliably, the links between them would have to do the right kind of computation. Taken to its extremes, this kind of argumentation will eventually render any view/perspective/filter/translator-model useless. The understanding of notions like knowledge or information illustrates this situation.

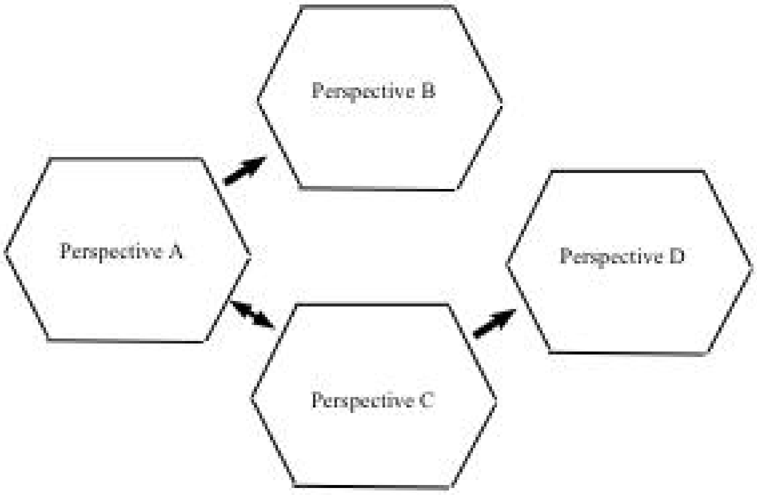


Figure 2: Perspective based models.

4. Knowledge and Computation

Computer science notions like data and information have long been adopted outside computer science or science in general. With respect to terms like "knowledge" the situation is more complex: Other disciplines use the same words, but the notions might be different. In fact, words like "knowledge" are part of every day language, and as such open for re-interpretation by every one. Scientific disciplines have each developed their own specific understanding of such terms, in a way that suits their core goals. In the case of computer science, knowledge was framed to primarily suit the needs of computation.

When computational models of design refer to knowledge, they generally use this notion in accordance with the knowledge level hypothesis formulated by Newell (1982), Figure 3. The knowledge level is at times quoted explicitly, as for instance by Brazier et al (2001). More frequently, use of knowledge is implicitly based on an understanding compatible with Newell's hypothesis, in work using terms like "knowledge-based" or "knowledge-intensive", as for instance by (Tomiyama 1994). Newell's definition is therefore a good source for analysing the understanding of knowledge within the computational paradigm.

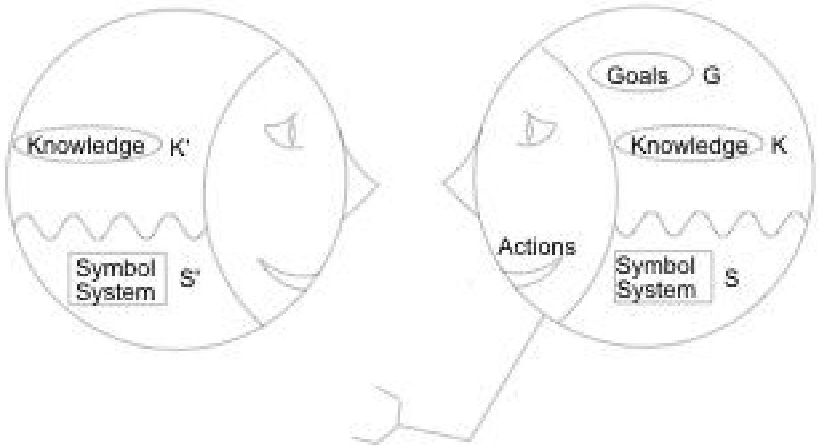


Figure 3: Knowledge verification according to Newell

His hypothesis states the existence of a computer system level which is the sole and exhaustive location for knowledge in an agent. This level has all the properties of a standard computer system level: among other things, it can be implemented without references to internal details of other levels, and it can be reduced to the level below it (the symbol level) by defining it's medium (knowledge), components and laws via those (symbols) of the level below it. According to this hypothesis, knowledge could be seen as an abstract property of (computer system or human) agents implementable via various different forms of symbolic representations in the same way that symbolic representations are implementable via various different forms of electronic hardware.

Such an understanding of knowledge would make it impossible to directly verify or falsify the presence of a specific element of knowledge in an artificial agent: the highest directly observable system level contains symbols that might or might not encode a specific knowledge, but the knowledge itself would reside one level above those representations and would be removed from direct observation. Newell proposed a mechanism of indirect verification for the knowledge level: If some (human or artificial) agent A can detect the impact of some specific knowledge in the actions of another agent B, agent A can verify the presence of such knowledge in agent B, Figure 4.

Through this hypothesis, Newell attempted to end an internal dispute among artificial intelligence researchers, a controversy centred around the question of the "best" form of knowledge representation. According to Newell, this understanding of knowledge is based in the general practise of computer science or artificial intelligence, and Newell (1993) also claims that a significant part of artificial intelligence research has been (implicitly or explicitly) based on this hypothesis.

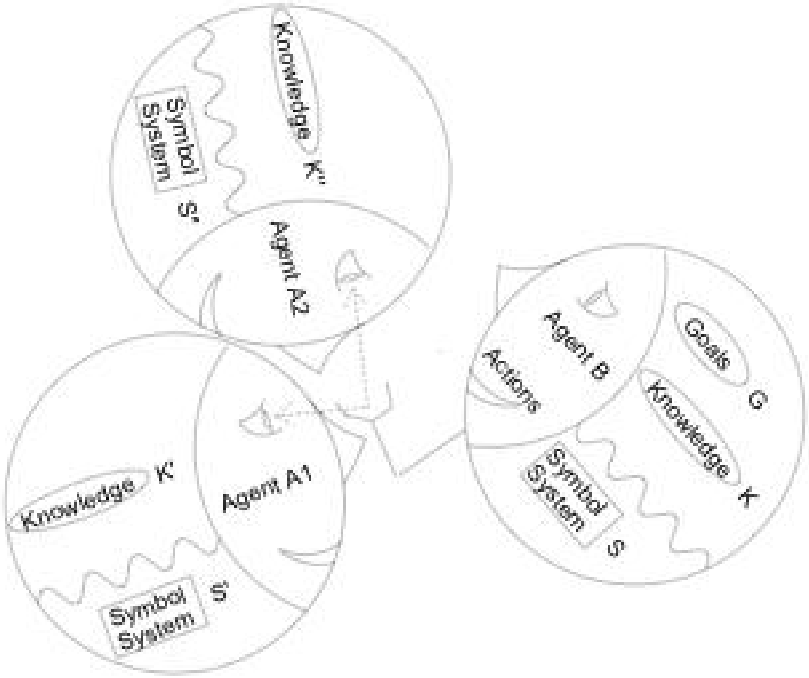


Figure 4: How do different observing agents agree on the presence of knowledge?

Irrespective of whether the hypothesis itself is correct, wide adoption of the corresponding knowledge notion demonstrates it's compatibility with computer engineering and computer science. Implicitly, such an understanding of knowledge is based on an objectivist world view (Stamper 1993), which can be detected by focusing on those aspects that authors like Newell do not discuss, and the questions that are not answered. A good example is: "Who is the agent that will verify the presence of knowledge in another agent?" More than one agent could take the role of the observing agent A in Newell's knowledge verification mechanism and the different As could come to different conclusions on whether knowledge is present in agent B, Figure 4.

Newell does not explain how the A agents would be able to come to any consistent conclusion on agent B's knowledge, and since their symbol levels might be mutually incompatible, it is unclear how they could even communicate their different views on agent B. The only conceivable way Newell's knowledge verification might yield consistent results is by relying on a standardized observer agent A that serves as the absolute reference on detecting knowledge. Newell implicitly assumes objective knowledge that would be the basis, rather than the result of attempts to create artificial intelligence. But if such a standard agent existed, Newell's entire knowledge verification procedure might be obsolete before it is ever applied: this standard verification agent would already incorporate the perfect embodiment of intelligence and knowledge, and any attempts to build more intelligent agents would have to fail.

The main effect of Newell's knowledge level hypothesis is not what it accomplishes, but what it prevents: the authority to interpret symbolic knowledge representations is restricted to computer systems, since their (virtual) behaviour is the only way for determining what knowledge is represented. Human subjective interpretation is excluded from the process of symbol interpretation, since Newell's artificial agents never directly expose their symbol level to human agents.

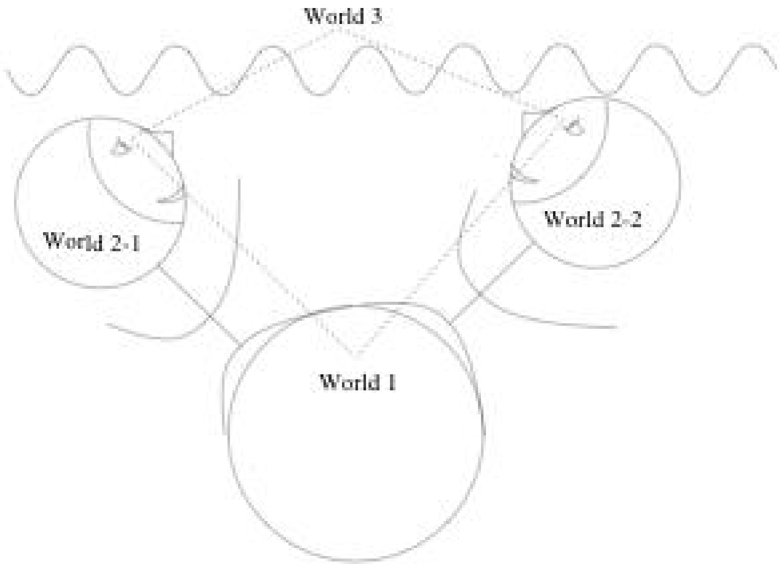


Figure 5: Popper's 3 worlds thesis

That aiming for objective knowledge does not necessitate deleting subject-relative aspects can be shown in comparison with Popper's three worlds thesis, Figure 5: World 1 is the (observer-independent) physical universe, world 2 is an observer's image of world 1, and world 3 is the collective symbolic representation of world 2 shared among a multitude of observers. These worlds are interrelated but distinct, World 3 is necessarily embedded in world 1, since observers are only able to communicate each other's symbolic representations if they are able to physically perceive them. Any action performed by one of the observers can be interpreted as a contribution to world 3, and scientific experiments are the most prominent example of this feature.

Popper's motivation for his three worlds thesis was somewhat similar to Newell's motivation for his knowledge level hypothesis: Popper wanted to show a path towards objective observer-independent knowledge. But in contrast to predominant computer science approaches, Popper assumed subject-relative knowledge and subject-relative representation as the starting point of this path. Objective knowledge is only achieved as the result of a long process of negotiation among subjects.

This process is permanent, since world 3 only approximates world 1, without ever reaching total consistency with it. It is notable that Popper describes the entire process of scientific development as embedded in the continuous approximation of world 3 to world 1. Newell's computer system level understanding of knowledge, on the other hand, precludes further adaptation of world 3 to world 1, due to the hierarchical relationship of symbols and knowledge, and due to lack of negotiation mechanisms regarding observing agent's judgements.

Candy and Edmonds's behavioural criteria prove hard to transfer into a computing framework, as long as notions like knowledge implicitly carry an understanding aiming for reducing user choice and user interpretive freedom. That this situation is deeply rooted can be shown with an even more fundamental notion: information. The original technical definition of information by Shannon is based on the ability to predict the next symbol in a stream of communication. Again, the open question is: "Who will predict the next symbol?" Different potential receivers of the same symbolic message will have different knowledge about the world in general, the language used for sending the message, and the sender. Thus different receivers will have different abilities to predict the next symbol, and the information content of the same message will potentially be different for each receiver, Figure 6. Shannon arrives at an objectivist result by assuming the existence of a subject-independent dictionary containing absolute probabilities for a given language.

The receiver of Shannon's messages turns out to be the same implicitly standardized perfectly knowledgeable observer that Newell uses to verify the existence of knowledge in computer systems. Shannon, like Newell, was motivated by the goal of eliminating subjective interpretation from his model of symbolic message content, and his information notion is still in use today. The discipline initially had good reasons for choosing this approach: At the time of Shannon, technical reliability of communication was the primary goal, and side effects on the potential processing of stored knowledge inside computer systems were largely irrelevant to the engineers that founded computer science. Wherever issues of subject-relativity come in conflict with engineering properties like reliability, predictability, and consistency, computer science has generally given preference to those views that favour engineering goals. Computer science has suppressed subject-relative aspects of knowledge since it's beginning.

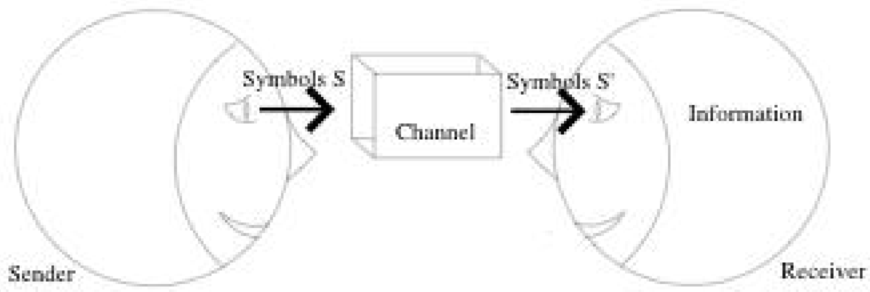


Figure 6: different receiver agents would receive different amounts of Shannon information

5. World Views

Scientists, engineers and non-engineering (creative) users rely on their respective education, and on world views implicit in it. As far as engineering is considered a scientific enterprise, it is based in the positivist view of the natural sciences. With respect to the application of engineering, the rationalist view becomes more relevant. The non-engineering user typically relies on quite different world views: Playing with variations in meaning, understanding the concepts implicit in specific computer software entities, moving data between computer applications and transferring information between the computer system and the outside world requires abilities based in interpretivist or relativist views, like those engaged in the humanities and arts.

Unfortunately, the attempt of bridging these differences by replacing one view with another or by merging the different views will not be successful. The positivist/rationalist views have been adopted in science/engineering for good reason: They are those views best adapted for understanding nature/engineering. Merging interpretivist views with positivist/rationalist elements is also not a real option: World views are self-sufficient, they offer a complete set of beliefs, a framework for understanding any situation. They are built on basic ontological assumptions, and the assumptions from different views are in general mutually incompatible. Positivism assumes a pre-existing reality, and descriptions of this reality are assumed to be correct or incorrect depending on their match with this pre-existing reality. Relativism on the other hand is built on the assumption of subject-dependent correctness, with reality some sort of evolving agreement among groups of subjects. So engineer and user views are justified, necessary, self-sufficient, and mutually incompatible. At least in a pure scientific or philosophical sense. In a more general sense, they can be engaged in parallel, as a detailed analysis of the creative computer use criteria illustrates:

In IS behaviour criterion 1, the dominant world view is clearly interpretivist: Multiple views incorporating multiple forms of knowledge representation can be used without restriction, implying that the relationship between knowledge and knowledge representation is flexible as well. On the other hand, the computer is expected to somehow enable the switch from one type of knowledge representation to another, implying an objective way of translating between these representations, firmly grounded in positivist expectations. A similar interpretivist-rationalist contradiction is true for IS behaviour criterion 2: interpretivist freedom to mix and match tasks ad libidum is contrasted with the rationalist expectation of keeping individual tasks and knowledge interaction consistent. As a mirror image to the above, IS behaviour criterion 3 is primarily positivist, but with interpretivist undercurrents: exploring implications of existing knowledge representations and evaluating them implicitly assumes a positivist link between knowledge representations and knowledge, but dynamically including heterogeneous knowledge sources or new constraints implies interpretivist freedom in linking subjects, knowledge, and goals.

In summary, these criteria fall into two groups: positivist/rationalist expectations towards computer system performance, and relativist/interpretivist expectations towards the effect of computer performance on human abilities. A combined model of human-computer co-creativity will therefore have to be more "world view aware" than either a model of human or of computational creativity alone. And elements of such a model will inevitably motivate reconsidering both computing and creativity research. In computing, the added value of leaving room for user control, even for the price of reduced system reliability, would have to be concpetualised. Recent approaches like meta design (Fischer and Giaccardi 2004) already call for increased user "participation" in system "design". Eventually, such research directions would effect the theory of computation itself. Wegner (1997) already claims that the concept of algorithmic computing power has been over-applied in computing, and that interactive computing has superior qualities, even in terms of computing power as such. So the computing side will benefit by obtaining access to more subjectivist/relativist/interpretivist views, and the reverse is true for the creativity research side: acknowledging the objectivist/positivist/rationalist support role in shaping creative processes will enrich theories on human creativity as well.

6. Conclusion

Attempting to combine HCI research results with those based on computer engineering paradigms for a theory of HC 3D raises issues of world view dissonance between them. A complete model should incorporate the views of all contributing disciplines, so their particular bias and understanding has to be acknowledged. Creative design like all creative processes shows two at times conflicting properties: novelty and usefulness/reliability. The differences in how the scientific fields handle these two notions have direct and indirect repercussions on how results from these fields should be synthesised in a model of HC 3D.

The direct impact can be found in how the different approaches handle novelty or reliability in models of creativity or design: The particular bias of primary research has be offset in order to include them in a synthesis. The indirect impact can be found in their understanding of notions like knowledge: Understanding of the sources depends on re-interpreting their language and translating these notions into an intermediary language capable of supporting all these views. Overcoming these obstacles is challenging, but promises to yield added value not only for the task of understanding HC 3D, but also for the more general areas of computing and human creativity.

References

Brazier, F, Moshkina, L and Wijngaards, N: 2001, Knowledge level model of an individual designer agent in collaborative distributed design, *Artificial Intelligence in Engineering* **15**(2): 137–152.

Burghardt, MD: 1995, *Introduction to the Engineering Profession*, Addison Wesley, NY.

Candy, L and Edmonds, E: 1997, supporting the creative user: a criteria-based approach to interaction design, *Design Studies* **18**(2): 185–194.

Committee on Information Technology and Creativity: 2004. *Beyond Productivity: Information Technology, Innovation and Creativity*, National Academy Press.

Cropley, DH and Cropley, AJ: 2005. Engineering creativity: A systems concept of functional creativity, *in* JC Kaufman and J Baer (eds), *Faces of the Muse: How People Think, Work and Act Creatively in Diverse Domains*, Lawrence Erlbaum, Hillsdale, NJ, USA, pp. 169–185.

Engelbart, DC: 1962, *Augmenting Human Intellect: A Conceptual Framework*, Technical Report AFOSR-3233, Stanford Research Institute, Menlo Park, CA, USA.

Fischer, G and Giaccardi, E, 2004. Meta-design: A framework for the future of end user development, *Communications of the ACM* **47**(9):33–37.

Guilford, JP: 1950, Creativity. *American Psychologist* **5**: 444–454.

Haymaker, J, Fischer, M and Kunz, J: 2002, Perspectors: Inferring spatial relations from building models, *in* JS Gero (ed.), *Artificial Intelligence in Design 02*, Kluwer Academic Publisher, Dortrecht, NL, pp. 593–615.

Hewett, TT: 2005, Informing the design of computer-based environments to support creativity, *International Journal of Human-Computer Studies* **63**(4-5): 383–409.

Hoffmann, O, Cropley, D, Cropley, A, Nguyen, L and Swatman, P: 2005, Creativity, requirements, and perspectives. *Australasian Journal of Information Systems* **13**(1): 159–175.

Hoffmann, O, Stumptner, M and Chalabi, T: 2001, Tolerating inconsistencies: The distributed perspectives model, *in Computer-Aided Architectural Design Futures*, Kluwer Academic Publisher, Dortrecht, NL, pp. 375–386.

Lubart, T: 2005, How can computers be partners in the creative process: Classification and commentary on the Special Issue, *International Journal of Human-Computer Studies* **63**(4-5): 365–369.

Machado, P and Cardoso, A: 2002, All the truth About NEvAr, *Applied Intelligence* **16**(2): 101–118.

Mayer, RE: 1999, Fifty years of creativity research, *Handbook of Creativity,* Cambridge University Press, pp. 449–460.

Newell, A: 1982, The knowledge level, *Artificial Intelligence* **18**(1): 87–127.

Newell, A: 1993, Reflections on the knowledge level, *Artificial Intelligence* **59**(12): 31–38.

Popper, K: 1972, *Objective Knowledge: An Evolutionary Approach*, Oxford University Press, Oxford, UK.

Resnick: LB: 1987, *Education and Learning to Think*, National Academy Press, Washington, DC, USA.

Saunders, R: 2002, *Curious Design Agents and Artificial Creativity: A Synthetic Approach to the Study of Creative Behaviour,* PhD thesis, University of Sydney.

Searle, JR: 1980, Minds, brains and programs. *Behavioural and Brain Sciences* **3**(3):417–457.

Shannon, CE: 1948, A mathematical theory of communication*, Bell System Technical Journal* **27**: 379–423 and 623–656.

Shneiderman, B: 2002, Creativity support tools, *Communications of the ACM* **45**(10): 116–120.

Stamper, RK, 1993. Social norms in requirements analysis, *in* M Jirotka, J Goguen and M Bickerton (eds), *Requirements Engineering, Technical and Social Aspects,* Academic Press, NY, USA, pp. 107–139.

Suri, H: 2004, Synthesising research for diverse purposes: Moving beyond "What Works*?", Proceedings of the annual conference of the Australian Association for Research in Education*, Australian Association for Research in Education.

Tomiyama, T: 1994, From general design theory to knowledge-intensive engineering. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **8**(4): 319–333.

Wegner, P: 1997, Why interaction is more powerful than algorithms*, Communications of the ACM* **40**(5): 80 – 91.

KEYNOTE 2

Creativity•Rules

Terry Knight

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 155-174

CREATIVITY • RULES

TERRY KNIGHT
Massachusetts Institute of Technology, USA

Abstract. The creativity of a computational or generative design system is usually considered in terms of the ability of the system to enable creativity – either to simulate a creative process or to generate creative output. Here, a different perspective is adopted. The creativity of the system itself, as a designed artifact, is considered. Qualities of a system other than those to do with process or output are examined. These qualities point to an overlooked but important way in which creativity and computation intersect. Shape grammars are the focus of this study.

1. Introduction

Ideas about creativity, computation, and design have been juggled and related in a variety of ways. Here, I will consider creativity in relation to a particular kind of computational or generative design system called a shape grammar. Computational design systems are systems developed to create and explore ranges of design possibilities or solutions. They include, for example, cellular automata, genetic algorithms, shape grammars, and other types of grammars. Much of what is said here about shape grammars is not new, but is reframed in the context of creativity and creative design.

First, some prefatory remarks on the idea of creativity. Considerable effort has gone into defining creativity and to pinning down the nature of the creative process. A supposition motivating much of this work is that creativity is a cognitive or psychological function – a phenomenon rooted in individual human minds. I am skeptical of this supposition, and the idea that something called creativity even exists as an independent phenomenon to be studied. See Coyne, 1997 for a discussion of cognitive approaches to creativity. I will skip the cognitive view of creativity here, and approach creativity simply as a language term with meanings that are culturally constructed and that are context or situation dependent. In other words, I will treat "creativity" and "creative" just as words – a noun and an adjective. I will assume that we have some shared, culturally agreed upon understanding of these words, and will use other words to elaborate on their meanings.

2. Creativity and Shape Grammars

A commonly asked question about shape grammars is:

Can shape grammars be creative?

The usual interpretation of this question is:

Can shape grammars do creative design – can they replace or augment a creative human designer?

This is a question often asked of any computational design tool or system. It's a question about computation and creativity in general. It involves consideration of the processes or the products of a computational design system. For instance, it might involve looking at how the system generates or explores designs (see for examples, Gero and Kazakov 2000 and Boden 2004). It might involve looking at the output of the system, that is, whether it generates new, original designs.

I am interested here in a different interpretation of the question above which is:

Can shape grammars be creative as artifacts in their own right?

This question does not look at whether a grammatical process simulates a human creative process (for example, whether it transforms a conceptual design space as described by Boden 2004, pp.5-6), or whether the output of a grammar is creative. It looks instead at whether the grammar itself – as a designed thing – is creative. It considers qualities of a grammar (discussed below) other than those to do with process or products. These qualities point to an important but overlooked way that computational design can be creative. They suggest another dimension by which the creativity of a computational system can be evaluated.

3. How Can a Shape Grammar be Creative?

Shape grammars are algorithms. They are sets of rules, expressed graphically, that apply in a step-by-step way, called a computation, to generate designs. There may be choices of ways to apply rules which lead to different computations, which in turn may lead to different designs. To be judged as creative, shape grammars might at least need to satisfy criteria for "good" algorithms. These criteria usually include correctness of results, efficiency (or simplicity or performance), understandability, and elegance. With the possible exceptions of correctness and efficiency, these criteria are subjective and qualitative in relation to shape grammars. Still, it's possible to talk about the ways they are satisfied by a shape grammar. But they are not criteria associated with creative things generally. Perhaps they should be. It's hard to imagine an artifact judged as creative that is inefficient, overly complicated, abstruse, or awkward.

Beyond the attributes above, what might be expected of a shape grammar to count as creative? Algorithms are not usually judged in terms of their creativity. But shape grammars have to do with creative design, so it's reasonable to think of them as creative or not. So what might it mean for a shape grammar to be creative? Definitions of creativity use adjectives like "new, surprising, and valuable" (Boden 2004). Other adjectives like "original", "nonobvious", "interesting", and "purposeful" might do as well. However, it remains to be seen how a shape grammar can be new, surprising, and so on. I will propose an obvious way.

A shape grammar is creative if it has something new, surprising, etc. to say. To be more specific, a shape grammar is creative if it frames problems or questions, and suggests solutions or answers, that are new, surprising, and so on. A creative shape grammar often frames questions and answers about the geometries of the designs it generates. However, the questions and answers could go beyond compositional ones, and have to do with issues of function and structure, of context and history, or with computation, or even with concerns outside of design. Whatever they are, the questions may not be ones that are defined at the outset, but ones that emerge as a shape grammar is being developed or even after it is completed.

The notion of problem-framing as an aspect of creativity is not new. Earlier studies of creativity and of the design process have proposed that problem-framing is fundamental to creative design. For example, Getzel and Csikszentmihalyi correlated "problem-finding" behaviors as well as "problem-solving" behaviors with creative processes and products (Getzel and Csikszentmihalyi 1976). Schön is well known for stressing the importance of problem-setting in the design process (Schön 1990). Others have elaborated on these ideas (see, for example, Suwa, Gero, and Purcell 1999). However, most studies of creativity in relation to computation do not consider this aspect of creativity. They focus instead on the question above, with its general interpretation: Can a computational system do creative design?

Take, for instance, a work often used as a platform for speculations on computational creativity – Harold Cohen's computer program AARON (Cohen 1995). AARON generates representational drawings that include human figures and other objects. Discussions of AARON usually focus on the program's potential to be an autonomous, creative designer. Cohen is mostly concerned with developing code to generate particular results. The plausibility of the output is key. Whatever code works best is used. Human figures are drawn from the front plane to the back plane, from the feet up, and so on. Cohen does consider to some extent human art-making in his development of AARON, and reflects on the correspondence of his program to the history of art and art techniques (Cohen 2002). But the emphasis is not on what AARON's code asks and reveals about the drawings generated. The emphasis is not on AARON as a creative artifact in it's own right.

Here, shape grammars are looked at as creative artifacts. This is a telling exercise since shape grammars at their best are particularly vivid examples of creativity. At their best, shape grammars not only generate designs that are themselves considered creative (the objective of AARON and other generative design systems). The rules and computations of grammars also embody new, interesting design problems or questions together with possible answers or solutions. Further, the visual/ spatial representation of shape grammars allows for expressiveness – an understandability, simplicity, and elegance – not possible with other kinds of design algorithms or generative techniques.

4. Four Examples

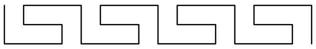
To demonstrate the idea of creative shape grammars, I will revisit four shape grammars. The grammars I've chosen are ones with which I am particularly familiar. Three are early grammars documented in the shape grammar literature; one is recent. They are: the grammars for ancient Greek meander designs (Knight 1994), the ice-ray grammar (Stiny 1977), the Palladian villa grammar (Stiny and Mitchell 1978), and a grammar for building screens or facades called the Subtle Grammar. All are two-dimensional grammars, but represent a range of types of shape grammars and designs. Two are for relatively simple, abstract designs, one is for more complex architectural plans, and one is for architectural elements within a larger project. Three grammars are analysis grammars, that is, grammars developed to describe designs that already exist; one grammar is an original grammar, that is, a grammar for creating new and original designs. Two grammars are for vernacular designs, one is for "high-style" designs, and one is for a student design project.

All four grammars satisfy easily the criteria given above for good algorithms. Beyond these criteria, each grammar also raises important and interesting questions about design and about computation.

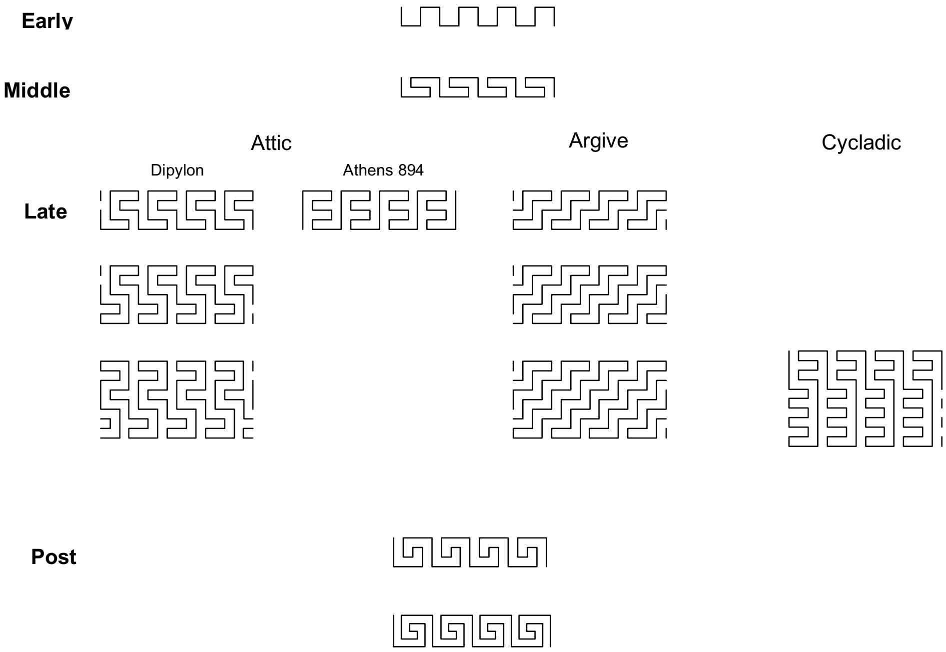
4.1. THE MEANDER GRAMMARS

The meander grammars are a set of grammars for meander designs on ancient Greek pottery from the Geometric period (900 BC-700 BC). Within this time period, meander designs vary chronologically (Early, Middle, and Late Geometric) and geographically (Attica and other regions). Within a geographic region, meander forms vary by individual painter or workshop. Historians and archeologists have used these variations, in part, to attribute pottery to particular times, places, and painters. However, descriptions of meander forms have been minimal and clumsy in comparison with the precision and style of the designs themselves.

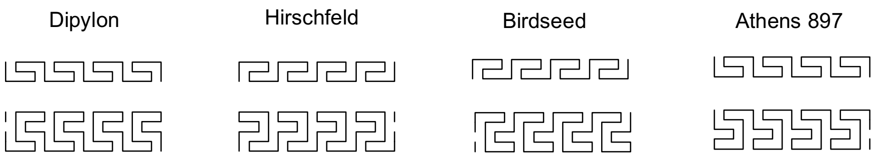
The most common meander form – one that is recognizable not only from Greek pottery but from works of other cultures and times – looks like this:



These are the main chronological and regional variations of the meander:



These are some workshop variations of meanders within the Attic region:



This is a Late Geometric vase with several different meander forms:

Several interesting questions are posed and answered by the meander grammars. Three are below. One question has to do with the designs themselves, one has to do with archeological evidence and notions of style, and one has to do with shape grammars generally:

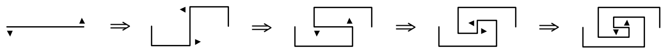
Question 1. How meaningful is the naming of these designs as "Geometric"? In particular, is this mathematical name relevant only to the surface appearance of designs (straight lines and simple shapes), or can it be extended to underlying principles and structure? Are the seemingly ad-hoc designs from different places and painters related in any fundamental way?

Question 2. Is it true that, in the words of a prominent researcher in the field, "linear design is not conducive to the expression of individuality"?

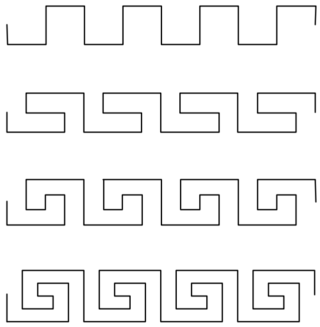
Question 3. Can a shape grammar discover, or recover, an actual design process?

Let's look at some excerpts (modified here for ease of presentation) from the grammars for answers – answers which are simple, but surprising and nonobvious. The grammars disclose very elementary formal principles such as recursion, repetition, and isometric transformations underlying all of the different meander variations. The basic rule for all meanders is perhaps the most obvious. It is a recursive, fractal-like rule for generating a meander motif, the repeating unit in all meander forms:

The rule replaces a line segment with an S-curve. Triangular labels identify the line that can be replaced. The rule applies recursively to generate increasingly complex meander motifs:

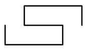


Motifs are repeated horizontally and vertically to produce continuous lines of meanders. A rule (not shown here) for horizontal repetitions of a motif generates these designs from the last four motifs above:



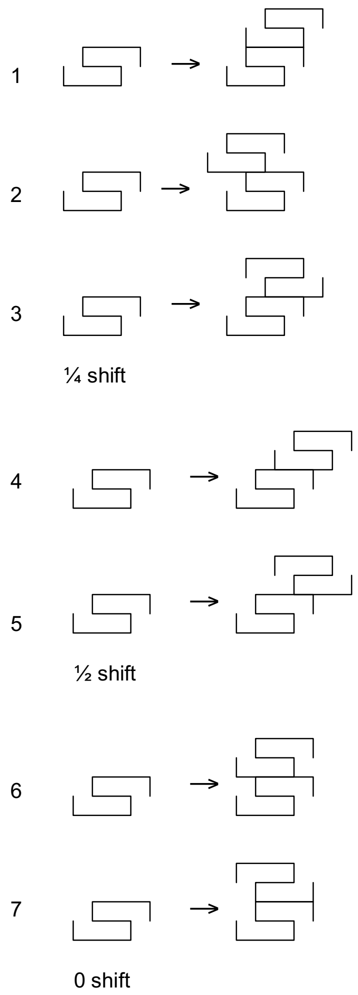
The first and second meanders are early and middle Geometric meanders. The third and forth meanders are more elaborate, post-Geometric meanders.

What happens in between the Early/Middle meanders and Post-Geometric meanders? In between are all the scribbly, more complicated, multi-story Late Geometric meanders. These are generated by repeating, vertically, rows of the most common meander motif:

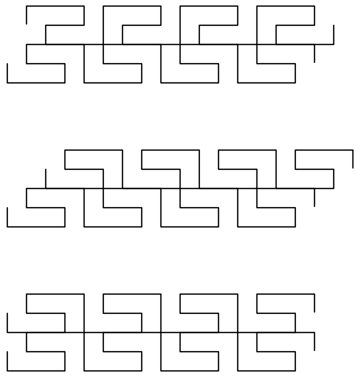


Each rule takes a motif and adds another motif above. The added motif may "run" in the same direction as the one underneath, or it may run in the opposite direction. In each rule, the added motif is translated or shifted to the right or to the left by a different amount – either 0, 1/4, or 1/2 the length of a motif. Different rules correspond to the different meander forms from different regions. Two of the rules (2 and 5) were not used, or at least there is no evidence of them being used.

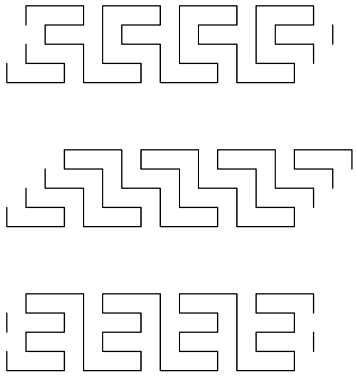
Here are the vertical repeat rules:



Together with the meander motif rule and the horizontal repeat rules described above, the vertical repeat rules generate designs like the ones below. Vertical repeat rules 3, 4, and 6 are used for the top, middle, and bottom designs, respectively.

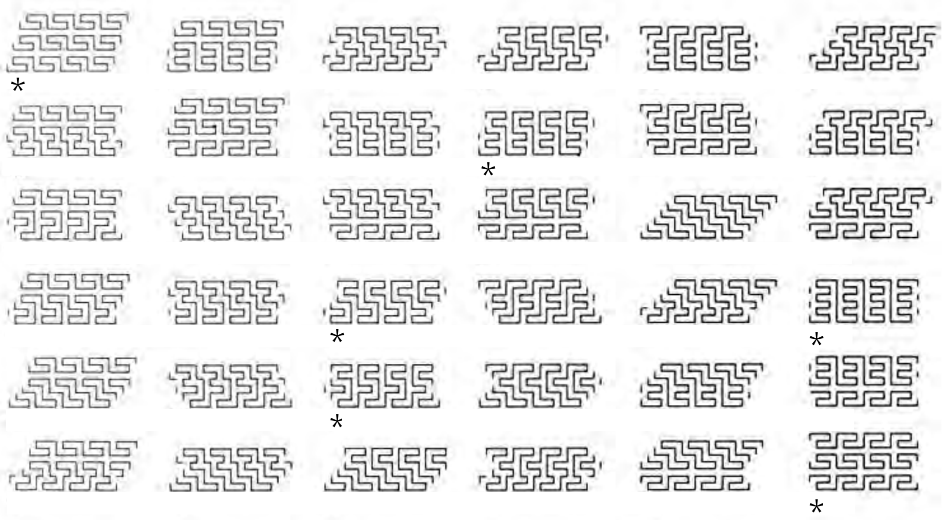


One simple step remains. Look carefully at the horizontal lines formed by the stacked rows of meanders in each design above. If line segments not shared by rows of meanders are erased, then continuous line, multi-story Late Geometric meanders are generated. Another simple rule, a subtraction rule (not shown here), applies to produce the designs below from the ones above:



Within a region, subtler variations of meanders exist. To distinguish their work, different painters within a region used different orientations of the same meander form. Different painters' meanders are simply vertical or horizontal reflections of one another (see the figure on page 5). These differences are expressed in specific workshop grammars by orienting the starting shape in each grammar in the appropriate way.

The meander grammars generate a host of new, hypothetical, possibly undiscovered meander variations in addition to extant ones. Below are all possibilities for 3-story meanders. Meanders known to have been used are marked with an asterisk. All others are new.



To return to the three questions above: The answers are straightforward because the grammars attend to the visual nature of the designs and the importance of seeing.

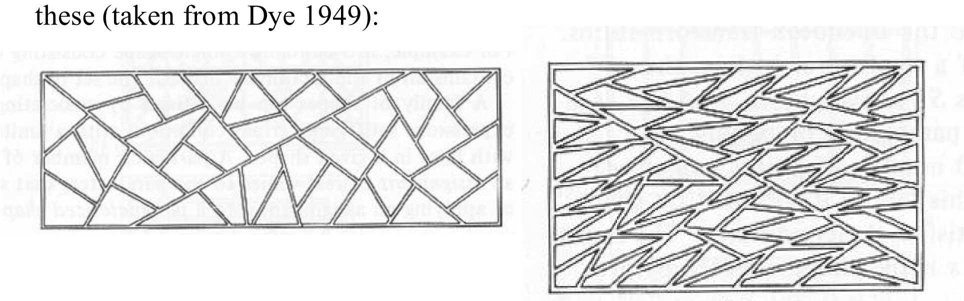
Answer 1. The grammars point out the very simple and elegant formal principles underlying and relating all of the different Geometric meanders. The complicated Late Geometric meanders are not random or adhoc, but are produced with definite rules. Different meander forms are related by subtle rule variations. The term "Geometric" is meaningful beyond surface appearance.

Answer 2. Historians and archeologists of the Geometric period (and perhaps in general) appear to be hampered by a prejudice that geometric design does not have the richness and variation of representational design. They have been blind to the visually sophisticated vernacular language with which Greek pottery painters across a wide stretch of time and space were conversant. The grammars demonstrate what they've been missing. Particular meander forms were not only region and time specific, but also specific to individual painters, and can be used to identify painters with as much certainty as a signature. Simple, linear, geometric designs can be important stylistic indicators.

Answer 3. Authors of analytic grammars usually make no claims that their grammars represent the actual design processes or thoughts of the original designers. In fact, it is impossible to make such claims even with the testimonies of the original designers who may not be aware of their own processes. However, some grammars are so simple and compelling that it is hard to imagine any other way that the original designs could be constructed. The Late Geometric meander grammars are a case in point. They appear to discover a design system used by ancient Greek painters. A key discovery is the erasing of non-overlapping lines to produce continuous line meanders. The grammars suggest a picture of pottery painters 3,000 years ago sketching out rows of meanders, and seeing what would happen when certain lines – emergent lines – are erased. Here is a compelling example from long ago of visual emergence and Schön's "reflection-in-action" (Schön 1990).

4.2. THE ICE-RAY GRAMMAR

The ice-ray grammar is a grammar for traditional Chinese lattice designs like these (taken from Dye 1949):



The designs are called "ice-rays" because they look like the lines formed by cracking ice.

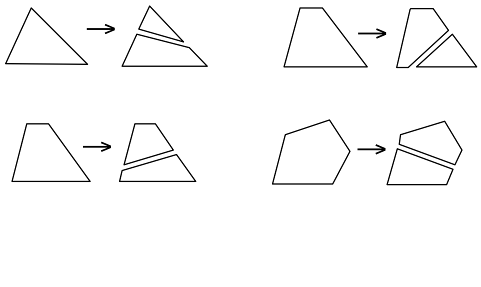
Some of the questions framed by the ice-ray grammar are similar to those framed by the meander grammars. Three are below. The first question pertains the designs themselves, the second has to do with real-world design processes, and the third has to do with computational design strategies.

Question 1. How meaningful is the naming of these designs as "ice-rays"? Are the designs like ice cracking – random, naturalistic, etc?

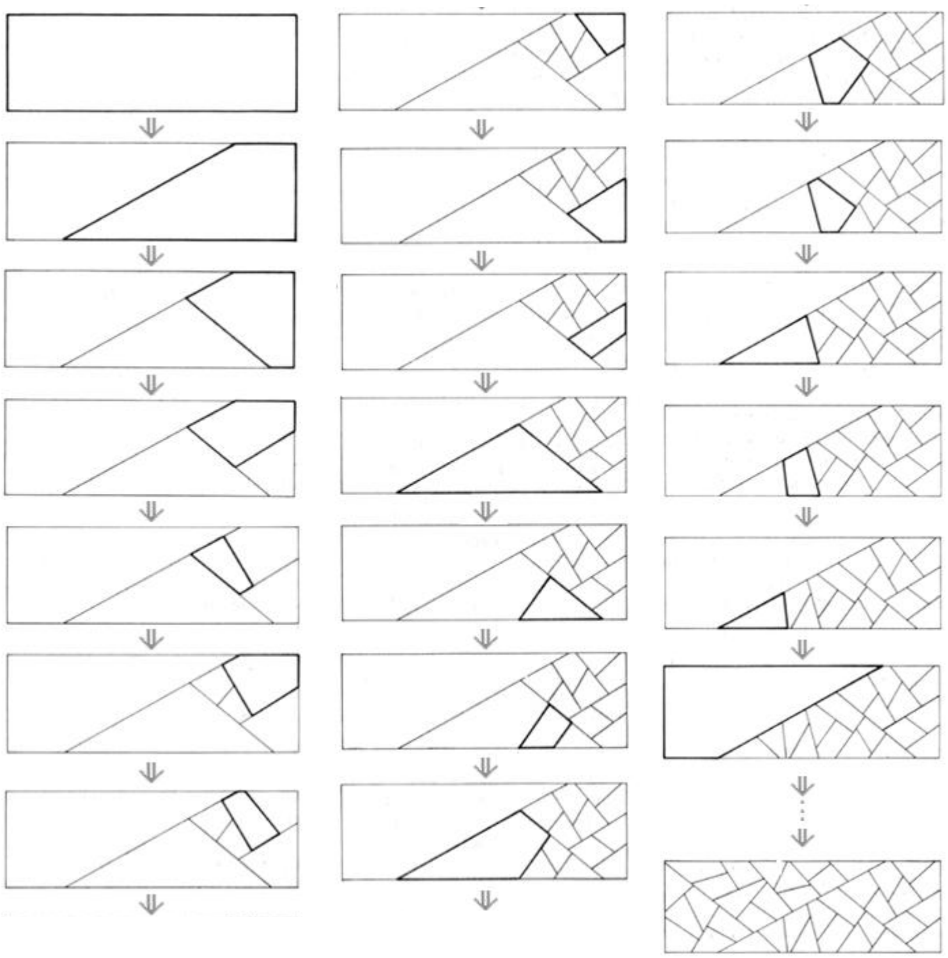
Question 2. Can a shape grammar discover (or recover) not only a schematic or conceptual design process, but also a construction process?

Question 3. Are the particular computational strategies of a shape grammar generalizable and relevant beyond the grammar itself?

Let's look at the grammar for answers. These are the rules:



The rules subdivide polygons – triangles, quadrilaterals, and pentagons – into smaller polygons. The rules are parametric. (Parameters are not shown here for simplicity of presentation.) They apply to polygons of varying dimensions and sizes to generate smaller polygons of varying dimensions and sizes. A computation of an ice-ray design looks like this:



Like the meander grammars, this grammar attends first and foremost to seeing and visual discrimination. Responses to the questions above flow from this visual bias.

Answer 1. The rules of the grammar selectively focus or defocus on particular lines from among the assortment of seemingly randomly placed lines in designs. They reveal an underlying structure with a nice balance of order and complexity, of systematicity and randomness. Like the meander motif rules, the ice-ray rules are fractal rules. They recursively subdivide polygons to generate designs with an underlying order. The parameterization or dimensional variations of the rules give the designs their random, naturalistic effect. Ice-ray designs are fractals, and are indeed similar to irregular or random natural, fractal phenomena, like cracking ice.

Answer 2. The meander grammars above suggest a vernacular, schematic design or sketching process. The ice-ray grammar suggests, or discovers, a vernacular construction process. As the author of the grammar, George Stiny writes (Stiny 1977):

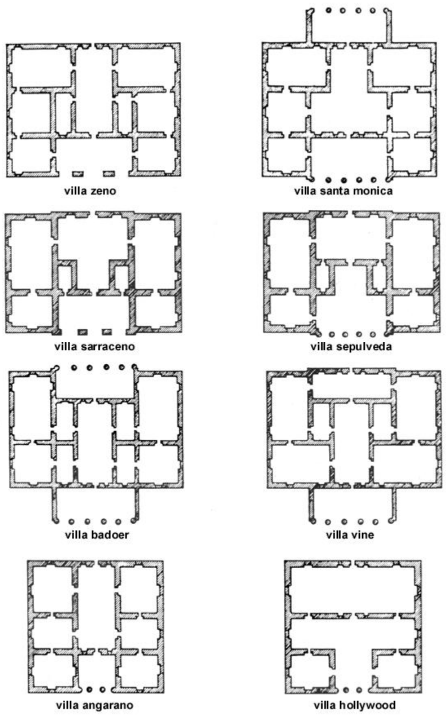
> *One can imagine a Chinese artisan, summoned to the building site, bringing with him tools and implements and a collection of finely finished sticks. Shown a rectangular window frame, he is asked to create an ice-ray lattice. He begins his design by selecting a stick of the appropriate length and carefully attaching it between two edges of the existing rectangular frame, thus forming two quadrilateral regions. He continues his work by subdividing one of these areas into a triangle and a pentagon … Each [further] subdivision is made in the same way: attach an appropriately sized stick between two edges of a previously constructed triangle or quadrilateral or pentagon so that it does not cross previously inserted pieces. Each stage of the construction is stable … Indeed, the steps in the ice-ray lattice generation … could well comprise the frames in a motion picture of the artisan creating his design!*

The ice-ray grammar shows that generative rules can be rules for construction, as well as rules for design.

Answer 3. The ice-ray grammar is a paradigmatic and seminal shape grammar on several counts. It has just a few rules with high explanatory value. It suggests a conceptual design, if not an actual construction process. It lays out fundamental design strategies that are emulated in later shape grammars as well as in other generative design tools. The ice-ray rules exemplify a top-down, recursive, subdivision process. They are the prototype for the rules of a number of subsequent grammars for designs of quite different kinds. These include the grammars for *de Stijl* paintings, Álvaro Siza's Malagueira houses, and the façade of Frank Gehry's Experience Museum project. The ice-ray rules are also an early example of parametric design, a concept that has been taken up in recent years with great interest in the development of architectural design software, and is used uniquely here in a rule-based context as well. The ice-ray grammar has had consequences well beyond the particulars of its rules and the designs it generates.

4.3. THE PALLADIAN GRAMMAR

The Palladian villa grammar generates the groundplans of villas from Palladio's *I Quattro Libri dell' Architettura* (Palladio 1965) as well as new, hypothetical villa plans in the same style. Here are some original plans (left column) and some new ones (right column):



Like the meander and ice-ray grammars, this grammar raises questions beyond the particulars of the designs generated. The Palladian grammar was the first shape grammar to look at architectural designs. Previous shape grammars focused on more abstract designs. The Palladian grammar was developed in large part to answer this question:

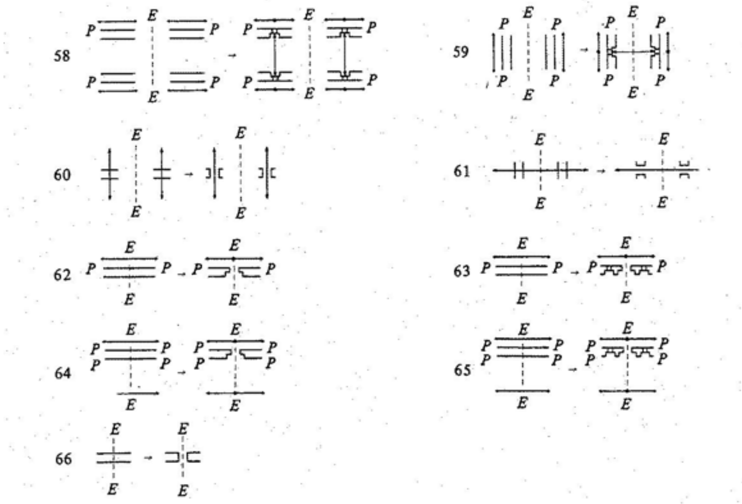
Question 1. Can a set of complex architectural designs – for example, the designs of a distinguished and influential architect like Palladio – be understood generatively or algorithmically?

Two subquestions follow:

Question 2. How would a generative definition of Palladian villas, or designs of comparable complexity, be approached, and

Question 3. What would be learned from it?

The grammar is too lengthy to show in its entirety. Here is a subset of the rules – ones for windows and doors.



Here are answers to the questions. Some are discussed explicitly by the authors of the grammar.

Answer 1. Palladio gives rules for architecture, including villa designs, in his Four Books. The rules are prescriptive, and are conveyed through words and illustrations. The aim of the shape grammar was, in the authors' words, "to recast parts of Palladio's architectural grammar in a modern, generative form". This aim was achieved with about seventy rules divided into several design stages. The grammar has been the basis for other generative studies of Palladio's villas, and the impetus for many other shape grammars for architectural designs. The first of its kind, it shows clearly and elegantly that is is possible to describe a complex design language computationally. It provides a strong 'proof-of-concept" of shape grammar theory.

Answer 2. The authors approached their task by attending to aspects of Palladio's designs they considered to be essential and ignoring others. Their attention was visual, but influenced by their knowledge of Palladio's and others' writings on the form, function, and history of the villa designs. The authors point out the subjectivity of their approach, that it is arbitrary in some respects. Different interpretations of the villas might lead to different grammars. This subjectivity is typical of any kind of compositional analysis. But it is novel in the domain of algorithms where output is generally not meant to be interpreted. The Palladian grammar was the first to suggest that the definition of algorithms – of formal, precise rules – in design is subjective, personal, and reflective of point of views and varying perspectives.

Answer 3. The implications of recasting Palladio's grammar in a "modern, generative form" are several, including the one discussed in Answer 2 above. Additionally:

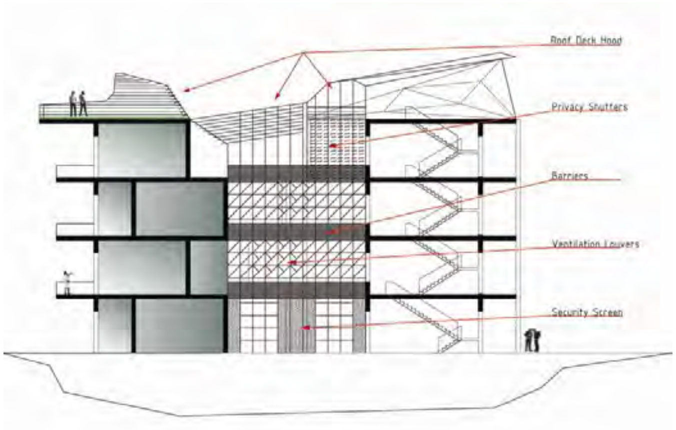
The Palladian grammar is too complex to correspond, at the level of individual rules, to an actual design process. However, it introduced the idea of stages in an algorithmic design process that correspond to stages in a real design process. In the Palladian grammar, the stages correspond to an intuitive, top-down process of progressive refinement and detailing. This strategy was taken up in subsequent shape grammars.

The Palladian grammar introduced a new paradigm for the characterization of "style". The authors spell out three criteria for a definition of a style: descriptive, analytic, and synthetic. A definition of a style should *describe* the underlying commonalities among works in a given corpus, it should provide criteria to *analyze* a work and determine if it belongs to the style, and it should provide mechanisms to *synthesize* new, hypothetical instances of the style. The last criterion is the most novel, and is possible only with a generative description of a style. All three criteria are illustrated well by the Palladian grammar.

Last, the Palladian grammar showed that the value of a shape grammar analysis can extend beyond an understanding of form and composition. A shape grammar can provide a critical foundation for addressing noncompositional issues. Shape rules can be linked to other, nongeometric descriptions. In the Palladian grammar, the explicit characterization of plan geometry in rules can be tied directly to aesthetic, historical, and other concerns. Questions such as "How deep (or superficial) was Lord Burlington's appreciation of his mentor's system of design?" can be answered (Stiny and Mitchell 1978).

4.4 THE SUBTLE GRAMMAR

Unlike the three grammars above, this grammar was developed to explore new and original designs, not to understand existing designs. It was developed by an MIT graduate student, Daniel Bonham, as part of a larger studio design project. The grammar was Bonham's first attempt at developing a grammar for design, and was very much a beginner's experiment. The studio project was for a dense urban housing development in the Colon neighborhood of Habana, Cuba. The grammar was developed to explore variations of structural grids or screens to provide shade, security, ventilation, privacy, and safety barriers on the façade and interior of the building complex. Here is a vertical section through the building showing locations of screens:



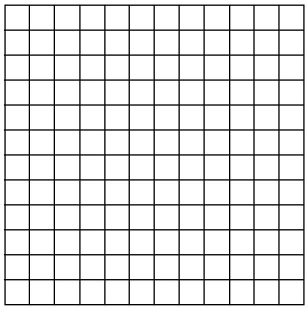
Bonham named his grammar the Subtle Grammar. The grammar is recent, so it can't be viewed with the same retrospective eye as the three grammars above. It may not have the long-term, broad implications of those grammars. However, it's an excellent example of a simple, design-focused grammar that, on public showing, evoked the kinds of responses creative things often evoke: surprise, awe, and interest.

The grammar frames this question:

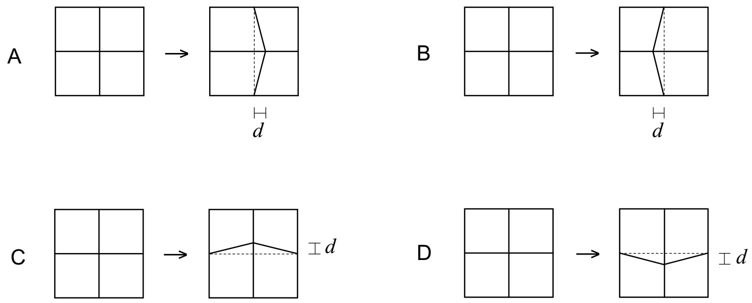
How can a simple design idea be elaborated into more sophisticated and appropriate design possibilities? In particular, how can this be accomplished generatively?

This question is not unusual within the domain of generative design. It's a question frequently asked of, and by, design students new to computation. But it's important, new, and interesting to each student as it is asked anew. Good responses give new meaning to the question. In this case, the strong response makes the question all the more compelling.

Bonham's initial design idea was a 2-dimensional grid of squares – a simple, regular kind of screen:



His thought was to deform the regular grid in some subtle but systematic way to create irregular grids. Here is his solution, the four rules of the Subtle Grammar:



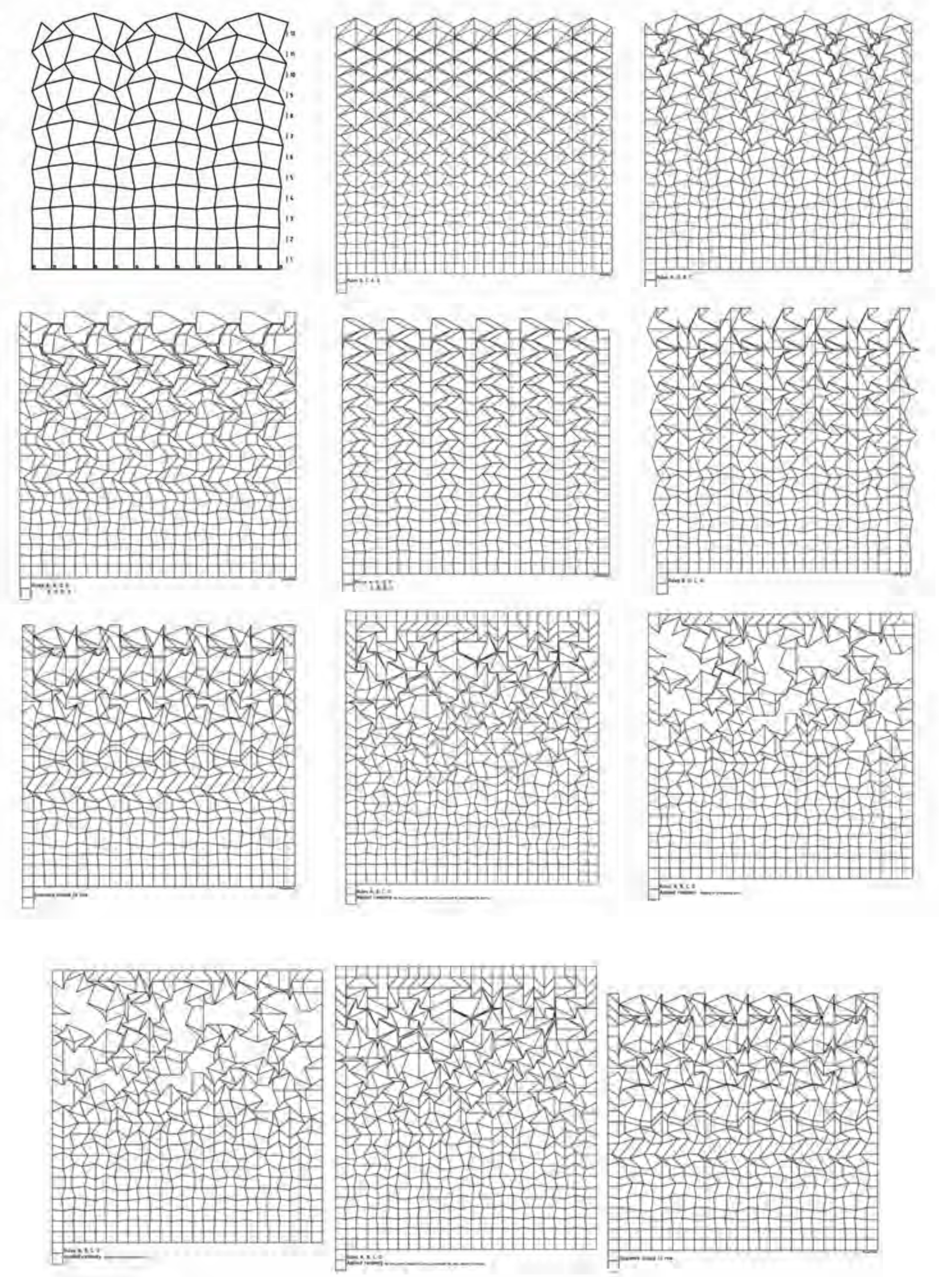
The rules tweak the intersection points in the grid. They are parametric rules. Each rule offsets an intersection point by some distance *d*, either to the right, to the left, above, or below the intersection point. The rules are applied in parallel, or simultaneously, to every intersection point in the initial grid. Different rules can be applied to different intersection points. The choice of a rule for each intersection point, and the assignment of a value for *d* in that rule, lead to a great variety of design possibilities.

Bonham chose to explore a small subset of these possibilities by applying his rules in particular ways. Within each row, rules are applied in a fixed, repeating pattern – for example, ADBC, ADBC, ... The value of *d* is fixed within a row, and is a function of the position of the row within the grid. Starting with the bottom row, the value of *d* increases in some predetermined way with each successive row. Some results of different rule sequences or patterns are shown below. An additional rule is used in the generation of the last design. It removes grid cells with intersecting lines.

The Subtle Grammar certainly satisfies all the criteria for a "good" algorithm. It's efficient, understandable, elegant, and produces the desired results. More importantly, it answers well the question above. The grammar is a succinct demonstration of the power of generative systems, in particular, the power of "local" rules to generate designs with unanticipated global properties. The rules are simple and embody a subtle design gesture. The starting point is simple. Applying the rules to the starting point leads to complex, unpredictable, and diverse results.

5. Discussion

Computational design can be creative in multiple ways. Usually, creativity is understood to inhere in the designs generated or in the process used to create them. Here, creativity is considered with respect to the computational tool or algorithm itself, with special attention to the originality and substance of the problems it raises and the answers it suggests. Shape grammars may have an edge here over other kinds of generative design techniques.



Shape grammars were developed in the tradition of earlier generative grammars to be explanatory, to give insights into the designs they generate.

The rules of shape grammars are meant to be "smart rules". They are meant to have something to say. The pictorial representation of shape rules endows them with an expressiveness and transparency that provide opportunities for the kind of creativity described here.

This does not mean that other computational systems cannot be creative in the ways that shape grammars can be creative. Many are. But most often when a system is evaluated in its own right, it is evaluated in terms of effectiveness, simplicity, and other attributes of algorithms, or in terms of the inventiveness of its underlying technical mechanisms. Conversely, not all shape grammars are creative, or even need to be creative. Many just get the job done, that is, generate the desired results. But when a shape grammar has something to say, not just something to do, it can reveal much more about creativity and computation.

References

Boden, MA: 2004, *The Creative Mind: Myths and Mechanisms*, 2nd edition, Routledge, London and New York.

Cohen, H: 1995, The further exploits of AARON painter, *in* S Franchi and G Guzeldere (eds), *Constructions of the Mind: Artificial Intelligence and the Humanities*; special edition of *Stanford Humanities Review* **4**(2): 141-160.

Cohen, H: 2002, A self-defining game for one player: On the nature of creativity and the possibility of creative computer programs, *Leonardo* **35**(1): 59-64.

Coyne, R: 1997, Creativity as Commonplace, *Design Studies* **18**: 135-141.

Dye, DS: 1949, *A Grammar of Chinese Lattice*, Harvard University Press, Cambridge, MA.

Gero, JS: 1996, Creativity, emergence and evolution in design: concepts and framework, *Knowledge-Based Systems* **9**(7): 435-448.

Gero, JS and Kazakov, V: 2000, Adaptive enlargement of state spaces in evolutionary designing, *Artificial Intelligence in Engineering Design, Analysis, and Manufacturing* **14**: 31–38.

Getzel, JW and Csikszentmihalyi, M: 1976, *The Creative Vision: A Longitudinal Study of Problem Finding in Art*, John Wiley and Sons, New York, pp. 77-106.

Knight, TW: 1994, *Transformations in Design*, Cambridge University Press, Cambridge, pp. 111-167.

Palladio, A: 1965, The Four Books of Architecture, Dover, New York; reprinted form the 1738 translation by Isaac Ware of *I Quattro Libri dell' Architecttura.*

Schön, DA: 1990, *Educating the Reflective Practitioner*, Jossey-Bass, San Francisco, pp. 3-7.

Stiny, G: 1977, Ice-ray: a note on the generation of Chinese lattice designs, *Environment and Planning B* **4**: 89-98.

Stiny G and Mitchell WJ: 1978, The Palladian grammar, *Environment and Planning B* **5**: 5-18.

Suwa, M, Gero, JS. and Purcell, T: 1999, Unexpected discoveries and s-inventions of design requirements: A key to creative designs, *in* JS Gero and ML Maher (eds), *Computational Models of Creative Design IV,* Key Centre of Design Computing and Cognition, University of Sydney, Sydney, Australia, pp. 297-320.

MODELS OF CREATIVE PROCESSES

Primitives and principles of synthetic process for creative design
Toshiharu Taura and Yukari Nagai

Cue-based memory probing in idea generation
Matti Perttula and Lassi Liikkanen

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 177-194

PRIMITIVES AND PRINCIPLES OF SYNTHETIC PROCESS FOR CREATIVE DESIGN

Taxonomical relation and thematic relation

TOSHIHARU TAURA
Kobe University, Japan

and

YUKARI NAGAI
Japan Advanced Institute of Science and Technology, Japan

Abstract. Although many studies have revealed that synthesizing two concepts is the key to creative design, these concept-synthesizing processes have not been systematized, and the kind of primitives and how these primitives are related to creativity have not been clarified. In order to gain a deeper understanding of the nature of creative design and to develop methodologies for creative design, primitive processes for synthesis should be determined. We describe two topics of design study. First, the concept-synthesizing process (combining, blending, and integrating) is systematized from the viewpoint of creativity. Second, the relationships between creativity and design primitive processes, focusing particularly on the relationship types - taxonomical relation or thematic relation - are empirically studied. The 1st primitive of the concept-synthesizing process is ‘concept abstraction,’ and its principle is ‘similarity’ in ‘taxonomical relations’. The 2nd primitive of the concept-synthesizing process is ‘concept blending,’ where the principle is ‘similarity’ or ‘dissimilarity’ in ‘taxonomical relations’. The 3rd primitive of the concept-synthesizing process is ‘concept integration,’ and its principle is ‘thematic relations’. We conducted a design experiment to examine the relationships between higher creativity and the primitives of the concept-synthesizing process. The design task was to form a new concept by synthesizing two concepts. The design process was analyzed focusing on the extension of idea space and factors of extension. Protocol analysis was adopted to investigate what type of relation was effective in the design process. We present the results indicating that the thematic relation driven by the 3rd principle of concept integration process has an effect on higher creativity in design through the extension of idea space.

1. Introduction

Many studies have been conducted to analyze the characteristics of the design thought process from the viewpoint of creativity. As a result, it has been found that concept-synthesizing processes, such as combining, blending or integrating two different concepts, are keys to creative thinking. Analogical reasoning and metaphor are known to play very important roles in creative design (Gero and Maher 1991; Goldschmidt 2001). For example, the 'Swan chair', a famous example of design, was imaged using analogy. Its form resembles a swan, and users understand its message of 'this chair is soft and elegant like a swan'. Figure 1 shows some examples of design analogy (Swan chair 1958; Mushroom stool 2003; Easy chair 2000; Living Design Club 2004). Chairs designed using analogical reasoning resemble a swan, a mushroom and a helicopter. Figure 2 shows a sample of a product designed using metaphor. Its message is that 'this is a new object that will induce mellow feelings in your daily life' (Hayashi 2002).

From the viewpoint of mental cognition in the domain of cognitive science, Finke et al. (1992) described conceptual synthesis as an efficient means of developing creative insights into new inventions, and carried out experiments on creation as mental products generated by imagery synthesis. To support human creativity, it has been pointed out that it is significant to develop creative thinking that is related to the transforming of concepts (Boden 2004) and this is comprehended as conceptual spaces (Gardenfors 2000). On the other hand, in studies on cognitive linguistics, Fauconnier (1994) focused on the construction process of meaning in ordinary discourse. He analyzed how conceptual integration creates mental products and how to deploy systems of mapping and blending between mental spaces. From the viewpoint of mental space theory, he showed that conceptual integration operates on two input mental spaces to yield a third space which is called 'the blend'. That blended space inherits partial structures from the input spaces and has emergent structures of its own. Both mental products, imagery and discourse, have shown emergent features and they have stimulated creativity. Fauconnier and Turner (2002) suggested that the design of a watch is an example of conceptual blending.

Although it has been pointed out in many studies that synthesizing two concepts is the key to creative design, the concept-synthesizing processes have not yet been systematized, and the kind of primitives and how these primitives are related to creativity have not been clarified. In order to gain a deeper understanding of the nature of creative design and to develop methodologies for creative design, we believe that primitive processes for synthesis should be determined. We hypothesize that primitive processes are useful for explaining the creativity in design rather than a general process model, in which only the superficial design action is generalized and the hidden thought mechanism is not dealt with.

Normally, an 'abstraction process' based on a 'taxonomical relation' has been regarded as a primitive process in creating a new concept. In addition, another important process for recognizing two concepts is pointed out. It is called the integrating process, in which two concepts are related thematically. For example, from the two concepts, milk and cow, a scene of milking a cow can arise from the thematic relating process. This process is expected to be effective for creative design. However, how the thematic relation is effective for design creativity has not been clarified.

In this paper, we describe two topics. First, the concept-synthesizing process (combining, blending, and integrating) is systematized from the viewpoint of creativity. Second, the relationships between creativity and design primitive processes, focusing particularly on the relation types-taxonomical relation or thematic relation - are empirically studied.

Figure 1. Swan Chair (left), Mushroom stool (center) and Easy Chair (right)

Figure 2. 'Sound Object' designed by Anna Von Schewen (2002)

2. Systematization of synthesizing process

2.1. CONCEPT ABSTRACTION

Analogical reasoning and metaphor are understood to be methods of concept creation via the transfer of a new concept from an existing concept. In practice, they are frequently used in the design process. For example, `designing a musical instrument like a dress' is one way of creating a new concept of a musical instrument. We can imagine many new instruments in this way by using metaphors, for example, 'an instrument like a harp', Figure 3. In this thought process, the design result (a musical instrument) is such that it and a dress share some common features, such as shape and function. Generally speaking, the primitive process of recognizing common features is the 'abstraction process' based on 'taxonomical relation (explained in 2.3)' focusing on the 'similarity' between two things. Therefore, the 1st primitive of the concept-synthesizing process is 'concept abstraction,' and its principle is 'similarity' in 'taxonomical relations.'

Figure 3. An idea designed by using metaphor

2.2. CONCEPT BLENDING

Although we recognize that analogical reasoning and metaphor are powerful for generating a new concept, we suspect that there is a more creative design method because the main roles of analogical reasoning and metaphor are to understand or to transfer a known concept; that is, it is analytic rather than synthetic since its primitive process is the extraction of some features from a known concept by analyzing it.

We can think of a concept-blending process as that in which two basic concepts are blended at an abstract level and a new concept that inherits some abstract features of the two base concepts but concrete features of neither is generated. For example, 'design something by combining the concepts of a musical instrument and a dress,' where the design result could be a guitar, the outside and sound of which can be changed to suit the surroundings like changing a dress, or a melody costume, that is, a wearable musical instrument. Another example is a wine glass which induces melody by blending the concept of a party and that of strings, Figure 4. This concept-blending process seems to be similar to analogical reasoning or the metaphor process. However, these two processes are different in the following points. In the case of analogical reasoning, the harp, a musical instrument, is predicted to induce dressy feelings of elegance and distinction. Therefore, the harp is a medium and the dress is an intention similar to a relationship between sign and meaning in semiotic relations. Also, in the metaphor process, a musical instrument, as a medium to express the meaning of dress, again has the role of a sign. In both cases, the roles are the same. In contrast, the relationship between a musical instrument and a dress in the concept-blending process is different. One does not express the other. The new concept is not just the medium of an instrument nor is it a dress. It has no strong association with the two base concepts. Therefore, it presents a high possibility of creating a novel concept. In the concept-blending process, not only 'similarity' but also 'dissimilarity' is pointed out, since the specific features belonging to each individual concept are blended. Therefore, the 2nd primitive of the concept-synthesizing process is 'concept blending' and its principle is 'similarity' and 'dissimilarity' in 'taxonomical relations.'

Figure 4. An idea designed by concept blending

2.3. CONCEPT INTEGRATION

In the research on recognizing the relation between two concepts, it is pointed out that there are two kinds of relations (taxonomical relation and thematic relation) between two concepts. Wisniewski and Bassok (1999) studied the relative tendency to use comparison versus integration in making similarity judgments by orthogonally varying pairs of objects so as to be taxonomically or functionally related. As a result, it was shown that not only a taxonomical relation but also a thematic relation is important in recognizing the two objects. The former is a relation that represents the physical resemblance between the two objects, for example, "milk and coffee are drinks." The later is a relation that represents the relation between two concepts through a thematic scene. For example, a scene of milking a cow is recollected from the two concepts of milk and cow. In such a sense, milk and cow are related to each other. In this kind of thematic relation, a dress is not physically related to a musical instrument but people can imagine a scene in which a dressy lady plays the violin, for example.

In design, the result (product) must be meaningful to people. Therefore, the designer must carefully consider not only its attributes (shape, material, etc.) but also its function and interface with the user, that is, consideration of the human factor is important. Recognizing objects in a thematic relation is to recognize them from the human viewpoint. Consequently, the thematic relation is expected to be closely related to design creativity.

Therefore, the 3rd primitive of the concept-synthesizing process is ‘concept integration’ and its principle is ‘thematic relations.’

The above ideas are summarized in Table 1.

TABLE 1. Systematization of design process primitives and principles

	Design Process Primitive	Principle
1st	Concept Abstraction	taxonomical relation (similarity)
2nd	Concept Blending	taxonomical relation (similarity and dissimilarity)
3rd	Concept Integration	thematic relation

3. How design principle affects design creativity

How the design principle (taxonomical relation or thematic relation) affects the design creativity is clarified using both the design results and the thought process, focusing on the extension of idea space.

3.1. METHODS

In this research, a design experiment is performed, and not only the design results but also the thought process are analyzed. In particular, the difference between design spaces in the concept-synthesizing process focusing on the extension of idea space of the subjects and the effect of the difference in the relationships (in taxonomical relations for the 1st and 2nd primitives, or in thematic relations for the 3rd primitive) on creativity is analyzed in this study.

3.2 ANALYSIS OF DESIGN PROCESS

In this research, protocol analysis is adopted for gathering utterances as protocol data for designing. In this method, the subjects are requested to vocalize what they are thinking while performing a task. The utterances are recorded and the data are analyzed. In order to identify which relationship between two concepts the subject considered, the reason behind the design idea was examined. However, it is difficult to obtain data on such reasons, because the subjects do not always state the reasons behind their thinking. Therefore, in this research, the method of protocol analysis based on the explanation of design activities is adopted (Taura et al. 2002).

3.3 CREATIVITY EVALUATION OF DESIGN RESULT

The design results are evaluated based on the method of Finke et al. (1992), that is, from the two viewpoints of practicality and originality, on a five-point scale.

3.4 METHOD OF THE EXPERIMENT

In this research, the design experiment is conducted to examine the extension of the idea space that occurs through design space blending (Taura et al., 2005). The experiment is composed of two parts, the design session and the interview session.

3.4.1 Design task

The subjects were each asked to perform two kinds of design tasks at random. Base concepts were selected based on the research of Wisniewski and Bassok (1999).

・Task A: Design new furniture starting from the word “Cat-hamster”

・Task B: Design new furniture starting from the word “Cat-fish”

The reason for showing the synthesized word as “Cat-hamster” and “Cat-fish” is that the subject will be able to understand the idea of “conceptual blending” easily (Harakawa et al. 2005).

3.4.2 Method of experiment

1) Design session (10 minutes)

The subject is made to perform the design task by the think-aloud method, and the utterances and the sketch are recorded with a tape recorder and a video camera. The purpose of this session is to obtain the protocol data and the sketch.

2) Interview session (30 minutes)

The subject is asked to explain the reason for each design activity while playing the video recorded during the design session. The purpose of this session is to determine why a new concept was generated (where it came from).

3) Creativity evaluation

The design results are evaluated based on the two viewpoints of practicality and originality on a five-point scale. Only the designs with more than 3 practicality points are evaluated from the viewpoint of originality.

3.5 RESULT OF DESIGN EXPERIMENT

The design experiment was conducted with three subjects. A total of fifteen design ideas were presented (eight as the design results of task A, and seven as the design results of task B). Because the subjects were not experienced designers, creativity was evaluated on the basis of the design concept. The experimenter made design concept summaries on the basis of the design idea and the interview of the subject. The fifteen design concepts in the two tasks (A1-A8, B1-B7) are shown below as the design results.

- *Task A: Design new furniture starting from the term “Cat-hamster”*

Design result 1 (Design concept A1)
‘A wardrobe with pet rooms’
There are rooms for the cat and hamster in the lower drawers of the wardrobe. When the higher drawer is opened, the cat’s meow is heard. When the second drawer is opened, the hamster begins to play.

Design result 2 (Design concept A2)
'A wardrobe shape like a cat'
The wardrobe can move like a cat. The person orders the hamster to bring a suit. The hamster touches the cat's tail, and then the cat delivers the suit.

Design result 3 (Design concept A3)
'Traveling bag that cares for the pet during travel'
A panel is attached on the side, and an image of the pet is displayed when the panel is opened. Some buttons on the panel enable food to be given to the pet or the pet to be fondled.

Design result 4 (Design concept A4)
'Chest of drawers-ball'
This chest of drawers is ball-shaped and it moves continuously. It can enter narrow spaces. Because it is a ball that moves about freely, the chest of drawers can be repositioned easily.

Design result 5 (Design concept A5)
'Desk-chair'
This chair is like a desk. In a word, it is the size of a desk although its appearance is that of a chair. We use it as a chair.

Design result 6 (Design concept A6)
'Chair that can be folded like an umbrella'
A chair that can be folded by the mechanism of a folding umbrella can be stored in a narrow space. It is possible to store it in an underground compartment after use.

Design result 7 (Design concept A7)
'Chair which runs about trying to escape'
This chair runs away when a desk approaches. It resembles a rat being chased by a cat.

Design result 8 (Design concept A8)
'A revolving shoebox'
This rotary shoebox is doughnut-shaped and the size of a person. It rotates when the user stands in front of it, and shoes can be chosen. It is easy to choose shoes appropriate for the outfit because the section for the feet is transparent.

- *Task B: Design new furniture starting from the word "Cat-fish"*

Design result 9 (Design concept B1)
'A sideboard with a monitor'
Usually an image of fish in an aquarium is displayed on the monitor. However, it is also a television that can be operated by remote control. The monitor is at eye level when the viewer is sitting on a chair.

Design result 10 (Design concept B2)
'A case for marine sports'
It has a heater so items such as a wet suit can be dried. Part of the case is a water tank in which fish can be kept.

Design result 11 (Design concept B3)
'Water tank with casters'
There are legs like those of a chair attached to the bottom of the water tank. Because they have casters, it is possible to move the tank easily.

Design result 12 (Design concept B4)
'A coat hanger that refuses to hang clothes'
This coat hanger will not hang clothes. The clothes will be dropped when hung on this hanger.

Design result 13 (Design concept B5)
'Chest of drawers inside itself'
This is a nested chest of drawers behind a door. There are more drawers inside the drawers.

Design result 14 (Design concept B6)
'Water tank table'
This is a table of a hollow structure made of glass. It is possible to store water inside it like a water tank. Fish appear to be swimming in the table.

Design result 15 (Design concept B7)
'Sea cushion'
This cushion can float in the sea. It is possible to sit and to sleep on it. It is possible to join many of them to form a lounger.

3.6 CREATIVITY EVALUATION OF DESIGN RESULT

The design results (design concepts) are evaluated on the basis of the two viewpoints of practicality and originality, on a five-point scale by 8 people (4 of them are experienced in design). Table 2 shows the average rating for each design concept.

According to the judging standard, the practicality ratings of A1, A2, A4, A7, B4 and B5 are less than 3 points, whereas A3, A5, A6, A8, B1, B2, B3, B6 and B7 satisfy the required practicality score. Originality is high in the order of A6, A8, B2, B6, B7, A3, B1, A5 and B3 (bold face type). As a result, it can be said that there is no difference between design tasks A and B. It is said that creativity is also high in that order. Therefore the highest creativity is shown by A6, and these nine ideas (A6, A8, B2, B6, B7, A3, B1, A5 and B3) are judged to be creative design ideas.

TABLE 2. Creativity evaluation

Concept No.	A1	A2	A3	A4	A5	A6	A7	A8
Practicality	2.250	2.175	3.750	2.625	3.000	4.125	2.000	3.000
originality	2.625	3.000	2.875	3.625	2.375	3.875	3.000	3.625

Concept No.	B1	B2	B3	B4	B5	B6	B7
Practicality	4.250	3.750	4.125	1.500	2.750	4.250	4.125
originality	2.625	3.500	2.000	2.875	2.625	3.000	3.000

3.7 EXTENSION OF IDEA SPACE

To identify the extension of idea space, new nouns have been extracted from the utterances recorded during the design task and in the interview by the protocol analysis. There are many new nouns in the nine creative design ideas selected (A6, A8, B2, B6, B7, A3, B1, A5 and B3), as shown in Table 3. This result reveals that there is a relationship between the number of new nouns and high creativity (A3, A8, B1, B2, B6 and B7).

TABLE 3. The numbers of new nouns

	A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	B6	B7
New nouns	6	5	12	5	5	7	3	11	13	11	5	7	5	9	21

Next, focusing attention on the distance between concepts, we examine the relationship between the new nouns arising during the experiment and the terms Cat, Hamster, Fish and Furniture. The distance of the new nouns from Cat, Hamster (Fish) and Furniture are measured using the concept dictionary (EDR electric dictionary 2005). The scatter charts are shown in Figures 5. A6 shows the highest creativity, and A5, B3 are two of the lowest creativity results. The abscissa indicates the distance from Cat or Hamster. The ordinate indicates the distance from Furniture. It is understood from the scatter chart that A6, A8, B2, A3, B6, B7, A3, A5 and B3 are evaluated to have high creativity since many new nouns are concentrated away from the two axes.

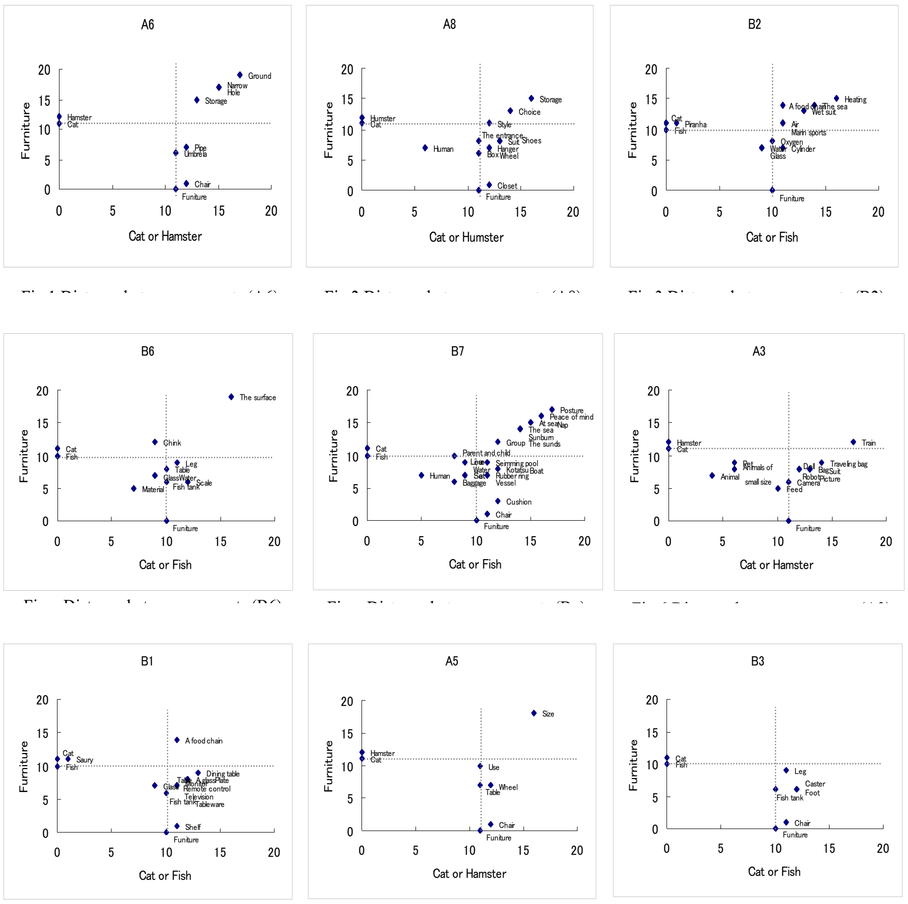


Figure 5. Distance between concepts on nine creative design ideas (A6,A8, B2, B6, B7, A3, B1, A5 and B3)

We examine the extension of idea space on the basis of distance between the concepts. The extension of idea space is defined as follows.

If $n\ (x_1, y_2)$ is a new noun in design result D,

then $\sum_{i=N}^{N} \frac{\sqrt{x_i^2 + y_i^2}}{N}$ (N = number of new nouns)

is the extension of idea space.

TABLE 4. Relationship between creativity and extension of idea space

Concept	A6	A8	B2	B6	B7	A3	B1	A5	B3
Creativity	3.875	3.625	3.500	3.000	3.000	2.875	2.625	2.375	2.000
Extension	16.32	14.07	14.27	12.86	14.83	13.25	12.74	13.99	12.43

Table 4 shows the relationship between creativity and extension of idea space for each of the nine creative design ideas.

Table 5 shows the mean and the standard deviation of creativity and the extension of idea space. Figure 6 shows the scatter chart. The correlation coefficient ρ is 0.73087 ($F(1, 7) = 8.02713$, $p < .05$), and it is significant. It is understood that there is a strong correlation between creativity and the extension of idea space. This demonstrates that there is a strong correlation between the extension of design space and design results with high creativity.

TABLE 5. Standard deviation of creativity and the extension of idea space.

	Creativity	Extension of idea space
—	2.986	13.862
SD	0.573	1.148

3.8 FACTORS FOR THE EXTENSION OF IDEA SPACE

The nouns that have the farthest distance from the axes were examined to determine what was associated with these nouns. In the analysis of the protocol data, we examined the design activities for clues on the design process up to the time of noun utterance.

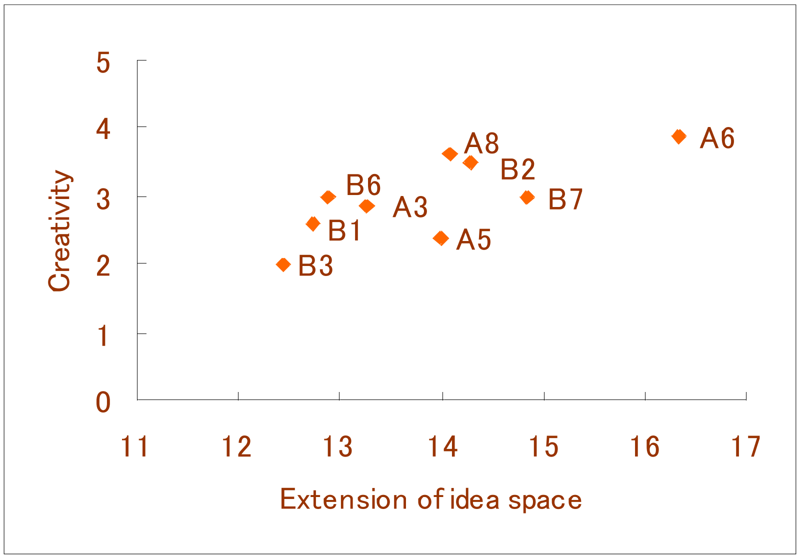


Figure 6. Correlation between creativity and the extension of idea space

Examples:

A3) Train, Bag and Traveling bag
→"Person taking a cat on a train.", "Go on a trip."
Camera, Picture, Doll and Robot
→"Monitoring a pet left at home."
A6) Ground, Hole, Narrow, Folding and Store
→"The hamster (or Cat) enters narrow spaces."
A8) Wheels, Run around, Revolution, Choice and Store
→"The hamster is playing with the wheels."
B1) A food chain
→"The cat is holding a fish in it's mouth."
Water tank, Monitor, Television and Remote control
→"Fish are swimming in the water tank."
B2) The sea, Marine sports, Wet suit and Cylinder
→"Fish are swimming in the sea."
Heating
→"When coming home from the sea,
the wet suit can be dried."
B3) Water tank
→"Fish are swimming in the water tank."
B6) Water tank, Surface and Glass

→"Fish are swimming."

B7) Water, The Sea, Sunburn, Beach and On the sea

→"A fish is floating in water."

Cushion, Kotatsu and Nap

→"The cat arches its back on the cushion (kotatsu)."

Parent and child

→"The fish are swimming in a school."

As shown above, a noun judged to be far from the two axes was thought up when the subject recollected various scenes and situations. It is thought that the new nouns leading to the extension of an idea space were uttered under the influence of the relationship between cat or fish and the new concept that the subject conceived in the design process. As we already identified the possible factors of the extension of idea space during the design synthesizing process, we extract the characteristic of these factors, focusing on the thought process during the design tasks. Therefore, the processes for A6, A5 and B3 were analyzed. A6 shows the highest creativity result and the highest extension of idea space in Figure 6. A5 shows the second lowest creativity result but its idea space is expansive. B3 shows the lowest creativity result among the nine creative ideas and its idea space does not expand greatly. The relationships between the new noun and the next nouns in the process for three creative design ideas were classified into two categories: taxonomical relations or thematic relations judged using the Concept Dictionary (EDR, 2005). Example of the classification of design process for A6 is shown in Table 6. Table 7 shows the frequency of thematic relations in each process (60% for A6, 28% for A5, and 22.2% for B3). Given these results, there may be a correlation between the thematic relations of each consecutive pair of new nouns and the extension of the idea space in creative design. The result reveals the thematic relation, which is the principle of concept integration (the 3rd design process primitive) in the design process, as we described above, may have an effect on higher creativity in design through the extension of idea space.

It will be necessary to further consider the relationship between the extension of idea space and high creativity in the future because it is possible that there are factors which do not affect higher creativity even though they affect the extension of idea space. It is important to recognize the characteristics of factors that affect the extension of idea space and also higher creativity.

TABLE 6. Example of the classification of design process (A6).

No.	New nouns	Reason (from the interview session)	Distance between each consecutive pair of new nouns	Relation type
17	Narrow	Narrow	18	thematic
18	Chair	Chair	18	thematic
19	Drawer	Narrow	2	taxonomical
20	Narrow	Narrow	18	thematic
21	Books	Narrow	19	thematic
22	Narrow	Narrow	19	thematic
23	Narrow	Narrow	0	-none
24	Ground	Narrow	6	taxonomical
25	Ground	Ground	0	none
26	Narrow	Narrow	6	- none
27	Ground	Ground	6	- none
28	Hall	Narrow	4	- none
29	Furniture	(key word)	17	- none
30	Pipe chair	Structure	1	thematic
31	Tube	Hall	8	- none
32	Structure	Hall	10	thematic
33	Umbrella	Structure	9	thematic
34	Fold umbrella	Umbrella	0	taxonomical
35	Ground	Ground	19	- none
36	Narrow	Narrow	6	- none
37	Umbrella	Umbrella	17	thematic

TABLE 7. Frequency of thematic relations in each process.

Design concept No.	A6	A5	B3
Creativity	3.875	2.375	2.000
Extension of idea space	16.32	13.99	12.43
Thematic relations (%)	60.0	28.0	22.2

5. Conclusion

In this study, two topics were examined. First, primitives and principles of the concept-synthesizing process (combining, blending, and integrating) were systematized from the viewpoint of creativity. The 1st primitive of the concept-synthesizing process is 'concept abstraction,' and its principle is 'similarity' in 'taxonomical relations'. The 2nd primitive of the concept-synthesizing process is 'concept blending,' and its principle is 'similarity' and 'dissimilarity' in 'taxonomical relations'. The 3rd primitive of the concept-synthesizing process is 'concept integration,' and its principle is 'thematic relations'. Second, the relationships between creativity and the design primitive processes, focusing particularly on the extension process of idea space in terms of the difference between the taxonomical relation and thematic relation, were empirically studied. The results of synthesizing two concepts on the basis of a thematic relation in the design process affects the extension of idea space and it results in high creativity, driven by the 3rd primitive of the concept-synthesizing process. The thematic relations of each consecutive pair of new nouns in design process effect on the extension of the idea space in creative design. The principle of concept integration (the 3rd design process primitive) may have an effect on higher creativity in design through the extension of idea space.

In this study, we showed three primitives. However, there may be other primitives. For example, we hypothesize that the process by which idea space (design space) is created may be another principle. We will continue to systematize the primitives and principles in future.

References

Boden, AM: 2004, *The Creative Mind Myths and Mechanisms,* Routledge.

Fauconnier, G: 1994, *Mental Spaces*, Cambridge University Press, UK.

Fauconnier, G and Turner, M: 2002, *The Way We Think - Conceptual Blending and the Mind's Hidden Complexities*, Basic Book, NY.

Finke, R, Ward, T and Smith, S: 1992*, Creative Cognition: Theory, Research, and Applications*, Cambridge, the MIT Press, A Bradford Book, London.

Gardenfors, P: 2000, *Conceptual Space*, the MIT Press, A Bradford Book, London.

Gero, SJ and Maher, ML: 1991, Mutation and analogy to support creativity in computer-aided design, GN Schmitt (ed.), *CAAD Futures '91*, ETH, Zurich 241-249.

Goldschmidt, G: 2001, Visual analogy, in C Eastman, M McCracken and W Newsletter (eds), *Cognition in Design Education*, Elsevier, UK, 199-219.

Harakawa, J, Nagai, Y and Taura, T: 2005*,* Conceptual synthesis in design creation, *Proceedings of 2005 IDC, International Design Congress* IASDR, 2005 (in press).

Hayashi, M: 2002, *Three Swedish Design*, Living Design, 21, Living Design Center, Tokyo, 76-82.

Living Design Club (ed.): *Living Design Collection*, 2004 (Jacobsen, A: Swan Chair 1958, Tendo : Mushroom-stool 2003, Long Island : Easy Chair 2002), http://www.ozone.co.jp

Taura, T, Nagai, Y and Tanaka, T: 2005, Design space blending-a key for creative design, *Proceedings of International Conference on Engineering Design (ICED05),* the Design Society, Melbourne, CD-Rom.

Taura, T, Yoshimi T and Ikai, T: 2002, Study of gazing points in design situation -A proposal and practice of an analytical method based on the explanation of design activities, *Design Studies* **23**(2): 165-186.

Wisniewski, EJ and Bassok, M: 1999, What makes a man similar to a tie?, *Cognitive Psychology* **l**(39): 208-238.

*Concept Dictionary, CPD-V030, 2005, EDR Electronic Dictionary, National Institute of Information and Communications Technology.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 195-210

CUE-BASED MEMORY PROBING IN IDEA GENERATION

MATTI K PERTTULA
Helsinki University of Technology, Finland

and

LASSI A LIIKKANEN
University of Helsinki, Finland

Abstract. This paper highlights cue-based memory probing as a central part of the idea generation process. We propose a cognitive model of image retrieval within the idea generation process based on this conception. The basic depiction is that stimulus elements, e.g. problem statement and prior examples, provide the basis for the retrieval cues that are used to attain appropriate knowledge structures serving as precursors to the final ideas. The model is described in detail, along with discussions on its application to studies of idea generation.

1. Introduction

One of the central creative tasks in product design is idea generation. Virtually every development project includes an idea generation session or meeting. The objective of these meetings is to visualize a number of possible solutions for a design problem. The produced concepts serve as a roadmap for the succeeding design phases as they present the set of design options for the design team. A design problem refers to a particular main function coupled with a set of functional requirements. In this paper, a concept refers to a design representation that displays the working principle and primary structure of a future artifact. Terms 'idea' and 'concept' are used interchangeably.

Design is fundamentally a cognitive task that can be characterized as ill-structured problem solving (Simon 1973; Akin 1986; Goel and Pirolli 1992). Memory functions are a part of task-oriented cognitive processes. Models of idea generation should also consider this view. The theory of information processing proposes that idea generation is basically memory cognition (Nagasundaram and Dennis 1993; Brown et al 1998; Nijstad 2000; Potter and Balthazard 2004). However, this view has not been properly introduced to design science to be used as a framework for mapping parts of the idea generation process. As will be discussed and demonstrated in this paper, stimulus elements, including e.g. task materials and earlier sketches, possess definitive roles in the problem solving process.

In this paper, we present a cognitive model of memory retrieval in idea generation, from the perspective of cue-based memory search. The model is called CuPRIG (Cue-based memory PRobing in Idea Generation). We outline the idea generation process to contain the following stages: stimuli interpretation, cue formation, image probing and recovery, and idea synthesis. CuPRIG is mainly a model of memory search, and therefore, does not aim to be an autonomous model that explains creative thought in idea generation comprehensively.

Case-based reasoning (CBR) has been introduced as a possible solution to the problem of knowledge retrieval and reuse (cf. Gero 1990). CBR paradigms have been used effectively in a variety of domains to explain and support memory functions. However, a CBR system will only be successful in design when its focus is on producing new target designs by retrieving and adapting similar designs (Smyth and Keane 1996), which hardly is suitable for our cause. The focus of our model is on the creative process, and therefore, we need to put an emphasis on the manifestation of unique ideas. It has been shown that the emergence of unique ideas is correlated with the production of a high number of diverse ideas (see e.g. Diehl and Stroebe 1987). Thus, as opposed to simple similarity matching, we stress the role of cues as medium for accessing remote task-relevant images. The basic idea is that cues may be manipulated in order to retrieve new images and spread activation within one's semantic memory. However, we also assume that context guided similarity-matching plays an important role in the generation of new ideas, since solutions to 'new' design problems are likely to share resemblance to previous designs.

2. Related models: SIAM and Matrix model

Several authors state that external stimuli (e.g. ideas of other group members) may stimulate the production of additional ideas due to 'cognitive stimulation' (e.g. Osborn 1957; Connolly et al 1993; Dennis et al 1996; Brown et al 1998; Satzinger et al 1999; Nijstad 2000; Dugosh et al 2000; Paulus and Yang 2000; Ziegrel et al 2000; Nijstad et al 2002). This effect has also been demonstrated in several laboratory experiments (e.g. Nijstad et al 2002; Dugosh and Paulus 2005). To account for increased idea production two cognitive models have been put forth that are worth mentioning: Nijstad's (2000) model Search for Ideas in Associative Memory (SIAM) and Brown and colleagues Matrix model (1998). SIAM itself is an application of a more general theory: Search of Associative Memory (SAM), intended to explain memory retrieval in cued and free recall situations (Raaijmakers and Shiffrin 1981).

SIAM proposes a two-step model in which a knowledge activation phase is followed by an idea production phase. The two phases are represented by two feedback loops: the image retrieval loop and the idea production loop. SIAM assumes that knowledge is activated in the form of images that are localized sets of information having semantically related features. The activation of images is a controlled process in which search cues are applied. As in the Matrix model, the probability of which idea is activated depends on the strength of the association between the search cue and the image. In the idea production phase, the features of the activated image are used to generate ideas, by combining knowledge, forming associations, or applying knowledge to a new domain. (Nijstad 2000)

The basic representation for the Matrix model is a matrix of category transition probabilities. Each entry in the matrix presents a probability that when exposed to a stimulus idea from a particular category, the subject will generate an idea from the same or another category. The model predicts that the probability of retrieving an idea from the same category is higher than from another category, however this probability diminishes as more concepts are sampled from the same category. The assumption behind the model is that individuals sample ideas from their memory networks in a way that is consistent with the demands of the task; individuals first produce ideas that are most active and then move on to more salient representations, until they run out of ideas. (Brown et al. 1998)

Instead of developing a completely new model for memory search in idea generation, we build upon the previous models by sustaining several of their central properties. However, there are two main differences between CuPRIG and the models presented above. Firstly, CuPRIG is aligned with the general theory of Information processing (Newell and Simon 1972) in order to suit design tasks that are more complex than those that led to the development of SIAM and the Matrix model. Secondly, unlike SIAM and the Matrix model, CuPRIG emphasizes similarity in the properties of the cue and image, instead of the simple associative strength, as the governor of image retrieval. To explain this difference, consider the following example. When a person is asked to name a pair for the word ‘cat’ he will likely say ‘dog’. One interpretation of this is that the word ‘cat’ is *associated* with the word ‘dog’ thus being based on the associative strength between these two. However, an alternative interpretation is that ‘cats’ and ‘dogs’ are related since they link semantically e.g. they are both domesticated animals that are often portrayed as adversaries to each other. Even though dissimilarity between the models may seem superficial, we stress the role that semantics plays in order to capture the nature of contexts and cues. Hence, two concepts can be semantically similar regardless of whether they share similarity in internal structure (Thagard et al 1990). The notion of semantic similarity is highly relevant for our model. At the same time, we do not wish to reject the notion of association as a general explanatory concept for long term memory, instead we see it appropriate to consider organized knowledge structures that are built upon non-contingent associations.

3. Cue-based memory probing in idea generation

Design idea generation is an activity where a designer attempts to produce several solutions that deliver the needed functionality within given constraints. CuPRIG attempts to model memory search within the idea generation process. We outline the idea generation process to contain the following main phases:

- In the *interpretation* phase, the subject interprets the problem statement, and any other stimulus materials available, to form an internal presentation of the problem space;
- The memory *retrieval* (or search) phase is responsible for retaining appropriate knowledge structures from long-term memory. It is commenced by forming a probe in the working memory;
- The *adaptation* phase is responsible for synthesizing the final idea based on the retrieved knowledge.

A flow chart model of the idea generation process is shown in Figure 1.

According to Newell and Simon (1972) problems are solved within particular problem spaces. The basic idea is that the problem solver begins with an external task environment creating an internal representation of the given problem in order to produce a solution to it. This representation, as well as the required problem solving operators, makes up for the problem space. A problem space is therefore a formalization of the structure of processing shaped by the characteristics of the information system (i.e. designer), and the task environment (Goel and Pirolli 1992). Designer then makes moves within this problem space to progress towards a goal state. This serves as the basic arrangement for the problem solving task.

The proposed model suggests that memory search forms an essential part of idea generation. The major invariant of the task environment is the problem statement, i.e. description of what is to be designed. The designer interprets the task environment forming an internal representation of the problem's structure and then proceeds to solve the problem by making moves in the problem space. We assume that problem structuring includes problem decomposition, which results in an arrangement where the designer is faced with one or more sub problems to be solved. After a sub problem is set, and some initial state in the problem space is established through perceived constraints, the agent can proceed to search for solutions from its knowledge base. This search is modeled in CuPRIG.

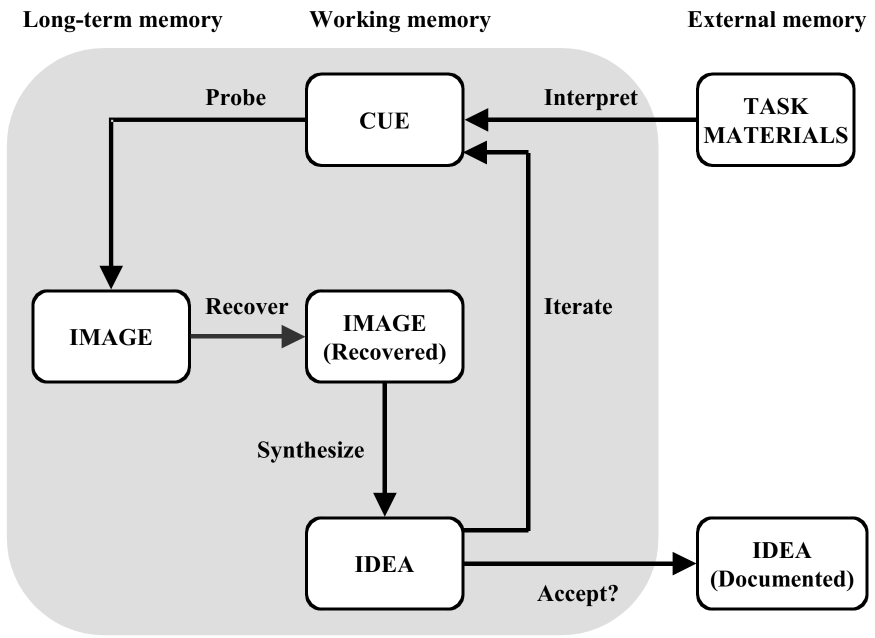


Figure 1. Cue-based memory probing within the idea generation process.

The interpretation of the problem is followed by a memory search requiring the agent to assemble a search cue in the working memory (Raajimakers and Shiffrin 1981). Along with the context, it is used to probe the long-term memory (LTM) for relevant images that serve as precursors to finalized ideas. For the purpose of making the model more understandable, we can assume that the cue may be presented as a predicate, e.g. throw, while the context would be portrayed by a noun, e.g. baseball (cf. Thagard et al. 1990). However the cue assembly is assumed to be mostly an automatic process, which is influenced by the agent's interpretation of the stimuli. Even though this normally happens without conscious effort, the agent can alter the process intentionally. We assume that strategies allow the agent to change not only the cue but also the context, which is normally constrained by the interpretation. Strategies can be learned as heuristic rules or adopted from the task environment that is from explicit or implicit instructions to consider the problem in a particular way.

The search for images is a probabilistic process governed by the context and the similarity of the cue in relation to relevant images. Images are organized in semantic networks of interconnected nodes (Raaijmakers and Shiffrin 1981). The notion of a semantic network represents several important cognitive factors related to idea generation (Brown et al 1998). A relevant characteristic of the search task is that some knowledge, given particular stimuli, is more privileged in a person's semantic network, i.e. more readily accessible given the particular cue and the context due to the associative strength.

After an image, if any, has been retained, it is interpreted and elaborated to form the solution to the initially modeled sub problem. This phase is referred to as idea synthesis. Synthesis will likely incorporate many additional cognitive processes that are more sophisticated than memory retrieval. Analogical mapping, conceptual synthesis and the like are possible functions for synthesis. Synthesis may in many cases turn out to be the most important part for the creativity of the final idea as the results of the memory search are by definition old ideas. Conversely, we are deliberately omitting an elaborated discussion about synthetic functions here as they are beyond the scope of this paper. In comparison, the described process can be considered some ways similar to the Geneplore model (Finke et al 1992) although CuPRIG emphasizes memory retrieval as the governing element of the generative phase.

After the idea has been synthesized, the agent evaluates the produced solution and makes a decision whether to produce the response, i.e. externalize the representation, and then decides whether to pursue further solutions, or terminate the search task.

In a decision to continue the search task, the agent iterates back to the interpretation of the stimulus materials. A relevant influencing factor in this iteration is that some features of earlier representations are likely to remain in the probe cue and context, as they are not just simply erased from the working memory. This may cause particular features to re-emerge in the following ideas. Implications of this feature are discussed later on.

In short, CuPRIG attempts to model the idea search process around the idea of cue-based memory search, guided by the search cues and context. We do not claim that memory retrieval as such is an adequate theoretical model for the creative process in totality. Instead, we claim that memory retrieval plays an indispensable part in most operations related to idea generation.

4. Formalization of memory search in CuPRIG

Memory probing refers to activating items in LTM via internal search. It has become a well-demonstrated fact that contextual cues may support memory recall (Sara 2000). Content-based image retrieval (CBIR) is an active research area that has led to several computational applications (see e.g. Smeulders et al 2000). The basic idea underlying these artificial intelligence applications is that by using queries, agents can obtain relevant information from databases. Queries are either constructed directly (e.g. use of keywords to retrieve images) or indirectly (e.g. parser interprets source and forms query). In order to retrieve one or several targets, CBIR systems usually try to match the query with the semantic qualities of objects in the database. Our model proposes a similar construct.

As a cognitive model, CuPRIG must commit to a format of long-term knowledge representation that is semantically organized. As this issue is still not adequately understood in design cognition, we need to rely on a more general solution. We use predicate calculus, which is often used in cognitive sciences for presenting information (e.g. Thagard et al 1990). While it is clearly inadequate in many cases we assume that design knowledge can be captured to some extent with this formalism. We use the term ‘image’ to refer to these knowledge representations. In the future, we wish to incorporate a more sophisticated and realistic model of knowledge representation (see e.g. Gero 1990 for a schema-based model).

A rough structure of the general retrieval process is illustrated in Figure 2. The structure is adapted and modified from Thagard et al (1990) who use the structure as a part of a computational model intended to explain analog retrieval, we assume that idea search operates in a similar fashion.

CuPRIG assumes that task-relevant items in LTM are images that have semantic properties. Image retrieval from LTM to WM is assumed to be a cue and context dependent process, governed by some function of the similarity between the elements of the probe and activated images possibly implemented via changes in associative strength. Hence, CuPRIG has three basic steps:

(i) A probe, consisting of the context and cue, activates a number of task relevant images;
(ii) The strength between the probe cue and images is measured;
(iii) The image with the highest strength with the probe is recovered.

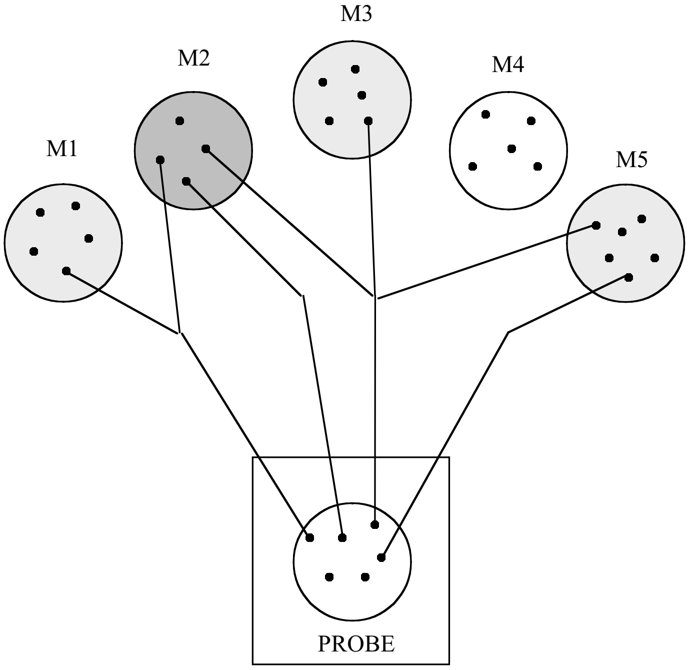


Figure 2. Probing from a structure into long-term memory via conceptual links (after Thagard et al 1990). The gray circles present activated images (M1 – M5). The dark grey circle (M2) presents the image with the strongest relation with the probe cue and context.

This is formalized as follows. A probe P consists of a context and/or a cue:

$$P_{ij}(C_{iT}, C_{jc}) \tag{1}$$

where C_{iT} is the set of attributes of context i; and $C_{1T}, C_{2T}, \ldots C_{nT}$ are different contexts. C_{jc} is the set of attributes of cue j; and $C_{1c}, C_{2c}, \ldots C_{nc}$ are different cues.

The strength S between a probe and an image is based on some function f of the similarity between these two:

$$_{i} = \quad (P \qquad _{i}) \tag{2a}$$

$$S_{i} = f(C_{T}, C_{c} \quad M_{im}) \tag{2b}$$

where M_{im} is the set of attributes of image i; and $M_{1m}, M_{2m}, \ldots M_{3m}$ are different images.

The probability R_i for recovering image i is:

$$_i(\quad | M_{im}) = \frac{S(\quad , M_{im})}{\underset{=1}{S}(\quad , M_{\ \ m})} \tag{3}$$

where n is the total number of images that share any relations with the context and cue c.

5. Cases explained through model

CuPRIG may be used to explain structural tendencies manifested in idea generation. These structural tendencies appear automatic and beyond person's conscious awareness (e.g. Ward 1994; Ward 1995; Finke 1996). Most importantly, CuPRIG is applicable to explain findings from studies of idea generation in groups. As noted earlier, idea exchange or sharing is an important function in the context of idea generation (see e.g. Paulus and Yang 2000). Hence, a major issue of cue-based probing comes from the research on idea exposure, i.e. subjects are shown examples prior to idea generation. In synthesis, these studies have shown that idea exposure may both stimulate and interfere one's creative processes, which can lead to either gains or losses in terms of design outcome.

A general foundation for explaining several cognitive factors involved in idea generation comes from the fact that items in LTM are organized into semantic networks (e.g. Collins and Quillian 1969; Collins and Loftus 1975; Anderson 1976). Items are thus organized into categories that are connected on the basis of shared attributes. Activation of one category member spreads to other category members, thus facilitating responses to those items (Darling and Valentine 2005), because semantically related items have strong mutual ties, i.e. they share similarity attributes (Tversky 1977). A relevant property related to individual's semantic networks is therefore category's accessibility.

We will start by presenting some evidence on structuring first ideas, and then move on to a discussion on effects of idea exposure.

5.1. STRUCTURING FIRST IDEAS

The initial step taken towards a solution is a critical one, because, as will be demonstrated, initial ideas have an effect on ideas that are subsequently generated. Since design ideas are generated in response to a particular design problem, the first context and cue is constructed on the basis of the problem statement, assuming that no other stimulus materials are present at that time.

'Routineness' is a key dimension of a design task. It depends on the designers' knowledge with respect to the design problem that he is confronted with (Visser 1996). In case of routine designs, a subject may simply recall a solution in its entirety, since all the necessary knowledge is available (see e.g. Gero 2000). In other words, the context and cue has one-to-one similarity with a specific solution (i.e. S = 1.00), thus operating according to the basic paradigm of case-based reasoning. In cases of less-routine designs, the subject must try a different approach, such as analogical transfer (see e.g. Visser 1996; Ball et al 2004). In the latter case, according to our model, the subject constructs a probe based on elements of the problem definition and retrieves a solution with the closest-match, which is then synthesized to adapt to the current situation. Intuitively, both of the cases will result in the production of a solution that is familiar to the individual. Thus, as pointed out by Smith (1993) "the first ideas may be facilitated within a context that invites limiting assumptions, rather than in a novel context that would obscure memory blocking effects".

A re-analysis of concepts from our earlier design experiment (Perttula and Sipilä 2005) demonstrates this effect. The experimental task was to generate design solutions for an "automatic device that collects balls from a playing field and delivers them to a goal-area". 38 out of 62 (61,3%) experimental subjects first produced a concept from the same category: a free-moving device that picked and delivered the balls, even that there were plenty of other solution categories available, such as blowers, levers, conveyors etc. Interpreted in terms of our model, this is due to the notion that the first context and cue constructed on the basis of problem interpretation will be similar across a number of subjects, since they end-up sampling images from the same category.

5.2. EFFECTS OF IDEA EXPOSURE: COGNITIVE STIMULATION AND FIXATION

Increase in the number of ideas generated after idea exposure is argued to be caused by the fact that ideas of others provide external cues that enable economical and remote sampling of knowledge structures (e.g. Nijstad et al 2002). There are some explanations as to why subjects should benefit from achieving access to others' ideas. Firstly, a range of knowledge remains highly accessible throughout the session. Secondly, ideas of others can activate knowledge that otherwise would not be accessible.

The first case is based on the logic that when one task-relevant category is activated, subjects have an ability of efficiently producing several ideas from that category, since they are highly interrelated due to similar attributes. Hence, subjects in idea generation sessions can achieve high ideational fluency through 'trains-of-thought' that occurs when they have successfully activated a rich category of semantically related images (Nijstad et al 2002). However, this usually happens at the expense of categorical flexibility (see e.g. Ziegler et al 2000), which means that the ideas produced share also similarity in content. This should be considered as poor performance, at least in cases where the objective is to generate a high number of different ideas. Hence, earlier ideas (or examples) may cause fixation that decreases the diversity of idea production, which is a major obstacle to successful idea generation (Jansson and Smith 1991; Purcell and Gero 1992). Design fixation relates to the tendency of designers to reproduce principles or features of earlier solutions, even when they are told not to (Jansson and Smith 1991). Fixation can cause 'mental-blocks' that obstruct the retrieval of additional task-relevant images.

Smith (1991, 1993, 1994) uses the concept of *fixation in memory* to explain how recent use of knowledge may cause blocks and constraints on retrieval of further targets. The basic depiction is that the probability of retrieving a new target response decreases if there are competing responses associated with the stimulus. Thus, the mechanism for memory blocks to occur is simple response competition (Smith 1993). After an initial idea has been produced, some of its features may remain in the probe, thereby facilitating retrieval of similar targets (e.g. Smith 1993). Cues (or their parts) that evoke, and activate, similar responses should be replaced or altered, before additional solutions can be found.

The second premise, which is held by several authors (e.g. Nijstad et al 2000; Brown and Paulus 2002) is that others' ideas may activate knowledge that otherwise would not be accessible for the individual, thereby leading to the development of further ideas. However, the hypothesis that novel ideas (statistically rare) should be more stimulating than common one's has not been confirmed in empirical trials (Connolly et al 1993; Dugosh and Paulus 2005). A plausible explanation for this is that even though a 'remote' idea category is activated, it results in the production of ideas from that category, thus the increase will be based on duplications or minor alterations of earlier ideas. The stimulus idea is strongly correlated with ideas from the same 'idea cluster', even if it where somewhat unfamiliar to the subject at start.

In summary, it seems that at least exposure to ideas (common or unique) leads to the production of rather similar ideas, instead of ones that differ significantly in content. Therefore, an attempt to use earlier ideas as probes that activate additional ideas, may fail, simply because similar images have strong correlations with one another. We believe that this is due to the fact that the cue formed on the basis of a solution will lead to rather 'close' relations with other ideas, instead of being based on a connection of more abstract properties.

Even though general evidence from idea exposure experiments points towards conformity effects, in the next section, we will present some evidence from events, in which examples help a designer to generate different designs.

6. Evidence from verbal protocols

In order to make use of the model as a framework for assessing the creative process of design idea generation, we need to have detailed empirical data on behavior that we are trying explicate. The think-aloud method and protocol analysis in particular (Ericsson and Simon 1980) is an effective tool for gathering information about the ongoing cognitive processes. Protocol analysis has been widely employed in design research (see e.g. Akin 1986 Cross 2005). In contrast to 'classroom experiments', arranged for studying e.g. idea exposure, protocol analysis brings important evidence on minute level designer actions. Protocol analysis captures the actual process, in addition to the task relevant output, i.e. documented ideas.

We present segments from transcribed design protocols, which provide examples of cue dependent probing affected by idea exposure. The protocols are from a larger unpublished design experiment, where subjects generated ideas for two tasks, 20 minutes each. In one of the tasks, four example solutions were given along with the problem statement, in order to study the effects of idea exposure. Figure 1 shows the task assignment and one of the examples.

We were interested in the immediate generative actions taken after a subject has attended to particular stimulus idea. Following the subject's gaze allowed us to observe this behavior. The direction of visual attention was then decoded from the video with one-second precision in order to separate concept development and observation, stimuli and brief inspection etc. Combining this analysis with verbal protocols makes it possible to analyze behavioral sequences that are of interest for our model. Hence, some instances of immediate cue-based probing may be revealed from the design protocols.

In one occasion after the subject A had looked at a solution example he verbalized as follows:

[02:51]…what are these like…
[02:55]…the explosion-machine is [er] yes…
[03:09]…yes, well then it could be like this…

(Subject A begins to develop new concept)

[03:13]...it could transform [the trunk] directly into useful ash…
[03:21]...the system…a great flame comes…
[03:30]…and actually, burns the trunk…

*** Page 1 ***

Background information:
After harvesting a forest, the tree stumps are left in the ground. These stumps still need to be removed, in order to make full use of the raw material. Currently the trunks are removed from the forest with one machine and transported outside the forest to be shredded with another machine. This is rather time-consuming and inefficient.

Assignment:
Your assignment is to generate as many different concepts as possible for an automatic device that shreds the wood trunks at the cutting area, i.e. already in the forest. The machine moves with its feet, you do not have to conceptualize its movement (See pictures.)

There are four example solutions to help you in this task. They are meant to awaken thoughts. Do not however reproduce them as such. You may use the task description and examples during the assignment.

*** Page 2 ***

Example 2. A hole is drilled into the tree-trunk. Then, an explosive is placed into the hole, which explodes and destroys the trunk.

Figure 3. Task assignment and one of the four examples

Another person, subject B, verbalized after looking at the examples as follows:

[02:31]…well, by looking at that, it crossed my mind…
[02:22]…actually there is that rasping system example…
[02:38]…it first came to my mind that it could be sort of a…

[02:40]…I'll draw it now…
[02:41]…this is the actual device…

(Subject B begins to develop new concept)

[02:44]…it has sort of legs here and here…
[02:48]…that is the rasping system…
[02:53]…it has sort of a…corkscrew-like drill…
[02:55]…that drills downward…and at the same time shreds it…

The previous excerpts show how an example helped the designers to generate an additional solution that entailed a different principle. The features of the example that caused this occurrence are not explicitly revealed from the verbal protocol. Cue formation is mostly an automated process, and therefore it can only be captured to some extent by concurrent verbalizing that relies on information available in WM. Still, the previous quotations clearly demonstrate the correlation of attending to an example and then producing a new concept.

7. Conclusions

In this paper, we introduced CuPRIG: a model of cue-based memory probing in idea generation. The model proposes that parts of the idea generation process may be conceptualized as cue-based retrieval, including stages of: stimuli interpretation, cue assembly, image probing and recovery, and idea synthesis. We believe that the model will help to uncover parts of creative thought processes of idea generation. The model provides a framework that can be used to study e.g. structural tendencies of idea generation.

As we are developing a model for a relatively new application domain there are still several issues to be settled. Model parts should also be empirically tested, with carefully designed experiments. In the future, we wish to develop the model to a degree of accuracy so that it could be realized as a functioning computational model. Implementation of the model will demand its architecture to be more elaborate and also will present new questions regarding its feasibility and computational complexity. In all circumstances the model should be helpful in evaluating the empirical findings of idea generation.

References

Akin, O: 1986, *Psychology of Architectural Design*, Pion, London

Anderson, JR: 1976, *Language, Memory, and Thought*, Hillsdale, Lawrence Erlbaum: NJ

Ball, LJ, Ormerod, TC and Morley, NJ: 2004, Spontaneous analogising in engineering design: a comparative analysis of experts and novices, *Design Studies* **25**(5): 495-508.

Brown, V, Tumeo, M, Larey, T and Paulus, PB: 1998, Modeling cognitive actions during group brainstorming, *Small Groups Research* **29**(4): 495-526.

Brown, V and Paulus, PB: 2002, Making group brainstorming more effective: recommendations from an associative memory perspective, *Current Directions in Psychological Science* **11**(6): 208-212.

Collins, AM and Quillian, MR: 1969, Retrieval time from semantic memory, *Journal of Verbal Learning and Verbal Behavior* **8**: 240–247.

Collins, AM and Loftus, EF: 1975, A spreading activation theory of semantic priming, *Psychological Review* **82**: 407-428.

Connolly, T, Routhieaux, RL and Schneider, SK: 1993, On the effectiveness of group brainstorming: test of one underlying mechanism, *Small Group Research* **24**(4): 490-503.

Coskun, H, Paulus, PB, Brown, V, and Sherwood, JJ: 2000, Cognitive stimulation and problem presentation in idea-generating groups, *Group Dynamics: Theory, Research, and Practice* **4**(4): 307-329.

Cross, N: 2004, Expertise in design: an overview, *Design Studies* **25**(5): 427-441.

Darling, S and Valentine, T: 2005, The categorical structure of semantic memory for famous people: a new approach using release from proactive interference, *Cognition* **96**: 35–65.

Dennis, AR, Valacich, JS, Connolly, T and Wynne BE: 1996, Process structuring in electronic brainstorming, *Information Systems Research* **7**(2): 268-277.

Diehl, M and Stroebe, W: 1987, Productivity loss in brainstorming groups: toward the solution a riddle, *Journal of Personality and Social Psychology* **53**(3): 497-509.

Dugosh, KL, Paulus, PB, Roland, EJ and Yang, H-C: 2000, Cognitive stimulation in brainstorming, *Journal of Personality and Social Psychology* **79**(5): 722-735.

Dugosh, KL and Paulus, PB: 2005, Cognitive and social comparison processes in brainstorming, *Journal of Experimental Social Psychology* **41**(3): 313-320.

Ericsson, KA and Simon, HA: 1980, Verbal reports as data, *Psychological Review* **87**(3): 215-251.

Finke, RA, Ward TB, and Smith SM: 1992, *Creative Cognition. Theory, Research, and Applications*, Bradford, Cambridge: MA

Finke, RA: 1996, Imagery, creativity, and emergent structure, *Consciousness and Cognition* **5**: 381-393.

Gero, JS: 1990, Design prototypes: A knowledge representation schema for design, *AI Magazine* **11**(4): 26-36.

Gero, JS: 2000, Computational models of innovative and creative design processes, *Technological Forecasting and Social Change* **64**(2): 183-196.

Gero, JS and Fujii, H: 2000, A computational framework for concept formation for a situated design agent, *Knowledge-Based Systems* **13**(6): 361-368 .

Goel, V., and Pirolli, P., 1992, The structure of design problem spaces, *Cognitive Science* **16**: 395-429.

Jansson, D and Smith, S: 1991, Design fixation, *Design Studies* **12**(1): 3-11.

Nagasundaram, M and Dennis, AR: 1993, When a group is not a group: the cognitive foundation of group brainstorming, *Small Group Research* **24**(4): 463-489.

Newell, A and Simon, HA: 1972, *Human Problem Solving*, Prentice-Hall, New Jersey

Nijstad, BA, Stroebe, W and Lodewijkx, H.F: 2002, Cognitive stimulation and interference in groups: Exposure effects in an idea generation task, *Journal of Experimental Social Psychology* **38**(6): 535-544.

Nijstad, B: 2000, *How the Group Affects the Mind: Effects of Communication in Idea Generating Groups*, Doctoral thesis, Utrecht University

Osborn, AF: 1957, A*pplied Imagination: Principles and Procedures of Creative Thinking*, Charles Scribner's Sons, New York.

Paulus, PB and Yang, H-C: 2000, Idea generation in groups: a basis for creativity in organizations, *Organizational Behavior and Human Decision Processes* **82**(1): 76-87.

Perttula, MK and Sipilä P: 2005, Time cycle effects in design ideation, In *Proceedings of the 15th International Conference on Engineering Design ICED'05*

Potter, RE and Balthazard, P: 2004, The role of individual memory and attention processes during brainstorming, *MIS Quarterly* **28**(4): 621-643.

Purcell, AT and Gero, JS: 1992, Effects of examples on the results of a design activity, *Knowledge-Based Systems* **5**(1): 82-91.

Raaijmakers, JG and Shiffrin, RM: 1981, Search of associative memory, *Psychological Review* **88**(2): 93-134.

Raaijmakers, JG and Shiffrin, RM: 1992, Models for recall and recognition, *Annual Review of Psychology* **43**: 205-234.

Sara, SJ: 2000, Retrieval and reconsolidation: toward a neurobiology of remembering, *Learning and Memory* **7**(2): 73–84.

Satzinger, JW, Garfield, MJ and Nagasundaram, M: 1999, The creative process: the effects of group memory on individual idea generation, *Journal of Management Information Systems* **15**(4): 143-160.

Smeulders, A, Worring, M, Santini, S, Gupta, A and Jain, R: 2000, Content-based image retrieval at the end of early years, *IEEE Transactions on Pattern Analysis and Machine Intelligence* **22**(12): 1349-1379.

Simon, HA: 1973, The structure of ill-structured problems, *Artificial Intelligence* **6**: 181-201

Smith, SM and Blankenship, SE: 1991, Incubation and the persistence of fixation in problem solving, *American Journal of Psychology* **104**(1): 61-87.

Smith, SM, Ward, TB and Schumacher, JS: 1993, Constraining effects of examples in a creative generation task, *Memory & Cognition* **21**: 837-845.

Smith, SM: 1994, Getting into and out of mental ruts: A theory of fixation, incubation, and insight, *in* RJ Sternberg and J Davidson (eds), *The Nature of Insight*, MIT Press, Cambridge: MA, pp. 121-149.

Smyth, B and Keane, MT: 1996: Using adaptation knowledge to retrieve and adapt design cases, *Knowledge-Based Systems* **9**(2): 127-135.

Thagard, P, Holyoak, KJ, Nelson, G and Gochfeld, D: 1990, Analog retrieval by constraint satisfaction, *Artificial Intelligence* **46**(3): 259-310.

Tversky, A: 1977, Features of similarity, *Psychological Review* **84**(4): 327-352.

Visser, W: 1996; Two functions of analogical reasoning in design: a cognitive-psychology approach, *Design Studies* **17**(4): 417-434.

Ward, TB: 1995, What's old about new ideas?, *in* SS Smith, TB Ward and RA Finke (eds), *The Creative Cognition Approach*, MIT Press, MA, pp. 157-178.

Ward, TB: 1995, Structured imagination: the role of category structure in exemplar generation, *Cognitive Psychology* **27**(1): 1-40.

Ziegler, R, Diehl, M and Ziljstra, G: 2000, Idea production in nominal and virtual groups: does computer-mediated communication improve group brainstorming?, *Group Processes and Intergroup Relations* **3**(2): 141-158.

KEYNOTE 3

Acquiring design expertise

Bryan Lawson and Kees Dorst

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 213-229

ACQUIRING DESIGN EXPERTISE

A first attempt at a model

BRYAN LAWSON
University of Sheffield, UK

and

KEES DORST
Eindhoven University of Technology, The Netherlands

1. Background

Design situations are generally now recognised to be unique thus demanding some degree of original thought. Design is widely seen as an inherently creative activity. We might therefore expect that designers who are thought to be expert will necessarily be creative. But what is the nature of this creativity? This paper thus delves inside creativity by examining the nature of expertise in design and its acquisition.

It suggests an overall model consisting of a number of states of expertise each having characteristic ways of perceiving, acting and reflecting. This is in line with other more generic models of cognitive expertise (Dreyfus 2002). Under such a model we would expect two kinds of development of expertise. Within each state we expect to see designers developing in the degree to which they operate. Between each state we expect to see designers changing the way they operate. Such a graph of progress consisting of a series of gentle slopes interspersed with steep cliffs is both characteristic of many learning processes and seems to match the experience of teaching design students.

The model is the result of putting together three strands of research; generic research on expertise, research on expertise from cognate areas or areas that have sufficient similarities with some aspects of designing, and the knowledge we have built up in design research about the nature of design problems and processes, and in particular a whole set of relatively recent work on expert designers. The generic expertise research will form the backbone of our argument here although we find it necessary to adapt the generic model in the context of designing. The research on expertise in cognate areas is used to help along this process of adaptation. The knowledge from design research is used to help to formulate the real design-specific nature of the cognitive development of designers. In this regard we focus more on the kinds of knowledge that designers use than on the more procedural aspects of much design research.

2. Generic Models of Expertise

There are several sources of generic research into the notion of expertise. In particular there is the work of Herbert Dreyfus with whom Kees Dorst has also held discussions about design (Dorst 2003). Dreyfus distinguishes seven distinct levels of expertise, corresponding with seven ways of perceiving, interpreting, structuring and solving problems. We begin by reporting that model in brief.

A **novice** will consider the objective features of a situation, as they are given by the experts, and will follow strict rules to deal with the problem. For an **advanced beginner** the situational aspects are important, there is sensitivity to exceptions to the 'hard' rules of the novice. Maxims are used for guidance through the problem situation. A **competent** problem solver works in a radically different way, selecting the elements in a situation that are relevant, and choosing a plan to achieve the goals. This selection and choice can only be made on the basis of a much higher involvement in the design situation than displayed by a novice or an advanced beginner. Problem solving at this level involves the seeking of opportunities, and of building up expectations. There is an emotional attachment, a feeling of responsibility accompanied by a sense of hope, risk, threat, etc. At this level of involvement the problem solving process takes on a trial-and-error character, and there is a clear need for reflection. A problem solver that then moves on to be **proficient** immediately sees the most important issues and appropriate plan, and then reasons out what to do. The real **expert** responds to specific situation intuitively, and performs the appropriate action, straightaway. There is no problem solving and reasoning that can be distinguished at this level of working. With the next level, the **master**, a new uneasiness creeps in. The master sees the standard ways of working that experienced professionals use not as natural but as contingent. A master displays a deeper involvement into the professional field as a whole, dwelling on success and failures. This attitude requires an acute sense of context, and openness to subtle cues. The master will perform more nuanced appropriate actions than the expert. The world discloser or **visionary** consciously strives to extend the domain in which he/she works. The world discloser develops new ways things could be, defines the issues, opens new worlds and creates new domains. To do this a world discloser operates more on the margins of a domain, paying attention to other domains as well, and to anomalies and marginal practices that hold promises for a new vision of the domain.

This model is intended for use generically in relation to problem-solving. We will not here rehearse all the arguments about whether or not design can usefully be considered to be problem-solving. However our position on this is not, we believe, out of step with much contemporary design theory that has at least also acknowledged the importance of other paradigms such as Schön's notion of reflective practice.

3. Models of Expertise in Related Areas

To move towards design then we next look at research on expertise from cognate areas of activity. The work by Chi on expertise in solving problems in physics and mathematics has some limited applicability in design (Chi et al. 1981). This work shows that experts are significantly better at recognising problem types. From then on in such a domain, the work proceeds more mechanically than can be the case in design. Design of the kind we are studying here has relatively few rules that enable set procedures to be followed to transform problems into solutions (Lawson 2004). However this work does highlight usefully for us the nature of expertise in seeing that a current problem shares a deep underlying structure with a type that is well understood even though superficially it may not resemble it. The work on software development by Adelson shows that experts can recall larger chucks of code and are more able to adapt them to meet the needs of a current situation (Adelson 1981). This has more relevance in design where, as Gero has pointed out, we are usually dealing with highly situated problems (Gero 1998). Schon of course goes so far as to suggest all design problems are entirely unique (Schön 1983). While such an idea may be technically correct it seems rather misleading in that most design problems share many features with many other problems. Gero's notion of 'situatedness' is thus probably more useful to us here in understanding the kinds of expertise designers need to acquire. In the generic model of Dreyfus the notion of situatedness is introduced at the advanced beginner level and then again in a much more central way at the master level. Since it seems to us that the very situatedness of design problems is one of the reasons why the conventional problem-solving model is not totally adequate for design, this will lead us to deviate from the generic model in due course.

Other research into high levels of expertise in chess playing by De Groot and his followers (De Groot 1965) suggests that experts, or chess masters, are also distinguished by their ability to recognise board situations, rather then having to rely upon them. This seems to have even more relevance to design. While chess players can never redesign the pieces, at the highest levels of performance they do need to combine situations in novel ways and ultimately to invent new types of moves or gambits. At the lowest levels however learning the rules is required before moving on to study previous games.

4. A Model of Design Expertise

The generic models of expertise share a common thread of defining a progressive series of levels of attainment. In such models performing at the lower levels is usually seen as a prerequisite for moving on up to higher levels. Our model follows a similar pattern. In such models the levels are often seen as plateau in the time versus performance curve, which is also a common notion in skill development. The reasons for this seem varied but most importantly because an acquisition of a certain amount of knowledge or experience enables a new way of operating or perceiving. Thus these models suggest that operating at higher levels of expertise is not just a matter of working harder, better or faster but working differently. In our model then we have tried to analyse the features of learning to design that seem to create these opportunities. We rely here on research into the performance of designers ranging in their expertise from early students right up to extremely successful and highly regarded designers. However because of the nature of such investigations the work relied upon uses a variety of research methodologies. We therefore present this as a 'rich picture' of relevant material which taken together seems to us to offer a first version of a model of expertise in design. What we present here then is a first attempt at trying to pull together the generic models of expertise acquisition with what we know about designing. So far this results in a model of expertise of designing which is similar to the generic models but with some very important special characteristics. We see this model initially as a research tool. We offer it as a way of locating debate among the design research community in a focussed manner, and we invite you to begin that debate.

4.1. NAIVE

We believe this state is required in a model of design expertise since design-like tasks are not only performed by professional experts but by ordinary people in their everyday life. This state of designing may thus be adequate for everyday use in conventional situations. It is usually based on some personal and unsystematically gathered knowledge of instances that have been seen before and thus involves a large degree of fairly routine copying. We might thus expect many students to enter design schools operating in this naïve state of expertise and to have their own attitudes and preferences for instances based on narrow experience. These value judgements are likely to be based on partial information as it were. They are likely to be recognising a relatively superficial set of attributes of design that they wish to emulate.

This may lead to a very direct and often inappropriate form of visual quotation in their work. Students may find these attitudes and preferences difficult to articulate since they are unlikely to have any structured language for expressing them and debating them. The phrase 'I know what I like' comes to mind here. The relatively recent proliferation of television design makeover programmes is testimony to the widespread use of such a level of design expertise.

Unless assisted by deliberate education the naïve designer is unlikely to shift to the next stage without some self realisation that this language needs to be acquired and that conscious effort will be needed to develop a more structured body of precedent. Indeed tutors of first year courses may well be familiar with a number of students who are either unwilling or unable to 'unlearn' this naïve way of thinking about design. To some extent then the first stages of a design course may well involve the establishment of some trust between student and tutor. Unless the student is trusting enough to be taken into the initially strange and more complex world of the more expert designer, the educational enterprise may have to be abandoned.

4.2. NOVICE

This state involves the deliberate seeking out and gathering of design precedents, rather than simply relying on experience. This is probably the state at which most university undergraduate design students enter their courses. Experience of recruiting such students over many years suggests that they have committed to the idea of learning about their chosen design domain, have begun to study precedents in a fairly unstructured way, but have little knowledge of design processes.

At this stage the main aim of education may be to generate that appreciation that the hard slog of precedent acquisition is necessary. It also requires the search for generic principles that link and classify precedents replacing the isolated instances of the naïve designer. At this level of expertise we might expect students to know about and understand why well documented, highly influential or classic examples of design are the way they are. As the Dreyfus generic model suggests, novices tend to follow strict rules. Understanding the rules and their origins may well be a matter for a later stage of expertise.

At this stage then design education would seek to give maximal experience of potential precedent through the use of printed images, visits, field trips and exhibitions of design work. It is not surprising perhaps that design education often includes substantial elements of history. Perhaps the teaching of a way of studying and understanding design through historical methods offers one way of developing the set of skills characterised by this level of expertise.

At this point it is worth rehearsing arguments that explain why precedent studies are so highly valued by designers. Design knowledge turns out to be far more episodic in its nature than semantic (Lawson 2004). Compared with many other professionals, designers have relatively few rules that enable them to turn problems into solutions and even less in the way or overarching theory that binds together such knowledge. One important reason for this seems to be in the nature of design solutions and their relationship to the problems they solve. It is the integrated nature of design solutions that gives the clue here. It is not normally the case that individual parts of the solution solve individual parts of the problem. Design problems and solutions simply do not map that way. Rather a design solution element may elegantly solve many parts of the problem (Lawson 1997).

At this point we should also remember that this novice stage is likely for many students to be the first time they have encountered design as a formal process. Although in this paper we are not primarily concerned with how such formal processes are taught, learned and acquired never the less it is important to recognise that designers are gradually increased levels of expertise in a whole series of techniques such as methods of representation through drawing or computer modelling, in the conscious management of time and effort in the central tasks of design processes themselves.

4.3. ADVANCED BEGINNER

This we submit might be the level normally attained during design education, and is thus the way we might expect to describe graduates. It is the acquisition of a language for discussing and criticising design which distinguishes this state of expertise from the previous ones. Many design courses seem almost based on the idea that this language will offer new ways of looking at the artefacts of the chosen design field. Characteristically, for example, architecture students report increased difficulty in discussing architecture with their family and close friends as this process unfolds.

We can present some evidence here to support the idea that the level of expertise acquired during education is characterised by significant increases in the use of schemata in describing designs. A recent study by Alexandre Menezes required students of architecture to describe drawings to another student of the same level who would try to reproduce the drawing from this description (Menezes 2004). Two drawings were used, a cartoon by Paul Klee and a design sketch by Mies van der Rohe. Two groups of students took part in the experiment, one from the first year of study and one from the final (6th) year. The approach is indebted to the work of Suwa and Tversky (Suwa and Tversky 1997), and Gero (Gero and McNeill 1998) for developing protocol analysis methods which gave rise to the ideas for analysing the descriptions used by these students. The more experienced students employed significantly more ways of describing the images than the novice students. This probably indicates a growing expertise in ability to analyse and think about visual images.

However the difference between the more experienced students and their novice counterparts was even greater for the design drawing than the art sketch suggesting they had significantly more conceptual ways of processing this material. All the descriptions were analysed in terms of being either 'formal' or 'symbolic' in nature. Formal references are related to physical and geometrical characteristics. They include descriptions as square, oval or line. Symbolic references are related to analogies and elements that are not represented in the drawings. They include descriptions as box, sausage or wall.

The drawings which were judged to be the most accurate reproductions of the originals were compared these with the least accurate. The best reproductions were the result of over three times the amount of conceptual references in the descriptions. They also showed a much smaller (55% increase) in formal references.

Taken together all this information suggests that at least one aspect of the increased expertise developed by these students during their education was in terms of their acquisition of schemata which would appear to be fairly specific to their field of design.

We expect that students will begin to acquire their own personal and specific areas of interest at this stage. There are some interesting questions to ask here about how this process works and what influences it. These issues are currently being explored at Sheffield University by Ishmael Samsuddin, and so far this research suggests that both individual personality factors and strong social mechanisms are both at work. Support for this idea comes from two pieces of work. One of these is by Wilson who studied UK schools of architecture and showed that the design preferences of students in those schools were significantly clustered (Wilson 1996). That is to say students from one school were in general significantly more likely to share preferences with other students from their own school than from others. The development of these personal interests into mature functioning approaches to design is one of the characteristics of the next level in our model.

A further characteristic of the next level in our expertise model is the recognition that design problems are highly individual and situated. In this sense design is probably less amenable to the use of standard solutions than might be the case in many other fields of activity. An obvious example of this would be the way in which the site imposes external constraints on a building. In Lawson's constraint model of design problems (Lawson 1997) it may be that the external constraints often make exceptions to standard problems which result in highly individual and innovative pieces of design. An example of this would be the great architect/engineer Santiago Calatrava telling us that he 'can no longer just design a pillar or an arch, you need a very precise problem, you need a place.' (Lawson 1994)

4.4. COMPETENT

The advanced beginner then has begun to appreciate the enormous richness and variability of design situations and is becoming adept at dealing with a wide range of them. We suggest however that the competent designer is more of a master of these situations and indeed able to create them.

The competent designer is one who can handle and understand all the normal kinds of situations which occur within the design domain being practiced. Not only are generic solutions known and understood but there is an ability to recognise exceptions and appreciate the ways in which they may vary from standard or known solutions. We note in relation to this the work of Eckert and Stacey studying fashion designers and helicopter engineers. They suggest that a very common form of communication between designers about new designs is in terms of variations to previous well understood designs. (Eckert and Stacey 2000) In this sense existing well understood designs have become complex schemata in their own right. That is to say a complex set of ideas can be communicated simply by naming the design solution. The competent designer may also work within a design practice that share a common understanding of the relative importance (as the members of the practice see it) of various known design schemata. In this sense a design schemata consists of coherent set of design elements interrelated in ways which relate consistently to sets of guiding principles.

In process terms a competent designer is likely to be able to create the design situation itself through strategic thinking. This means that by now in addition to the representational skills being acquired earlier such designers must be able to develop a brief with clients and understand the needs of their users. In addition they must have a certain amount of technical knowledge about the making and maintaining of the objects they design. They also need to be able to analyse those objects and evaluate them in terms of performance. However, as we know these skills and the knowledge they depend on cannot be entirely separated from the process of designing. Contemporary design research would suggest that competent designers must be able to develop a problem-solution situation and engage with it.

So far in the model we suggest that normally designers would progress from one state to another in a fairly linear way. By this we mean that we would expect most designers to progress from Naïve, through Novice and Advanced Beginner to Competent. Some may move very quickly through one or more states and others may get stuck in a particular mode for some time. We shall return to a discussion of this later. However importantly at this point we propose that the model should branch. There seem to be at least three ways to go from the competent state and we suggest that this progression depends very much on the mentality, perhaps even personality, level of ambition and insight of individual designers themselves. We call these three states ‘Proficient’, Expert/Master and Visionary.

4.5. PROFICIENT

A proficient designer may be thought of as one who is ‘good enough for the client’. Designers themselves may often feel some lack of enthusiasm for such proficiency. It may not show innovation or originality and may not contribute new knowledge to the design field. We might expect that graduates with some small degree of professional experience would be ‘proficient’. We note here that those professional bodies (e.g. RIBA in the UK for architecture) which regulate design courses usually have a period of post-graduate practical experience as a requirement before admitting a student to professional membership. The work they produce may well adequately solve fairly routine problems for clients and users but is unlikely to provide new insights and therefore not thought to constitute powerful precedents by other designers. Such designers are unlikely to be admired by their peers in the contemporary world of ‘signature designers’. Working at this level is probably a fairly comfortable experience that presents few challenges either in the development of a design or to the approach itself.

4.6. EXPERT

The expert designer may be one who has a rather more developed set of guiding principles. These have led the designer or design team to be known for a certain approach or set of values. In turn the designer has completed a body of work which has led to specialised expertise through practice. That is to say understanding the principles through applying them. In the general literature about expertise of this kind there are a number of indications that this level may be characterised by an ability to reduce the amount of cognitive analysis in favour of more or less automatic recognition of situations. Perhaps the best example of this is the work of De Groot and his followers on chess players (De Groot 1965). It seems the chess master does not analyse the chess board but rather recognises it. Effectively the situation on the board to a player of this level of expertise is a Gestalt. The whole situation is recognised and can be given a name. In the case of chess players this no doubt comes about not only through playing but through gaining what we call here accelerated experience by studying the recorded and documented games of great players. In the case of designers this accelerated experience probably plays a far greater role since the timescales of a game of chess and a design project are vastly different. Thus designers relying solely on their own experience would probably gain knowledge too slowly to reach this level of expertise. This provides more understanding for us about why gaining 'precedent' through magazines, exhibitions and so on is so important in the design world. It also suggests a very particular set of needs in terms of library provision for design education. Many recent events connected with the way university libraries are run in UK universities having design departments such as architecture suggest that this message is difficult for librarians to absorb.

Thus the chess master appears to hold a complex schemata representing knowledge about a chess situation. This can be used not only to recognise key features of the situation but also to suggest a range of appropriate gambits or actions that can be taken. As yet we have no hard evidence that designers operate in this way, although Schön and Wiggins work suggest something very similar (Schön and Wiggins 1992). An experiment currently being conducted at Sheffield University may begin to provide some more limited evidence.

Khairul Khaidzir has been recording the tutorial conversations between second year architecture students and their design tutors. These design tutors at such a university are very carefully selected and we might reasonably expect them to have acquired at least this level of expertise. Under our model we would normally expect the students to be operating on a novice or in exceptional cases an advanced beginner level. These conversations have been analysed using a modified protocol analysis technique of the kind we have seen explored for studying design teams or single designers asked to think aloud (Cross et al. 1996). This research also used a modified Linkograph technique developed by Goldschmidt for studying the way design issues are dealt with throughout the tutorial (Goldschmidt 1992). Each segment in the tutorial protocol was analysed along a number of dimensions. These include whether it is a process oriented or content oriented action. Whether it is about symbolic or structural material, and whether this represents a lateral or vertical transformation. The analysis also noted whether this is primarily a framing or moving or evaluating action.

What is without doubt in this data is that the tutors consistently show different patterns in this analysis to the students. There is of course no reason to be surprised about this but it reinforces the point that so many of our pieces of empirical knowledge about design processes are derived from experiments on students. If our model of design expertise has any validity at all then some of this knowledge may need questioning. The first impressions of this data suggests that this recognition process is indeed going on here. The tutors seem frequently to identify a situation, perhaps even name it by referring to a building or an architect, and immediately suggest a course of action to the student. The tutors made far higher ratio of moves to framing remarks than the students, and the vast bulk of these were additional structural moves. Associated with this, the tutors made more lateral rather than vertical transformations, to use Goel’s terminology (Goel 1995). That is to say a higher proportion of their moves were new ideas rather than developments of previous ideas. This work can be linked to previous work by Pereira who has suggested that in such tutorial encounters tutors are playing several roles (Pereira 1992). She pointed out that they may be help to solve a problem; in effect acting as a consultant. They may be trying to widen the student’s experience or challenge the student’s approach, and so on. It must therefore be accepted that these tutorial sessions are not exactly like normal design conversations. Never the less this data strongly suggests that experts, in the form of tutors, can see far more possible moves for a given frame than can novices, in the form of students. It also lends support to our notion that more expert designers work differently rather than simply being better at doing the same thing as their less expert counterparts.

4.7. MASTER

The master designer is really a development of the Expert who may have taken their set of guiding principles to a level of innovation such that their own work is seen as representing new knowledge in the field. An interesting parallel with the work of De Groot on chess is again useful here. The chess master it seems can play one of these demonstrations where many ordinary club chess players are taken on simultaneously. Of course to do this the master relies on recognition and game situation schemata that contain gambits. Without this the analysis that would be necessary would make the whole thing impractical. However when playing another chess master the assumption has to be that this is not good enough since the opponent will also know these gambits and the counter responses. Here the chess master has to invent new gambits. At this level of performance then designers are producing design ideas that are innovative responses to situations that may have been previously well understood. Such work is published and becomes the new precedent for other designers to study. This was demonstrated by Lawson’s study of famous architects (Lawson 1994)and also can be seen in other work by Cross (Cross 2003) and by Candy (Candy and Edmonds 1996).

We might then expect this very high level of expertise to be one where new gambits are invented.

4.8. VISIONARY

We feel it necessary to put in this rather odd level of expertise to complete the model. The visionary designer may be one who has become so interested in developing new ideas that the normally expected level of competence is no longer important. This may be a feature of expertise peculiar to the design world. The work of such designers may not always be realised and the design world deliberately creates an opportunity for this with design ideas competitions and exhibitions. Of course it is also the case that some of this design is realised. One might suggest an example here could be seen to be the Sydney Opera House. This design was produced in a clearly visionary way with little knowledge about the practicality of building it. The jury appointed to assess the designs in the competition had little or no expertise themselves in theatre, concert hall or opera theatre design, and certainly no expertise in acoustics. One of the judges had considerable experience of the rather dramatic forms being suggested but otherwise the technical issues were not represented on the jury. As we all know, this building was eventually produced at enormous cost and delay. To this day it remains hugely impractical in many ways. The extent to which it is visionary however remains absolutely undeniable. It is largely forgiven all its faults and has inspired many other designers. Other examples of such largely impractical and yet visionary design might include the Philippe Starck Lemon Squeezer. We suspect that although this object is widely admired and purchased it is seldom actually used for its apparently intended purpose.

5. Progression and moving through the model

We advance this model of discrete states, although it is far from clear that individuals would necessarily progress solely one level at a time. However the levels are distinct in that what is required developmentally to move up a level in each case is different. For this reason it seems that this model may be helpful in testing the intentions and methods of design education.

Often embedded in many pedagogical approaches is what we call here the ‘talent’ model of design expertise. Although seldom analysed such a view is often heard expressed by tutors in design schools in our experience. In this view some students are described as ‘talented designers’ or ‘creative designers’ implicitly suggesting that their ability is innate or given rather than capable of being developed. We also note that quite often design tutors prefer to work with such students and in such a world the development of skills may be neglected. Such views of design education may be challenged if our model is accurate.

One model of design education that seems to have much implicit currency is that students progress by being asked to solve increasingly difficult problems. This makes a great deal of sense within the context of our model of expertise. The nature of design problems is such that individual designers can tackle them at their own level of expertise. Perhaps the trick of design education is to encourage the student to see the need to challenge this and try to move into the more dangerous territory of the next level. Those who have had experience of teaching design are generally aware of the plateau nature of student development. It seems common for students to flatten out almost repeating a successful formula and then quite suddenly go through a period of confusion before emerging on a new plateau.

What the model suggests is that progression within a state may be gradual. This begs the more interesting question of what triggers a change of state. We suggest that two conditions may be necessary here. Firstly it may be necessary in the lower or earlier model states simply to acquire sufficient knowledge. Thus the acquisition of a substantial body of precedent may be necessary in order to move from Naive to Novice and a body of design schemata may be necessary to move from Novice to Advanced Beginner. Secondly it may be necessary to undergo some mental realisation that this additional knowledge van be used in a different way. If this is so then it may be that there may be two major tasks for design educators. The first task may be to provide the knowledge or at least access to the knowledge and encouragement to absorb the knowledge. The second task may be to offer the challenge to provoke developing designers into asking questions about their ways of perceiving and acting. Looking at design education, the curricula of design courses and the important role of the studio may give us supporting evidence for these ideas.

Earlier in this paper we relied upon some research into expertise in cognate areas. One of those areas was that of mathematics or physics. We note here that there are real differences in the cognitive development of designers and mathematicians. The latter are commonly expected to do some of their very best work in their twenties. By contrast Hugh Pearman argues that 'in architecture, you are young if you are under 50, an infant if you are under 40 and a babe in arms if you are under 30' (Pearman 2005) A recent book published by the Urban Redevelopment Authority in Singapore defines 'young' architects as those under 45 years of age (URA 2004). We would argue that our model, which stresses the acquisition of precedent and the development of guiding principles, depends on the gathering of experience and thus the acceleration of such a process seems to be problematic. It is certainly not unusual to find for example professional architects criticising the academic system for not producing graduates who are already competent. This is true even in spite of a system that generally requires seven years to full professional qualification.

The advent in recent years of national systems for research assessment in many countries have provided an uncomfortable challenge to many who work in design departments in universities. Certainly this has been the case in the UK. Many have felt that design knowledge is advanced by the actual act of designing itself. They have felt reluctant to accept the natural science paradigm of research implicit in so many RAE systems, in which good knowledge is only thought to exist inside peer review journal papers. In fact the UK RAE system has explicitly recognised this and has considered design to be an acceptable form of research. But some tricky problems remain. One of these is to do with peer review. The other linked problem is whether all design can be seen as research or only some. Our model suggests a possible way forward here. Expert, Master and Visionary designers can be seen to produce work which goes beyond the solving of a local problem for the client. They produce valuable precedent upon which others depend. They recognize new links and parallels between previously unconnected information. They generate new gambits which eventually may become standard or common practice. They may even offer new visions which intrigue us even though we may not yet be able to see how they can be made practical. We commonly think of such work as being ‘creative’, but perhaps it also ought to be thought of as a kind of research, or at least a major contribution to knowledge (Lawson 2002). However the routine work of Competent designers may be thought of as simply consultancy (Yeomans 1995). Distinguishing between these through some form of peer review however remains difficult to do reliably in practice.

6. Expertise in Design Practices

Our model so far has dealt with individuals, but much design is produced in teams. An important question here therefore is the extent to which design teams, groups, practices or studios can be said to have creative expertise. Perhaps much more work needs to be done on design teams before we can attempt a full answer to such a question. However it does seem quite likely that this model could also be used to study design teams. Design practices can for example share precedent. Trips and visits as well as lectures may be used to reinforce this. Practices that are highly successful and well known are often attached to the titular head but in reality work collectively. Clearly the idea of Guiding Principles can apply here. There is some evidence from interviews with significant designers who lead large practices that they appreciate this. Lawson has shown how architects such as Richard MacCormac, Ken Yeang and John Outram explicitly require their staff to embrace the guiding principles of the practice and to contribute to their development (Lawson 1994).

How teams come to negotiate shared precedent, guiding principles and design gambits offers a most interesting set of research questions. Gero and his group have offered some possible ways of exploring this phenomenon through their function, behaviour, structure model (Gero and Kannengiesser 2004). The makeup of successful design teams and their communication could also be explored through this expertise model. Do successful, creative and admired teams have members all at one level of expertise or many? The research done by Lawson on successful architects suggests that it may be possible to create teams of both kinds. However there would seem some possible benefit to having more rule-based lower level expertise in a team led by the apparently more intuitive higher level expertise.

7. Design Tools

Designers must also communicate with their clients and users. Some recent work suggests that it may be possible to have at least three ways of looking at a design process (Lawson et al. 2003). There may the actual process as carried out (practice). There may be a formal description of the process in documents, contracts, terms of engagement and so on (intention) and there may a process that those actually involved may wish to follow (aspiration). These three images may be aligned or not which may give rise to considerable confusion when communicating with other stakeholders such as clients. The model of expertise may also give us some insight into the way this works. Certainly at the more apparently intuitive higher levels of expertise it may prove much more difficult to accurately produce descriptions which enable easy collaboration.

This leads us on the development of design tools such as computer aided design techniques. It is not the role of this paper to explore that large and complex area in any detail. However it is probably fair to say the field as a whole has rather disappointed us in its realisation now over a substantial period of time. As Nigel Cross so succinctly puts it; "why isn't using a CAD system a more enjoyable, and perhaps, also a more intellectually demanding experience than it has turned out to be?" (Cross 2001) There was much early optimism about the role that computers could play in the design process. Although of course the computer is now fully embedded as a means of representation, there are very few well established genuinely useful and fully adopted computer based design tools. It is however not unusual to find computer tools developed in academia which students are expected to use in their studios. We suggest that perhaps is easier to develop tools which relate to the rule-based lower levels of expertise than tools which relate to the more intuitive higher levels of expertise. Perhaps we have yet to understand the kinds of tools highly expert designers would actually find useful.

8. Quo Vadis?

This paper has introduced a first version of a model of design expertise. It bears considerable resemblance to, and some differences from, other more generic cognitive expertise models. It appears to us to fit reasonably well with what we know about design from the literature of design research. It seems to us to offer some explanations for characteristics of student development that we are familiar with from our own teaching experience. It appears to be able to offer a spine along which we can place designing from the most naïve inexperienced amateur work right up to the most well known and highly successful designers.

The model needs testing far more rigorously than we have been able to in the course of developing this paper. It also offers the opportunity to connect research on design processes through this common spine which might in due course enable us to develop a more integrated model of the design process.

One way of progressing this idea might be to test the model by populating it with what we know, or what we can discover, about the various skills involved in designing at each of the levels. Lawson has proposed an overarching description of these skills (Lawson 2005). In this description they are clustered under the headings of 'formulating', 'moving', 'representing', 'evaluating', and 'reflecting'. We could look to see whether each of these clusters of skills normally develop in parallel or whether in some cases one or more get ahead of the others. Differential levels of these skills could also be identified as possibly giving rise to different patterns of expertise leading to different specialisms. Perhaps those with highly developed evaluation and reflection skills make good critics for example. We could look to see the balance of apparent time and effort in which these skills are employed in design processes. The work of Khairul Khaidzir quoted earlier currently in progress suggests that competent designers see more possible moves for the same number of problem formulations or frames, for example.

We thus see this model as offering a stimulus to develop research questions that can be combined into an overall research strategy involving many projects perhaps in many places. For us, this model begins to get us inside the concept of creativity as it is applied to design. It suggests ways of explaining how the ability to produce work generally thought to be creative can be developed. It might bed used to raise questions about design education such as the value of Visionary designers as role models for Novice students. However primarily at this stage we offer this preliminary model of design expertise for development and debate.

References

Adelson, B: 1981, Problem solving and the development of abstract categories in programming languages, *Memory and Cognition* **9**(4): 422-433.

Candy, L and Edmonds, E: 1996, Creative design of the Lotus bicycle: implications for knowledge support systems research, *Design Studies* **17**(1): 71-89.

Chi, MTH, Feltovich, PJ and Glaser, R: 1981, Categorization and representation of physics problems by experts and novices, *Cognitive Science* **5**: 121-152.

Cross, N: 2001, Can a machine design? *MIT Design Issues* **17**(4): 44-50.

Cross, N: 2003, The expertise of exceptional designers, *in* N Cross and E Edmonds (eds), *Expertise in Design: Design Thinking Research Symposium 6*, Creativity and Cognition Studios Press, Sydney, pp. 23-36.

Cross, N, Christiaans, H and Dorst, K (eds): 1996, *Analysing Design Activity*, Wiley, Chichester.

De Groot, AD: 1965, *Thought and Choice in Chess*, Mouton, The Hague.

Dorst, K: 2003, The problem of design problems, *in* N Cross and E Edmonds (eds), *Expertise in Design: Design Thinking Research Symposium 6*, Creativity and Cognition Studios Press, Sydney, pp. 135-147.

Dreyfus, HL: 2002, Intelligenece without representation- Merleau-Ponty's critique of mental representation, *Phenomenology and the Cognitive Sciences*, **1**: 367-383.

Eckert, C and Stacey, M: 2000, Sources of inspiration: a language of design, *Design Studies* **21**(5): 523-538.

Gero, J: 1998, Conceptual designing as a sequence of situated acts, *in* I Smith (ed.) *Artificial Intelligence in Structural Engineering*, Springer-Verlag, Berlin, pp. 165-177.

Gero, J and McNeill, T: 1998, An approach to the analysis of design protocols, *Design Studies* **19**: 21-61.

Gero, JS and Kannengiesser, U: 2004, The situated function-behaviour-structure framework, *Design Studies* **25**(4): 373-391.

Goel, V: 1995, *Sketches of Thought*, MIT Press, Cambridge, Mass.

Goldschmidt, G: 1992, Criteria for design evaluation: A process-orientated paradigm, *in* Y Kalay (ed.) *Evaluating and Predicting Design Performance*, John Wiley and Sons, New York, pp.

Lawson, BR: 1994, *Design in Mind*, Butterworth Architecture, Oxford.

Lawson, BR: 1997, *How Designers Think*, Architectural Press, Oxford.

Lawson, BR: 2002, Design as research, *Architectural Research Quarterly*, **6**(2): 109-114.

Lawson, BR: 2004, Schemata, gambits and precedent: some factors in design expertise, *Design Studies* **25**(5): 443-457.

Lawson, BR: 2004, *What Designers Know*, Elsevier-Architectural Press, Oxford.

Lawson, BR: 2005, *How Designers Think (4th Edition)*, Architectural Press, Oxford.

Lawson, BR, Bassanino, M, Phiri, M and Worthington, J: 2003, Intentions, practices and aspirations: Understanding learning in design, *Design Studies* **24**(4): 327-339.

Menezes, A: 2004, *Sketching and Visual Perception in Conceptual Design*, PhD Thesis, School of Architecture, University of Sheffield.

Pearman, H: 2005, A river of talent? *The Sunday Times* 19 June 2005.

Pereira, ATC: 1992, *A CAAD Expert Help System*, PhD Thesis, School of Architecture, University of Sheffield.

Schön, DA: 1983, *The Reflective Practitioner: How Professionals Think in Action*, Temple Smith, London.

Schön, DA and Wiggins, G: 1992, Kinds of seeing and their function in designing, *Design Studies* **13**(2): 135-56.

Suwa, M and Tversky, B: 1997, What do architects and students perceive in their design sketches? A protocol analysis, *Design Studies* **18**: 385-403.

URA: 2004, *20 Under 45*, Urban Redevelopment Authority, Singapore.

Wilson, MA: 1996, The socialization of architectural preference, *Journal of Environmental Psychology* **16**: 33-44.

Yeomans, D: 1995, Can design be called research? *Architectural Research Quarterly* **1**: 12-15.

COMPUTATIONAL SUPPORT FOR CREATIVE DESIGN

Creative design in a tangible user interface environment
Mi Jeong Kim and Mary Lou Maher

Idea improvement in different design environments
Tom Kvan and Gao Song

Creative architectural design by ITC enhanced collaboration
Gianfranco Carrara and Antonio Fioravanti

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 233-249

CREATIVE DESIGN IN A TANGIBLE USER INTERFACE ENVIRONMENT

MI JEONG KIM AND MARY LOU MAHER
University of Sydney, Australia

Abstract. This paper shows that tangible user interfaces support cognitive actions that are associated with creative design. The evidence for this is a case study of designers using a tangible user interface environment for manipulating 3D models on a digital design workbench. Focussing on how the new interface technology changes designers' spatial cognition, we compare designers using tangible user interfaces with designers using graphical user interfaces in a collaborative design task. The results show that the combination of tangible interaction with Augmented Reality display techniques improve designers' perception of spatial relationships between 3D models and encourages designers to discover hidden spatial features. These characteristics of designing are associated with creative design.

1. Spatial Cognition and Creativity in Design

Creativity is generally characterised by aesthetic appeal, novelty, quality, unexpectedness, uncommonness, peer-recognition, influence, intelligence, learning, and popularity (Runco and Prizker 1998). Thus, creativity in the design process is associated with discoveries and ideas that are fundamentally novel, where designers discover hidden features in a representation and recognise a key concept as a sudden insight. We expect that a new tangible user interface environment for design can play a critical role in the creative design process by improving designers' spatial cognition. The changes of designers' perception of spatial knowledge when using tangible user interfaces might lead to such discoveries and to the production of creative ideas. We consider the existing digital workbenches as defining a class of design environments that use tangible user interfaces (TUIs) to be a departure from the traditional graphical user interfaces (GUIs) that designers are currently using to create and interact with digital design models.

We associate a designer's perception of the form and spatial relationships of the design components with the designer's spatial cognition. In our research, the meaning of 'space' to the designers is not an abstract of empty space, but rather of the identity and the relative locations of the objects in space. Space then is decomposed into particular objects and the spatial relationships among them. The spatial relationships may include functional issues since designing attempts to satisfy intended functions. Thus, we investigate designers' spatial cognition or improved understanding of the form and spatial relationships between 3D objects with a focus on unexpected discoveries. This paper presents the results of a case study using protocol analysis.

1.1. CREATIVE PROBLEM SOLVING IN DESIGN

Gestalt theorists have emphasised productive thinking in contrast with reproductive thinking in the domain of creative problem solving (Wertheimer 1982). Productive thinking depends on past experience in only a general way and involves new structural understanding of the specific requirements of a problem. Gestalt analysis of creative thinking indicates the negative influences of past experiences on creative thinking. On the other hand, reproductive thinking theorists argue that the important issue for creative problem solving is not to abandon reproductive thinking itself but to reorganise the past experience for the current situation. Reproductive thinking applies some past knowledge to a present problem directly. Creative thinking is closely associated with the concepts of restructuring, which may form the basis for insight into the problem (Ohlsson 1984). Weisberg (Weisberg 1982) posed the results of case studies that creative thinking moves beyond established practises only slowly as a modification of the past rather than rejection of the past.

Cross and Dorst proposed that creative design can be modelled in terms of the co-evolution of problem and solution spaces, as described by Maher et al. (Dorst and Cross 2001; Maher 1996). That is, creative design involves a period of exploration in which both the formulation of the problem and ideas for its solution are developed and refined together, with constant iteration of analysis, synthesis and evaluation processes between the two 'spaces'. Accordingly, a creative event occurs as the moment of insight at which a problem-solution pair is framed in a potentially resolvable form, where the designer's ability of framing a design problem is emphasised as a key aspect of creativity. They introduce the notion of 'default' and 'surprise' problem/solution space to describe creative design, which keeps a designer from routine behaviour by leading to framing and reframing of the design problem. The common characteristic of creative thinking in these studies is the restructuring of information available to the designer while designing.

1.2. COGNITIVE ACTIONS FOR CREATIVE DESIGN: INSIGHT AND UNEXPECTED DISCOVERIES

Sometimes, people suddenly realise the answers during problem solving, even though they cannot figure out how to get to the solution (Davison 1995). The occurrence of "insight" associated with this 'Aha!' experience is one of characteristic features of creativity in design (Akin 1990). There are two conventional views of insight; the "special-process" views and the "nothing-special" views. Included in the special-process view is the idea that insight results from a restructuring of a problem that is accompanied by an unconscious leap in thinking, that it results from greatly accelerated mental processing, and that it is due to a short-circuiting of normal reasoning processes (Perkins 1981). In contrast, the nothing-special view proposes that insight is merely an extension of ordinary processes of perceiving, recognising, learning, and conceiving (Perkins 1981). Here we focus on the restructuring of a problem, a change in a person's perception of a problem situation, where the contribution of 'unexpected discoveries' is stressed.

According to Suwa et al., "unexpected discoveries" refer to designers' perceptual actions of attending to implicit visuo-spatial features in sketches that are discovered in an unexpected way by later inspection (Suwa 2000). Designers sometimes notice consequences that were not intended when they drew (Schön and Wiggins 1992). They also argue that designers do not just synthesise solutions that satisfy initially given requirements but also invent design issues or requirements that capture important aspects of the given problem, and call this 'situated-invention (S-invention)'. In terms of co-evolution, unexpected discoveries can be regarded as the act of finding new aspects of the developing solution-space and S-invention can be regarded as the act of expanding the problem-space. They found that unexpected discoveries of visuo-spatial features in sketches and S-inventions become the strong impetus for the occurrences of each other by using protocol analysis. The findings provide empirical evidence for the co-evolution view.

Research in design cognition has primarily dealt with 2D sketches, so we interpreted concepts and findings from studies of designing with 2D sketches in terms of 3D design and then applied them to our research. Since characteristics of creative design can be modelled in terms of the co-evolution of problem and solution spaces, we look for designers' restructuring a problem and their exploration of the problem space and the solution space. More specifically, we look for unexpected discoveries and S-invention in designing using TUI and GUI environments.

2. Spatial Cognition While Using Tangible Interfaces to Digital Design Models

TUIs are new approaches to human-computer interaction that are often associated with "augmented reality" (AR). Since AR technology blends reality and virtuality, TUIs combine physical and digital worlds, which allow very different "reflective conversation" between the two environments (Arias et al. 1997). Above all, TUIs provide a tangible interaction by turning the physical objects into input and output devices for computer interfaces. The strengths of physical interaction can be explained by two aspects; direct, naïve manipulability and tactile interaction as an additional dimension of interaction. Thus, they enable designers to create and interact with digital models that go beyond the traditional human-computer interface of the keyboard and mouse.

The tangible interactions using TUIs in AR systems can be explained by the concept of "augmented affordance", posed by Seichter and Kvan (Seichter and Kvan 2004). From this point of view, TUIs can be seen as offering a conduit between the real or perceived affordances implied by the physical properties of the interface tool and the affordances created by the digital behaviours in the virtualised interface. The term "affordance" refers to the perceived and actual properties of the thing that determine just how the thing could possibly be used, which results from the mental interpretation of things based on our past knowledge and experience applied to our perception of the things (Gibson 1979; Norman 1988). We predict that tangible interaction in TUIs account for changes in the designers' spatial cognition of 3D digital models.

2.1. DESIGNERS' SPATIAL COGNITION

As a consequence of the diversity of approaches and related disciplines, there is little consistency in what is meant by the term "spatial" (Foreman and Gillett 1997). In this research we define a designer's spatial cognition as the designer's perception of the form and spatial relationships of the objects or spaces in 3D design. Associated with the physical interaction, touch is emphasised as a spatial modality linking motor and spatial processes closely while using TUIs to digital models. Kinaesthetic information through a haptic system provides us with the ability to construct a spatial map of objects that we touch (Loomis and Lederman 1986). It is the movement of a hand repeatedly colliding with objects that comes to define extra-personal space for each individual, as a consequence of repeatedly experienced associations (Foreman and Gillett 1997). Thus, the movement simulated by the mouse in desk-top systems lacks tactile and kinaesthetic feedback that normally accompanies movement.

Language draws on spatial cognition so that designers can talk about what they perceive and it thereby provides a window on the nature of spatial cognition (Anibaldi and Nualláin 1998). It is based on the assumption that people often use general purpose verbs and prepositions when the context is sufficiently clear to disambiguate them. Thus, we analyse the designers' conversation in order to investigate their spatial cognition. Gesture is also recognized as a good vehicle for capturing visual and spatial information as it is associated with visuo-spatial content. Furthermore, the movement of hands can facilitate recall of visuo-spatial items as well as verbal items (Wagner 2004). People produce some gestures along with their speech, and such speech-accompanying gestures are not just hand moving. Speech and gesture are both characterising the spatial relationships among entities, which are closely related to and may even be beneficial for cognitive processing (Goldin-Meadow 2003; Lavergne and Kimura 1987).

2.2. DIGITAL DESIGN WORKBENCHES

We reviewed various digital design workbenches: metaDESK, iNavigator, BUILD-IT, PSyBench, URP, MIXdesign and ARTHUR system. The metaDESK system was constructed by Ulmer and Ishii (Ullmer and Ishii 1997) with a focus on physical interaction to manipulate the digital environment. Standard 2D GUI elements like icons, and menus, are given a physical instantiation as wooden frames, phicons, and trays, respectively. iNavigator is a CAD platform for designers to navigate and construct 3D models, which consists of a vertical tablet device for displaying a dynamic building section view and a horizontal table surface for displaying the corresponding building plan. The display tablet is served as "a cutting plane" (Lee et al. 2003). BUILD-IT developed by Fjeld et al. (Fjeld 1998) is a cooperative planning tool consisting of a table, bricks and a screen, which allows a group of designers, co-located around the table, to interact, by means of physical bricks, with models in a virtual 3D setting. A plan view of the scene is projected onto the table and a perspective view of the scene is projected on the wall.

Brave et al. (Brave et al. 1999) designed PSyBench and inTouch, employing tele-manipulation technology to create the illusion of shared physical objects that distant users are interacting with. Although still in the early stage, it shows the potential of distributed tangible interfaces. URP developed by MIT media lab is a luminous tangible workbench for urban planning that integrates functions addressing a broad range of the field's concerns such as cast shadows, reflections and wind-flow into a single, physically based workbench setting. The URP system uses pre-existing building models as input to an urban planning system (Underkoffler and Ishii 1999). MIXDesign allows architects to interact with a real scale model of the design by using a paddle in a normal working setting, and also presents an enhanced version of the scale model with 3D virtual objects registered to the real ones (Dias et al. 2002). ARTHUR system is an Augmented Round Table for architecture and urban planning, where virtual 3D objects are projected into the common working environment by semi-transparent stereoscopic head mounted display (HMDs). Placeholder objects (PHOs) and wand are used to control virtual objects (Granum et al. 2003).

These various configurations of tabletop systems, with and without AR, show a trend in developing technology. The different configurations described above draw on specific intended uses to define the components and their configuration. Few of the publications about digital workbenches evaluate the new interface technology with respect to spatial cognition or improved understanding of the spatial relationships of the components of the digital model. While TUIs and GUIs will continue to be alternative design environments for digital models, we focus on the differences between them in order to clarify the benefit of TUIs for designers.

3. Experiment Setting: GUI-based and TUI-based Collaboration

In devising an experiment that can highlight the expected improvement in spatial cognition while using TUIs, we chose to compare design collaboration in the following settings: TUIs on a tabletop design environment and GUIs on a desktop design environment. We expect that this comparison will enable us to verify if and in what way TUIs affect designers' spatial understanding of 3D models in computer-mediated collaborative design.

3.1. DESIGN COLLABORATION IN A GUI ENVIRONMENT

The setting of the GUI design environment is a desktop computer with a GUI such as a mouse, a keyboard and a LCD screen shown in Table 1.

TABLE 1. GUI design environment

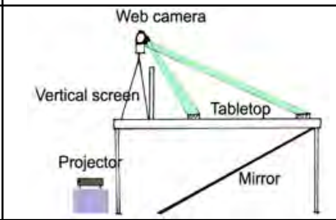
Hardware	Desktop computer/ Mouse & Keyboard
Application	ArchiCAD
Display space	Vertical LCD screen
Task space	Mouse & keyboard
Settings	 

We chose ArchiCAD as an application because it has typical GUIs feature such as a window, icons, menus and a pointing device. The mouse or keyboard produces indirect interaction with 3D models as a time-multiplexed input device controlling different functions at different times (Fitzmaurice 1996). Despite the physical form, the mouse has no physical contextual awareness and lacks the efficiency of specialized tools. The ability to use a single device for several tasks is a major benefit of the GUI, but given the nature of interaction where only one person can edit the model at a time, the GUI environment may change interactivity in collaborative design (Magerkurth and Peter 2002).

3.2. DESIGN COLLABORATION IN A TUI ENVIRONMENT

We used a digital design workbench with TUIs as a setting for the TUI-based collaboration. The digital design workbench is specifically configured for 3D design and visualization, where designers can manipulate 3D virtual objects directly in a semi-immersive environment and can be spatially aware of each other as well as the design. We employ a display screen to display the 3D augmented reality scene rather than HMDs or shuttleglasses. According to the research done by Billinghurst et al. (Billinghurst et al. 2003), the AR conditions with HMDs cause perceptual problems such as limited field of view, low resolution, and blurry imagery. The design of the digital workbench is shown in Table 2 (Daruwala 2004).

TABLE 2. TUI design environment

Hardware	Digital design workbench/3D blocks
Application	ARToolkit
Display	Vertical LCD screen & Horizontal table
Task space	Horizontal table
Settings	 

As multiple, specialized input devices for TUIs, 3D blocks with tracking markers in ARToolKit (Billinghurst et al. 2000) was used. 3D blocks are “space-multiplexed” input devices that can be attached to different functions, each independently accessible (Fitzmaurice 1996). They produce a direct hands-on style of interaction, which offers a form of tactile influence on the design as handles to the virtual objects.

3.3. EXPERIMENT DESIGN

We conducted four experiments, each experiment consisting of two sessions: a collaborative design task in a GUI environment and a collaborative design task in a TUI environment, Table 3. The use of two environments is the major variable in the study, while the remaining variables are set in order to facilitate the experiment but not influence the results. Each pair of designers participated in a complete experiment, so we could compare the same designers' across both environments. We will be reporting on one pair of designers in this paper since a change in designers may have a large impact on the results. The two design tasks were similar in complexity and type, and therefore shouldn't have an impact on the results. We needed to have different design tasks so the task would be new when a pair of designers moved to a different design environment. This ensures the designers were engaged in a design task at the same introductory stage. The relative complexity of ArchiCAD did not affect the results of the experiments because only several simple functions such as 'move' and 'rotate' were used for the design tasks.

TABLE 3. Experiment design

Experiment	**1**		**2**		**3**		**4**	
Sessions	TUI	GUI	GUI	TUI	TUI	GUI	GUI	TUI
Task	A	B	A	B	B	A	B	A
Participant	Pair 1		Pair 2		Pair 3		Pair 4	

Task A: Home office apartment, Task B: Interior design office

The design tasks were intended to simulate design review meetings for a studio renovation, a home office apartment or an interior design office - the designers inspected the current state of the 3D plan and then produced new ideas by working collaboratively. While the designers developed a 2D layout by placing the furniture, they also had to reason about 3D objects and their spatial relationships to satisfy a pre-defined set of specifications in the design briefs. We recruited 2nd year architecture students and did not allow them access to a pen or to the 2D view in ArchiCAD. A set of 3D objects were made available in the application's library for the furniture selection, and 20 minutes were allotted to them for working on the design task.

4. Segmentation and Coding Scheme

Our study is an adaptation of protocol analysis method: data collection, data segmentation, coding and analysis. During data collection, rather than ask the designers to think aloud, we recorded their conversation and gestures while they were collaborating on a predefined design task. The data collected for analysis includes verbal description of spatial knowledge and non-verbal data such as gestures. No questionnaire was used because we focus on capturing the contents of what designers do, attend to, and say while designing, looking for their perception of discovering new spatial information and actions that create new functions in the design.

4.1. SEGMENTATION

One way of segmentation is to divide protocols based on verbalization events such as pauses or syntactic markers for complete phrases and sentences (Ericsson and Simon 1993). Another way is looking at the content of the protocol, and divide the protocols into small units along lines of designer's intentions (Suwa 1998). We took the former approach because the intention-based segmentation that applies for single designers using think aloud protocols may be unsuitable for our communication protocols including pairs of designers. We chose individual designers' utterances as segments and retained the utterances as a whole rather than breaking down them into "meaningful" segments. Thus, each utterance flagged the start of a new segment, where we looked at the content of the protocols and coded them using our coding scheme.

4.2. CODING SCHEME

For each segment, we classified designers' cognitive actions into four categories including visual and non-visual information. Our categories and definitions are an adaptation of Suwa's coding scheme (Suwa 1998): 3D modelling actions, perceptual actions, functional actions and set-up goal actions.

The first category, 3D modelling actions, refers to physical actions including the selection, placement and relocation of 3D elements made by designers. We paid attention to the information of whether or not actions are new for each design action because we speculate that the revisited 3D modelling actions uncover information that is hidden or hard to compute mentally, and then this will play an important role in supporting designers' spatial cognition and idea production.

The second category, perceptual actions, shown in Table 4, refers to the designers' actions of attending to visuo-spatial features of the artefacts or spaces. We investigated three types of attentions to an existing design feature, two types of creations of new design features, and three types of unexpected discoveries as a measure of designers' perceptive abilities for spatial knowledge. In particular, unexpected discoveries are regarded as one key to gaining creative outcomes in the end and classified into three distinct types; "visual-feature-type", "relation-type", and "implicit-space-type" (Suwa 2000).

TABLE 4. Types of perceptual actions

Type	Definition: Behaviour	Definition: Dependent on	Feature
Type P1	attention to a visual feature of an element*	Look at previous layout	Attending to an existing one
Type P2	attention to a relation** among elements		
Type P3	attention to a location of an element		
Type P4	creation of a new relation	more than one "new" physical action	Creating new one
Type P5	creation of a new space		
Type P6	discovery of a visual feature	a single "old" physical action	Discovery
Type P7	discovery of a relation	more than one "old" physical action	
Type P8	discovery of an implicit space	implicit	

* The element can be an artefact or a space

** Each relation is divided into three classes; "furniture to furniture", "furniture to area" and "area to area"

The third category, functional actions, refers to actions of conceiving of non-visual information, but something with which the designers associate visual information. We include general functional actions, that is, thinking of a function of a space or an object, a circulation path, a view and a psychological reaction are involved. In particular, 'Re-interpretation' is coded when a designer defined a different function from a previous one when s/he revisits that part of the design.

The fourth category, set-up goal actions shown in Table 5, considers whether the segment indicates if a new goal has been defined. This category is closely related to Suwa et al.'s research (Suwa 2000). In particular, type 1.2, type 1.3, type 1.4, and type 2 are instances of the S-invention of design issues since the issue emerged at that moment for the first time. This category is important in spatial cognition while using TUIs because it highlights the designers' ability to find new relationships in these kinds of new interactive environments. We coded the goals of inventing new functions to clarify designers' problem finding behaviours in the different design environments.

TABLE 5. Types of goals to invent new functions

Type 1	goals to introduce new functions
Type 1.1	based on the given list of initial requirements
Type 1.2	directed by the use of explicit knowledge or past case
Type 1.3	extended from a previous goal (subtypes: concretizing & broadening)
Type 1.4	in a way that is not supported by type 1.1, type 1.2 and type 1.3.
Type 2	goals to resolve problematic conflicts
Type 3	goals to apply previously introduced functions in the current context
Type 4	repeated goals from a previous segment

5. Analysis

The following analysis is a preliminary interpretation of the data collected. We focussed on finding patterns of designers' behaviours and cognitive actions, specifically looking for significant differences in the data collected from the GUI sessions and the data collected from the TUI sessions.

5.1. OBSERVATION OF DESIGNERS' BEHAVIOURS

Through direct observation, we noticed that designers in the GUI sessions discussed ideas and decided on a solution before performing 3D modelling actions whereas designers in the TUI sessions communicated design ideas by gesturing at and moving the objects and deciding on the location of each piece of furniture as they were manipulating 3D blocks, Figure 1.

Figure 1. GUI-based collaboration

In terms of collaborative interactions, the TUI environment enabled designers to collaborate on handling the 3D blocks more interactively by allowing concurrent access to the 3D blocks and to produce more revisited 3D modelling actions before producing the final outputs. Designers in the GUI environment shared a single mouse compared to multiple 3D blocks, thus one designer mainly manipulated the mouse, Figure 2. On the other hand, with the direct, naïve manipulability of physical objects and rapid visualization, designers in the TUI environment seemed to produce more multiple cognitive actions and completed the design tasks faster.

Figure 2. TUI-based collaboration

5.2. CODING PERCEPTUAL ACTIONS

Looking into the content of cognitive actions, we found different patterns of behaviour between the GUI and TUI sessions in terms of perceiving an existing object or space (type P1, P2, and P3). Designers in the GUI session focused on the individual location itself whereas designers in the TUI session attended more to a spatial relation among objects or spaces. The following table shows an example of locating a sink in a design task A; the home office apartment. Designers in the GUI session just clarified the location of the sink without noticing the problem in relation to the bedroom whereas designers in the TUI session perceived an unwanted spatial relation.

TABLE 6. Perceptual actions on the location of a sink

Session	Transcript (GUI)	Category
GUI 2	Which she does not yet have… well she has a sink in her ba-bedroom, and then living/meeting area	Type P3
GUI 3	Where's the sink? That's the utility area	Type P3
Session	**Transcript (TUI)**	**Category**
TUI 1	It shouldn't be near the bathroom or I mean, I think it shouldn't be near the bedroom, sorry. It shouldn't have a kitchen sink.	Type P2
TUI 4	The sink sink, sink dosen't need to be in the bedroom. yeah sink in the kitchen. sink over here for now	Type P2

In terms of attending to a new relation or space (type P4 and P5), designers in the GUI session usually put an object in a position without considering any new relation or space based on the function of the object. On the other hand, designers in the TUI session created and attended to a new spatial relation by placing an object. Table 7 described an example of the placement of a new desk in design task B; the interior design office.

TABLE 7. Perceptual actions on placement of a desk

Session	Transcript (GUI)	Category
GUI 1	That one's got a little computer thing on it, and that can go in the corner….	none
GUI 4	How about we put in a new desk in this corner here	none
Session	**Transcript (TUI)**	**Category**
TUI 2	I am thinking of like a corner things. so we got…	none
TUI 3	We need a desk, first of all, for his um office area.. maybe one of this.. maybe in the corner there…..now we want the desk to go near the windows, so he can look out the window	Type P4

In comparison to the GUI session, designers discovered a hidden space among objects or a feature of an object unexpectedly when they were revisited (type P6, P7 and P8) more times in the TUI session. For example, even though a designer's initial intention was just to place a dining table near a sink, he or she happened to discover a couple of spaces in front of the sink as well as a spatial relation between these spaces. The following are examples of unexpected discoveries extracted from the verbal protocols of the two design sessions, Table 8.

TABLE 8. Unexpected discoveries in the two sessions

Session	Transcript (GUI)	Category
GUI 1	I don't like… it locks very empty there	Type P8
Session	**Transcript (TUI)**	**Category**
TUI 1	You end up with empty space in the middle. how this sofa faces onto her	Type P8
	You know how they have those kitchens that are just two long rows. And then that would be like, become like the bar. The breakfast bar.	Type P6

Table 9 shows the number of occurrences of perceptual actions derived from the 1st experiment. The overall distribution of number is different between the two design sessions. We noticed that designers using TUIs kept attending to existing elements through the design session whereas designers using GUIs produced design actions, not referring to their perception as much.

TABLE 9. The occurrences of perceptual actions

Types	TUI session		GUI session	
Type P1	14	75	5	23
Type P2	34		3	
Type P3	27		15	
Type P4	21	28	9	13
Type P5	7		4	
Type P6	4	13	0	2
Type P7	2		0	
Type P8	7		2	

We interpret the above findings as empirical evidence for the changes of designers' spatial cognition when using TUIs because they suggest that designers' understanding of the spatial relationships of the elements is improved in the TUI environment. Further, the fact that unexpected discoveries are more frequent in the TUI session indicates that the TUI environment encourages designers to perceive hidden features or spaces, which can be interpreted as one of pathways to creative design.

5.3. CODING GOALS FOR S-INVENTION

During the design sessions, the designers spoke about goals, and these segments were coded as set-up goals. Examples of set-up goal actions are shown in Table 10 and the number of goal actions for each type occurring in the 1st experiment is shown in Table 11. The largest number of goals is type 1 goals: the goals to introduce new functions for the four required spatial areas and relevant furniture layouts. This result could be from the kind of design tasks given to the designers. The design tasks are renovation tasks to be completed in a short time, so the designers rushed to provide new ideas based on their perception of the current states of the 3D design.

TABLE 10. Set-up goal actions in the two sessions

Session	Transcript (GUI)	Category
GUI 1	you can't have direct light on the drawing board, because of glare and stuff	Type 1.2
	our designer and utility in one half of the room…	Type 1.4
Session	**Transcript (TUI)**	**Category**
TUI 1	We need sleeping area, kitchen and working area	Type 1.1
	you've gotta leave a gap for walking	Type 1.2

Table 11 shows the differences in the number of goals generated in the two design sessions. Compared to the GUI session, designers in the TUI session set up goals to introduce new functions extended from a previous goal. This can be interpreted that the TUI environment stimulates designers to generate new ideas by broadening their previous ideas as the design process is going on.

TABLE 11. The occurrences of set-up goal actions

Types		TUI session	GUI session
Type 1			
	Type 1.1	4	1
	Type 1.2	23	17
	Type 1.3	10	2
	Type 1.4	23	16
Subtotal of Type 1		60	36
Type 2		0	0
Type 3		0	2
Type 4		15	5
Goals for S-invention (type 1.2, 1.3, 1.4 and type 2)		56	35
Total		75	43

5.3. CORRELATION AMONG COGNITIVE ACTIONS

We found several set up goal actions occurred with 3D modelling actions in the TUI session. Thus, we carried out a statistical analysis using the data of 1st experiment to roughly see whether or not there are correlations among designers' perceptual actions, 3D modelling actions and set-up goals actions. For this examination, we chunked every five segments, and re-categorised perceptual actions into four groups, type 1& 3, type 2, type 4 & 5, and type 6-8, which is related with the different patterns of perceptual actions discovered in the protocol analysis.

In the TUI sessions, correlations were produced between two types of perceptual actions of creating new one and goals for S-invention of functions, and between 3D modelling actions and three types of discoveries.

The two tailed Pearson coefficient of the correlations is more than 0.8. On the other hand, there was no significant result regarding the correlation in the GUI sessions. The correlation of 3D modelling actions and discoveries implies that 3D modelling actions in the TUI environment are the key actions to discover a hidden feature or space compared to the 3D modelling actions of the GUI environment. Further, the correlation of goals for s-invention and new attention to a relation or an empty space indicates that the designers' enhanced spatial cognition has a significant relationship with idea fluency. However, more protocols have to be analysed to reinforce these findings.

6. Results

The pilot study has shown that the TUI and GUI design environments produced different outcomes in terms of designers' behaviours and cognitive actions. The former was derived from the observation and the latter derived from the protocol analysis. Compared to designers using a GUI on a desktop computer, designers using a TUI on a digital design workbench exhibited the following behaviours:

- communicated design ideas by gesturing at and moving the objects visually;
- re-visited a design frequently while coordinating design ideas; and
- collaborated on handling 3D blocks interactively.

The differences in designers' cognitive actions are (TUI/GUI):

- attended to spatial relations among elements (34/3);
- created and attended a new relations or space by placing an object (21/9);
- discovered a space (7/2) or feature of an existing element unexpectedly (4/0);
- produced more goals to introduce new functions (56/35);
- indicated a correlation between two types of perceptual actions of creating a new design feature and goals for S-invention of functions; and
- indicated a correlation between 3D modelling actions and three types of discoveries.

7. Conclusion and Future Plan

The results indicate that the digital design workbench with TUIs effectively supports co-located, multi-user interaction and allows designers to attend to or to create spatial relations between artefacts or spaces. Further, the changes of designers' spatial cognition lead to idea production and to encourage designers to discover hidden features or spaces. Thus, we consider the digital design workbench as a very powerful platform for creative design that involves reasoning about 3D objects and their spatial relationships. Knowledge of the implications of the differences in spatial cognition provide a basis for developing and implementing new design environments as well as provide guidelines for their most effective use. In our next set of experiments, we will analyse design sessions in which a single designer designs using the think aloud method. We expect that the think aloud method will result in more verbal articulation of the perceived spatial relationships and spatial cognition.

References

Akin, O: 1990, Necessary conditions for design expertise and creativity, *Design Studies* **11**(1): 107-113.

Anibaldi, L and Nualláin, S: 1998, A Computational multi-layered model for the interpretation of locative expressions, *in* S Nualláin (ed.) *Spatial Cognition*, Benjamins BV, pp. 249-266.

Arias, E, Eden, H and Fischer, G: 1997, Enhancing communication, facilitating shared understanding, and creating better artefacts by integrating physical and computational media for design, *Designing Interactive Systems*, ACM Press, New York, pp. 1-12.

Billinghurst, M, Belcher, D, Gupta, A and Kiyokawa, K: 2003, Communication behaviors in co-located collaborative AR interfaces, *International Journal of Human-Computer Interaction* **16**(3): 395-423.

Billinghurst, M, Kato, H and Poupyrev, I: 2000, ARToolKit: a computer vision based augmented reality toolkit, *IEEE VR2000*, New Jersey.

Brave, S, Ishii, H and Dahley, A: 1999, Tangible interface for remote collaboration and communication, *Human Factors in Computing Systems (CHI'99)*, pp. 394-401.

Daruwala, Y: 2004, 3DT: *Tangible Input Techniques Used for 3D Design and Visualization*, Bachelor of Design Computing Honours Thesis, the University of Sydney.

Davison, J: 1995, The suddenness of insight, *in* R Sternberg and J Davison (eds.), *The Nature of Insight*, MIT Press, Cambridge, Mass, pp. 126-152.

Dias, J, Santos, P, Bastos, L, Monteiro, L, Silvestre, R and Diniz, N: 2002, MIXDesign, Tangible Mixed Reality for Architectural Design, *1st Ibero-American Symposium in Computer Graphics (SIACG)*.

Dorst, K and Cross, N: 2001, Creativity in the design process: co-evolution of problem-solution, *Design Studies* **22**(5): 425-437.

Ericsson, K and Simon, H: 1993, *Protocol Analysis: Verbal Reports as Data*, MIT Press, Cambridge, MA.

Fitzmaurice, G: 1996, *Graspable User Interfaces*, PhD Thesis, the University of Toronto.

Fjeld, M, Bichsel, M and Rauterberg, M: 1998, BUILD-IT: an intuitive design tool based on direct object manipulation, *in* Wa Fröhlich (ed.) *Gesture and Sign Language in Human-Computer Interaction*, Springer-Verlag, Berlin, pp. 297-308.

Foreman, N and Gillett, R: 1997, *Handbook of Spatial Research Paradigms and Methodologies*, Hove, UK, Psychology Press.

Gibson, JJ: 1979, *The Ecological Approach to Visual Perception*, Erlbaum Associates, New York.

Goldin-Meadow, S: 2003, Hearing Gesture: How Our Hands Help Us Think, Cambridge, MA, Harvard University Press.

Granum, E, Moeslund, T and Störring, M: 2003, Facilitating the presence of users and 3D models by the augmented round table, *in The 6th Annual International Workshop on Presence, Presence 2003*, Aalborg, Denmark, pp. 19.

Lavergne, J and Kimura, D: 1987, Hand movement asymmetry during speech: No effect of speaking topic, *Neuropsychologia* **25**: 689-693.

Lee, C, Ma, Y and Jeng, T: 2003, A spatially-aware tangible user interface for computer-aided design, *Human Factors in Computing Systems (CHI'03)*, pp. 960-961.

Loomis, J and Lederman, S: 1986, Tactual perception, *in* K Boff, L Kaufman and J Tomas (eds), *Handbook Perception and Human Performance*, New York, Wiley.

Magerkurth, C and Peter, T: 2002, Augmenting tabletop design for computer-supported cooperative work, *Workshop on Co-located Tabletop Collaboration: Technologies and Directions at CSCW'02*.

Maher, ML, Poon, J and Boulanger, S: 1996, Formalising design exploration as co-evolution: A combined gene approach, *in* JS Gero, F Sudweeks (eds) *Advances in Formal Design Methods for CAD*, Chapman and Hall, London, UK, pp. 1-28.

Norman, D: 1988, *The Design of Everyday Things*, New York: Basic Book,

Ohlsson, S: 1984, Restructuring revisited: I. Summary and critique of the Gestalt theory of problem solving, *Scandinavian Journal of Psychology* **25**: 65-78.

Perkins, D: 1981, *The Mind's Best Work*, Cambridge, MA: Harvard University Press.

Runco, M and Prizker, S: 1998, *The Encyclopedia of Creativity*, San Diego, CA: Academic Press.

Schön, DA and Wiggins, G: 1992, Kinds of seeing and their functions in designing, *Design Studies* **13**(2): 135-156.

Seichter, H and Kvan, T: 2004, Tangible interfaces in design computing, *eCAADe 2004*, pp. 159-166.

Suwa, M, Gero, J and Purcell, T: 2000, Unexpected discoveries and s-inventions of design requirements: Important vehicles for a design process, *Design Studies* **21**(6): 539-567.

Suwa, M, Purcell, T. and Gero, J.: 1998, Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions, *Design Studies* **19**(4): 455-483.

Ullmer, B and Ishii, H: 1997, The metaDESK: Models and prototypes for tangible user interfaces, *Proceedings of User Interface Software and Technology (UIST)' 97*, pp. 14-21.

Underkoffler, J and Ishii, H: 1999, Urp: A luminous-tangible workbench for urban planning and design, *in Human Factors in Computing Systems (CHI'99)*, pp. 386-393.

Wagner, S, Nusbaum, H and Goldin-Meadow, S: 2004, Probing the mental representation of gesture: Is handwriting spatial?, *Journal of Memory and Language* **50**.

Weisberg, R: 1982, Case studies of creative thinking: Reproduction versus restructuring in the real world, *in* S Smith, T Ward and R Finke (eds), *The Creative Cognition Approach*, MITPress, Cambridge, Mass, pp. 54-71.

Wertheimer, M: 1982, *Productive Thinking*, Chicago, University of Chicago Press.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 251-274

IDEA IMPROVEMENT IN DIFFERENT DESIGN ENVIRONMENTS

THOMAS KVAN AND SONG GAO
The University of Hong Kong, Hong Kong SAR, PR China

Abstract. We argue in this paper that remote design environments support creative thinking and substantiate the claim using analysis of protocols using linkographic techniques. Reviewing types of creative thinking, we note that creative thinking can be identified as component cues to enable further design actions as well as specific responses to particular contexts. Creative thinking thus reformulates problems by bringing new information; selecting new orders or settling new discipline and has great impact on subsequent design activities. Working remotely through text communication appears to enable richer creative communication.

1. Introduction

> Man's use of mind is dependent upon his ability to develop and use "tools" or "instruments" or "technologies" that make it possible for him to express and amplify his powers.
>
> Bruner 1966

After the invention of printing, a revolution took place in education that moved from oral legacies to a dependence on literacy (Olson 1974). Today, information and communication technologies are adopted increasingly as teaching tools. To understand how and why these tools can be applied in creative tasks, studies have been carried out to analyze creative cognition while using these tools (Kvan et al. 1997; Lahti et al. 2004; Scardamalia and Bereiter 2004). Unlike the popular notion of creative thinking, that it is "a light bulb flashing on in the thinker's mind", we approach creative action as a process consistent with problem framing or idea improvement (Scardamalia and Bereiter 2003) and examine information and communication technologies applied to creative collaborative work.

This paper investigates whether creative thinking is promoted and supported in design process when using online remote technologies compared with co-located designing. By using a representation technique, linkography, we identify that in a remote setting in which text is a mode of design communication can better support creative process than both co-located settings where speaking as a mode of communication.

2. Literature review

The first four parts of literature review will discuss feature of creative thinking. In the last two parts we will study the properties of cognitive actions raised by two types of representations, which are writing and speaking and finally examine the literature in remote collaboration.

2.1. PROBLEM FRAMING

Problem framing is the form of conceiving and planning (Buchanan 1995) belonging to creative activities (Newell et al. 1962). Tardif and Sternberg (1988:430-431) identify four trends of viewpoint on evaluating creative process:

- The creative process is an active search for gaps in existing knowledge, problem finding, or consciously attempting to break through the existing boundaries and limitations in one's field;
- Creative products are outcomes of random variations at either the generative or selection stage in creative processes;
- Creative processes may be seen as initiating from a previous failure to find explanations for phenomena or to incorporate new ideas into existing knowledge;
- Creative process is from a general drive toward self-organization through the reduction of chaos.

Problem framing therefore is creative process through which design ideas are produced to identify and formulate design problems. Ideas are representation of problem framing. In other words, the activities of problem framing are displayed by design ideas. An idea, which is instituted by observation, is a possible relevant solution of problem. It is a meaning when the meaning is conditionally accepted. Ideas, like suggestions from data or facts, problems and doubts etc., are essential to the process of discovery or reflective thinking. As long as the ideas are concerned, they could "guide new observations of, and reflections upon, actual situations, past, present, or future" (Dewey 1933:106). It becomes a tool "with which to search for material to solve a problem." There are two traits of an idea, one is merely a suggestion, "it is a conjecture, a guess, which in cases of greater dignity we call a "hypothesis" or a "theory". … which is a possible, but as yet doubtful, mode of interpretation"; the other is that idea acts a platform to direct inquiry and examination.

2.2. IDEA IMPROVEMENT

Good ideas initiate creativity and the intensive interlinking among ideas are the embodiment of creative and good design (Goldschmidt and Tatsa, 2005). The connection among ideas represents how ideas improve from one idea to a slightly different idea, therefore sustaining creative thinking.

Knowledge building is “creative work with ideas that really matter to the people doing the work”(Bereiter and Scardamalia 2003). The main focus of knowledge building is idea improvement (Bereiter and Scardamalia 2003; Scardamalia and Bereiter 2003). During the process of idea improvement, deep constructive activities will occur, such as “identifying problems of understanding, establishing and refining goals based on progress, gathering information, theorizing, designing experiments, answering questions and improving theories, building models, monitoring and evaluating progress, etc”(Scardamalia and Bereiter 2004). Problem framing is a process of problem reformulation by bringing new information; selecting new orders or settling new discipline, which is therefore similar with the concept of idea improvement in knowledge building.

2.3. INTERACTIVE VS. CONNECTIVE VIEWPOINT

How are ideas interlinked each other to contribute idea improvement? Theories about the interaction between cognition and representation might give us some answers. Two approaches taken are to consider interactive viewpoints (Bruner 1966; Rusch 1970; Oxman 2002) and connective viewpoints (Dewey 1930; Piaget 1950; Vygotskii 1965).

2.3.1. Interactive viewpoint

The interactive model of cognitive processing addresses the interaction between human cognition and representations. There are two senses in which representation can be understood (Bruner 1966), the first as the medium employed and the second the objective of representation. In terms of the first sense, we can understand “three ways in which somebody knows: through doing it, through a picture or image of it, and through some such symbolic means as language”, that is, through actions, images, and symbols respectively. Each form of representation can support symbolic manipulation, image organization, or the execution of motor acts. Each representation represents a level of cognitive development, and has its unique way of representing events. “We can talk of three ways in which somebody “know” something: through doing it, through a picture or image of it, and through some such symbolic means as language”(Bruner 1966:6). The three systems are parallel and each is unique. Bruner considers that “to understand the distinction between the three can achieved by viewing each as if it were external – though our eventual object is to view representation as internal." The three types of representation stand for three ways we adopt representation in learning or problem solving. He believes that in "know-how" process, an action system, representation is designed to guide and support symbolic activity. The cognitive growth is the cyclical development from enactive to symbolic representation.

Building upon Bruner's and Piaget's studies of cognitive development of children, Rusch (1970) further classifies awareness into four levels. They are emotional, kinesthetic, imaginal, and formal levels. Emotional level is depending on the state of satisfaction of one's basic needs. Kinesthetic level is that through repeatedly developing habitual actions, one begins to differentiate from the new activity requiring his total involvement. The imaginal level refers to literal or iconic images held by people "composed of surface cues and with little recognition of underlying structure". The last level is formal level in which people think logically and consistently. Rusch correlates the four levels with four stages of mental development (Figure 1).

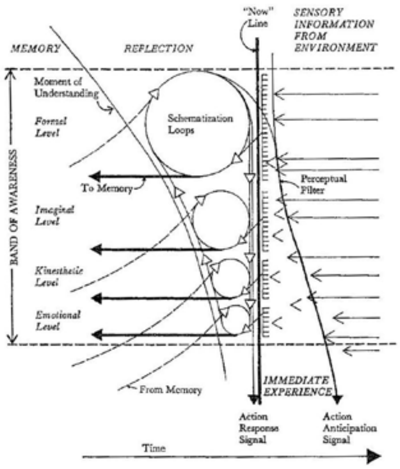


Figure 1. A functional model of mental process (Rusch 1970)

2.3.2. Connective viewpoint

Creative cognition does not arise formed and in isolation, it can be observed as "an active… intellectual process" (Dewey 1930) and consist of "concatenations and articulation of a complex set of interrelated moves" (Gruber 1980). This process is one of a communication between understanding, solutions and designer (Dewey 1930; Schön 1983). The transformation process has been identified as essential in concept formation in which the relationship between ideas plays a key role, allowing several ideas to form a complex. "In a complex, individual objects are untied in the child's mind not only by his subjective impressions but also by bonds actually existing between these objects. … A complex therefore, is first and foremost a concrete grouping of objects connected by factual bonds"; in all, five transformative complexes are identified, Table (Vygotskii 1965:112-113).

TABLE 1. Five types of transformation (after Vygotskii 1965)

	Type of complex	Meaning of each type of complex
1	Associative complex	Share a common trait or a contrast or proximity in space.
2	Collection complex	Objects are placed together on the basis of some one trait in which they differ and consequently complement one another.
3	Chain complex	A dynamic, consecutive joining of individual links into a single chain, with meaning carried over from one link to the next.
4	Diffuse complex	Attributes are sometimes considered similar, not because of genuine likeness, but because of a dim impression than they have something in common.
5	Bridge complex	It is between complexes and the final, highest stage in the development of concept formation.

In evaluating the effectiveness of a design conversation, therefore, we must identify the connections, not only the ideas that arise. By recognizing the contribution of interaction between cognition and representation, connective viewpoint examines the potential of different types of representation to produce effective or good ideas, those that last and inform subsequent design actions during the design process.

2.4. WRITING VERSUS TALKING

Verbal representations refer to the spoken words occurring in face-to-face settings, and written words for communication (Galaburda et al. 2002). Lawson and Loke (1997) observe that text plays a key role during design process for interpreting design ideas. The written notes attached with sketches are frequently used. This kind of representation, written by designers to communicate with themselves and others, thus is a kind of written words. In digital design written words are represented in form of email (asynchronous communication), chat-line (synchronous communication), or web-board (semi-asynchronous communication), etc. These tools provide additional channels for communication in contract with face-to-face settings.

2.4.1. Experiential and reflective cognition

Experiential cognition is essential to skilled behavior and appears to flow naturally. It is reactive, automatic thought, driven by the patterns of information arriving at our senses. In other hand, to make it possible might also requires years of training and experience (Norman 1993:25). This process can be separated into two phases: one is recognition and the other is emergence, which are both coping with visual discovery (Gombrich 1982). Recognition is clearly an act of remembering, but different with recall. Sometime people could recognize a picture but nothing to do with recall. The recognition is easy, effortless, immediate and almost automatic, thus largely unconsciousness. The unconsciousness refers to "those automatic processes to which we need not and often cannot attend." Naturally we need to focus on something, but never on everything. This process is called as selective attention, which is described in later part. Recognition is to select familiarity to attend without consciousness. "What we "see" is not simply given, but is the product of past experience and future expectations". Thus the result of recognition is the product of interaction between new interests and new visual experience, which are evoked by external representations.

Emergence is the product of recognition resulting in the inference or re-interpretation of images (Soufi and Edmonds 1996; Oxman 2002). Oxman further articulates emergence to "anticipated emergence" and analyzes Schön's "reflective conversation with situation" to draw a conclusion that this kind of emergence is "the recognition of visual shapes and images in design that enables emergence". In common with Oxman, Soufi and Edmonds (1996) consider that emergence involve two processes: first an interpretation and perceptual process, and, second, a transformational process. The first process is constraining while the second process opens up more alternatives. Fish (1996:208) distinguishes visual recognition into two processes: "automatic memory access process which occur unconsciously and those which are initiated with conscious intention is unavoidable". Summarizing these studies; we attribute both actions as recognition and emergence. The combination of the two processes are intuition, which is mostly are the acts of recognition (Simon 1996).

The distinctions and interaction between experiential and reflective cognition are discussed by Norman (1993:21-28). Compared with experiential cognition, reflective cognition is slow and laborious, "requires the ability to store temporary results, to make inferences from stored knowledge, and to follow chains of reasoning backward and forward, sometimes backtracking when a promising line of thought proves to be unfruitful. … the use of external aids facilitates the reflective process by acting as external memory storage, allowing deeper chains of reasoning over longer periods of time than possible without the aids. … The reflective cognition is conceptually driven, top-down processing".

2.4.2. Spoken words versus written words

McLuhan (1994:78-79) distinguishes three differences between spoken and written words. Written words could facilitate individualism and privacy contributing separate individual from group, while spoken words “do not afford this kind of extension and amplification of the visual power”. Second is that “the written word spells out in sequence what is quick and implicit in the spoken word.” The third difference is when using speech we intend to “react the each situation, reacting in tone and gesture even to our own act of speaking”; but “writing tends to be a kind of separate or specialist action in which there is little opportunity or call for reaction”.

The spoken words lack critical affordance; they are low-speed, and low-capacity communication. The information carried by spoken words is only available in the duration of sound itself. “Voice is serial, vision is parallel; voice is transient, printed or displayed images are permanent” (Norman 1993:108). Norman notices that writing permits ideas to be permanently recorded and allow people to read, thus prolonging the time for reflection. Compared with voice, therefore, text can facilitate more mental imagery, prolong the duration of reflection, and enable more reflective cognition. By these means, a designer may be able to engage in more effective reflection using text than spoken words. Text engages intellectual activity, initiates mental process and facilitates a creative attitude (Plocke 1996).

Language is a typical propositional representation. There are two cognitive actions raised by written words: one is reading and the other writing. Reading written words is to understand what those words mean. This action called by McLuhan (1994) as phonetic writing is adopted to compare with spoken words (see above). Norman considers that reading cannot service reflective thoughts if people do not know how to question and examine the content of the book, indicating reflective cognition is a conscious activity. He suggests two ways of reading: *reading* what presents; and is *naming* what presents. Experimental results show that naming takes longer than reading, which suggests that naming process is more complex than reading process (Fraisse 1969). This second way of reading is essential to framing, when designers to formulate and re-interpret a problem, they need to consciously question and examine what they are doing.

Olson (1994) examined the potential of writing to the development of meta-idea and points out that writing frees cognition from memory, allowing a new form of conversation. He considers that writing provides the model of speech. “Ideas are the counterpart of words; when words are seen as objects, so too are ideas. It is writing rather than speech, which encourages consciousness of the distinction between what I say and what I meant to say.

It is “what was meant” which comes to be seen as the mental” (Olson 1994:241).

In a study of online education environment, Harasim (1990) analyzes the advantage of textual communication over the face-to-face verbal communication. First textual communication helps designers engage more reflective cognition than talking in a face-to-face setting. Second text-based environment can enhance meta-cognition skill.

Several differences built upon the above literature can be drawn below,

- Written words facilitate individualism and privacy; while spoken words are not.
- Written words support reflective cognition; spoken words support “reaction”.
- Written words are superior to spoke words in that they provide a model of speech, thus might be called as meta-speech.

2.5. DESIGNING IN CO-LOCATED AND REMOTE ENVIRONMENTS

Media richness theory suggest that more informal and more interactive media are better suited for handling the more complex, equivocal, and emotional aspects of these task (Chalfonte et al. 1991) and provides a foundation on which to explore the application of different media in communication and collaboration, especially when comparing remote settings with co-located settings (Chalfonte et al. 1991; Kock 1998; Shah et al. 1998).

Daft et al.’s (1987) identify two problems in information processing, uncertainty and equivocality. Rich media reduce both and are thus considered better at supporting knowledge communication. Four criteria, Table 2, are set to evaluate the richness of each media (Daft et al. 1987).

TABLE 2. The description of four criteria

Criteria	Description
Feedback	Instant feedback allows questions to be asked and corrections to be made.
Multiple cues	An array of cues may be part of the message including physical presence, voice inflection, body gestures, words, numbers, and graphic symbols.
Language variety	Language variety is the range of meaning that can be conveyed with language symbols.
Personal focus	A message will be conveyed more fully when personal feelings and emotions infuse the communication. Some messages can be tailored to the frame of reference, needs, and current situation of the receiver.

According to these four dimensions, Daft et al.’s (1987) consider that face-to-face communication is the richest media compared with other three types of media, in decreasing order of richness: telephone, written, addressed documents, and unaddressed documents. In their words,

> Face-to-face is considered the richest communication medium. Face-to-face communication allows rapid mutual feedback. A message can be adjusted, clarified, and reinterpreted instantly. … Face-to-face also allows the simultaneous communication of multiple cues. …Face-to-face communication also uses high variety natural language and conveys emotion. (: 359)

In studying the selection of different communicational media by middle- and upper-level managers, Daft et al. found that managers prefer rich media for ambiguous communications and less rich media for unequivocal communications. Chalfonte et al (1991) examined the effects of the expressiveness component of rich communication by comparing voice to text. This expressiveness of rich media is developed from three above criteria (Multiple cues; Language variety; Personal focus). The data supported Daft et al.'s conclusions; "Rather it appears that in this case the richer medium was superior because it was more expressive, in part because it placed fewer cognitive demands on a communicator. These features of voice as a means of expression allow communication to devote more attention to the content of a message and encourage them to keep their audience in awareness during its creation." (Chalfonte et al. 1991:25).

The expressiveness of richness media proposed by Daft et al. (1987) and Chalfonte et al (1991) are nonverbal languages providing additional signs and cues to support communication. Although the expressiveness both studies emphasizing is crucial in some part of collaboration (like solving problems; providing additional information for explanation), the strongest points face-to-face communication provides are the interactionist (like instant feed-back) which the written environments they choose to compare can not offer.

Internet and computer technologies provide the possibility of interactionist that people could communicate synchronously through computers even in geographically distributed settings (Shah et al. 1998). Media richness theory later was mentioned by Shah et al., to investigate the use of multi-media tools through the Internet for the purpose of communication and collaboration synchronously between remotely located users; lacking experimental data, they only provide several predictions for the future usage of these tools. Taking media richness theory as a basis, Kock (1998) further divides different communicational media into two types, rich and lean. Face-to-face communication, for example is the richest form with its extremely short communication cycles that include verbal and non-verbal representation; email systems are examples of lean media that better support long-term cycles. The data collected from unstructured and structured interviews and transcripts of electronic postings from group members shows that electronic emails fostered better group outcomes. This finding appears to challenge media richness theory that claims that face-to-face communication is the richest media. Kock indicates that electronic emails, although considered lean media, provide richer or deeper perception than face-to-face communication. The reason is explained through a quotation from one of group members, “You think more when you’re writing something, so you produce a better contribution”.

Similarly, McCullough (1996:194) considers that “the more tacit expression, subtle interpretation, or latent content a medium is capable of communicating, the richer it seems”. In this sense, text based communications deepen comprehension and are rich media. In prior design process studies, text-based synchronous tools and web-board based semi-synchronous tools have been found to be rich media in supporting better design performance (Kvan et al. 1997; Maher and Gabriel 2000; Kvan 2002; Lahti et al. 2004).

This study builds upon these earlier findings to explore in greater depth the structure of these rich design communications. While earlier studies have found statistical evidence of improvements in design communication, the structure of this communication has not been revealed. The research reported here investigates this issue by employing linkographic technique as a tool to make explicit the content and nature of framing activities in collaborative design in co-located and remote environments.

4. Linkographic studies

Several methods have been proposed to map the content of design cognition and communication (Goldschmidt 1990; Taura et al. 2002; Lahti et al. 2004; Popovic 2004). In this study, we have engaged Goldschmidt’s linkograph as our representational technique as this method permits us to progress from earlier statistical examination of the protocols and provides succinct method for direct comparison between different protocols. It is a representation technique is “a system of notation and analysis of design processes that focuses on links among design moves” in which the structural connections between design actions is revealed particularly well (Goldschmidt and Tatsa 2005).

4.1. HISTORY AND APPLICATION

Linkograph technique was invented by Goldschmidt (1990). It is a graphic system in which “links among design moves are identified and graphically notated” (Goldschmidt 1990). This measurement is developed from Wang and Habraken’s study (Goldschmidt and Tatsa 2005). Goldschmidt and Tatsa (2005) describe this study thoroughly therefore we will not repeat here. The main advantage made by the research is to transform individual design decision into a network and identified an expert assessment called by them as critical path. Borrowing this term, Goldschmidt (1990) invents another type of graphic representation, which is linkograph. This type of representation could clearly depict the relation among different design actions as illustrated in the largest component in a protocol from our co-located setting, Figure 2.

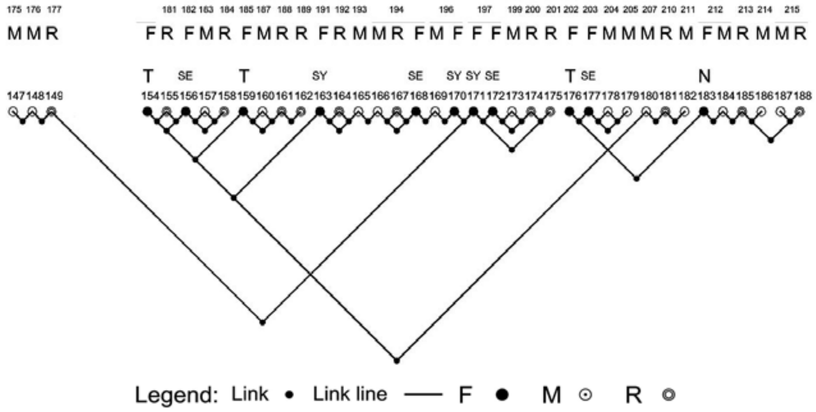


Figure 2. The largest component in a digital co-located setting (from Kvan and Gao 2005b)

It has been applied by others for different purposes (Goldschmidt and Weil 1998; van der Lugt 2000; Goldschmidt and Tatsa 2005; Kan and Gero 2005; Kvan and Gao 2005a). Van der Lugt (2000) apply linkographic technique to measure creative thinking in design meeting. They develop three types of links indicating three kinds of creative thinking. Kvan and Gao (2005a) apply this technique to represent two learning loops, single and double loop. Kan and Gero (2005) use a theory of communication to measure linkographic representations to identify entropy. The above three studies emphasize the individual properties of linkograph and do not holistically examine the full graphics of linkography representation. Distinct from these studies, Goldschmidt and Tatsa investigate the total number of links between design ideas. They adopt linkography as technique to measure correlates of design creativity. They hypothesize that "the more significant moves, or steps, or ideas in a process have the highest number of links to other moves or steps or ideas." The research method they applied in design studio was developed to track the idea development in studio setting. The results confirm the hypothesis they provide. In the end they conclude that good ideas or creative ideas are critical ideas with largest number of links.

Additionally, linkography reveals structure of design reasoning (Goldschmidt and Weil 1998). "[T]he link-pattern reveals the structure of reasoning, whereas the links, themselves, because they are determined by common sense, are largely based on the contents of the moves that they associate."

5. Research method

In common with several other studies in creative cognition (Finke et al. 1992; Vera et al. 1998; Maher and Gabriel 2000), we employed a controlled laboratory experiment to test the above hypothesis, in that this method can isolates variable to be studied.

5.1. EXPERIMENTAL DESIGN

The design of the experiment and methodology employed are derived from earlier work in the field, thus allowing some comparisons to be drawn later between these results and those already reported.

5.1.1. Design environments

The experiment has been used in previous studies to examine the efficiency of design learning in different computer supported collaborative settings (Kvan et al., 1997). This time we adopted one online remote studio setting from the previous studies and two co-located settings online co-located and paper based co-located, Figure 3.

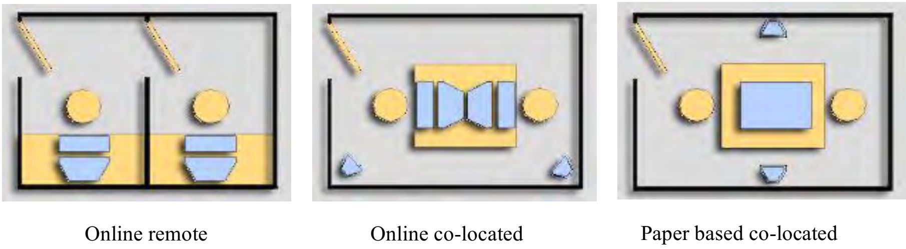


Figure 3. The layouts of the three settings

Both settings were recorded by digital-cameras set up to capture the verbal and visual data. To make these settings comparable we chose Microsoft NetMeeting including whiteboard and chat line as digital design tools and chose paper and pencils, etc. as paper-based design tools. This configuration has been adopted in previous studies to explore the design communications in computer supported environments (Kvan et al. 1997; Kvan et al. 1999). In the online remote setting, subjects are located remote from one another and communicate by chat line while drawing on a shared white board. In the online co-located setting, subjects drew on a shared white board when communicating face-to-face. Computer and Internet technology are becoming popular in design practice and studio. Paper-based design tools have been variously used in other studies, typically paper, pens, and rulers, etc. and the final representation of the design is produced on paper media (Schön 1985; Sellen and Harper 2001). Many researchers have studied design activities by using paper-based tools (Goldschmidt 1991; Schön and Wiggins 1992; Lawson 1994; Corona-Martinez and Quantrill 2003). In our paper-based co-located setting, subjects worked collaboratively on a shared drawing table sitting face-to-face by using paper, pens, and rulers, etc., a situation commonly found in design studios in educational or professional contexts.

5.1.2. Participants

The eighteen pairs of subjects are postgraduate students from the Department of Architecture in the University of Hong Kong. The subjects have been taught architectural design for more than three years in the same educational settings, therefore they are able to deal with this simple wicked problem by using shared design knowledge domain, and are supposed to finish the design task within the given time. In each setting, therefore six pairs of subjects are assigned. All of them are voluntary and only rewarded small money. Before the experiments, the experimenter asked them to sign a form of agreement in joining this design exercise. In both digital settings, subjects are trained to be familiar with the software before conducting real study. After experiments, subjects are required to fill in a questionnaire for the purpose of investigating their opinions of using these design tools.

5.1.3. Nature of data

According to the procedure of protocol analysis, the treatment of data occupies three parts, which are transcribing verbal protocols; coding protocols into categories and data analysis.

Transcription

The purpose of transcription is to transform verbal data into written words for data analysis. In this study, two types of design setting offer co-located collaboration in which verbal discussion is the recorded form of communication. The third design setting is online remote setting in which subjects use a chat-line to communicate; in this setting the textual supported communication is considered as equivalent to verbal communication in co-located settings. The language adopted for design communication, analysis and reporting is English, thus no translations were necessary; this was one of the daily languages of communication of the participants.

Coding schema

After full experiments were finished, the verbal discussion was transcribed into text. The researcher then coded the verbal protocol by using Schon's design paradigm (Schön 1984) and Minsky's frame system (Minsky 1977). The first coding schema is process-based type, used here to separate framing activities from other kinds of design activities. This schema follows Schon's design theory in which three design activities are involved, namely framing, moving, and reflecting. Schön's theory of "reflective conversation with the situation" describes the cyclical process of design in which the designer names, frames, moves and evaluates their work as the mechanisms of design. This schema has been adopted widely to articulate the design process. For example, Valkenburg and Dorst (1998) used these terms in study of design teams in which they proposed a model for Schön's process, identifying the stages as 'naming', 'framing', 'moving', and 'reflecting'. This last term they used, they say, in place of Schön's stage of 'evaluating' to emphasize the reflective nature of designing.

In their model, however, they introduce an important difference from Schön's use. Valkenburg and Dorst propose that Schön's framing encompasses the activities of moving and reflecting. This appears to be contrary to Schön's use of these terms. Elsewhere, Valkenburg (2001) has claimed that "Schön does not provide a clear, concise definition of the term 'frame'." However, as we have noted above, Schön does indeed clearly state that the process of framing is that in which they "determine the features to which they will attend" (Schön 1983:165). Similarly, Schön (1988) describes framing as that stage when the designer will approach a problem, "set its boundaries, select particular things and relations for attention, and impose on the situation a coherence that guides subsequent moves". This is very close to Schön's use of naming: "When a practitioner sets a problem, he chooses and names the things he will notice" (Schön 1987:4). We therefore propose that naming and framing can be taken together as a distinct prior step to moving and reflecting, where framing refers to the identification of a new design problem or idea, interpreted from design brief or recognition of new design ideas as the process is engaged or introduced as new design information that has not mentioned before. The other two terms are less problematic. Schön (1983:151; 1984:132) gives a clear definition of moving, stating that it is "to test a hypothesis … The very invention of a move or hypothesis depends on a normative framing of the situation". Moving refers to the production of a tentative solution for the problem at hand. Thus, moving comes after framing and is dependant upon it. Using Valkenburg and Dorst's term, we will refer to reflecting as the activity of evaluation of a solution, what Schön described as a state in which the situation "talks back", leading the designer to reframe, retest and re-evaluate. Thus, we will use the terms framing, moving and reflecting in the coding of protocols here, Table 3.

TABLE 3. The first coding schema (after Schön)

Coding category		**Definition**		**Examples**
Framing	:	Identify a new design problem; Interpret further from design brief.	:	We have to provide a sense of arrival at each site access point.
Moving	:	Proposed explanation of problem solving, a tentative solution.	:	Maybe some here can put the playground.
Reflecting	:	Evaluate or judge the explanation in 'Moving'.	:	I think it is ok. Just represent the design

The second coding schema is content oriented type, which was adopted to classify framing activities into four types (Minsky 1977). When engage in syntactic frames, designers raise design problems, which need to be solved. These design problems are mainly originated from design brief, which functions as stimulation. When engage in semantic frames, designers solve the design problem by using routine methods. This frame requires certain procedural knowledge. When engage in thematic frames, designers identify distinct design problems and profound design procedures. When engaged in narrative frames, designers work to make sense of thematic frames. We have further identified that these frames can be correlated with high and low level communication as identified by Kvan et al (1997) in which high-level design communication encompassed strategic and significant decisions; low-level design communication dealt with such aspects as the color of a line or placement of a detailed item, Table 4.

Using this definition of problem framing and frame systems, we can attribute high-level design communication to high-level frames; task oriented exchanges and low-level design communication to low-level frames. We observe that syntactic and semantic frames, as stimulus actions, arise mainly from the perception and action loop. These frames are not supportive of planning and abstract reasoning, therefore belonging to low-level frames. Thematic and narrative frames are evocative, engaging deep structures of memory, thus considered high-level frames.

TABLE 4. The second coding schema (after Minsky 1977)

Coding category		Definition	Examples
Low level frames	Syntactic frames	Mainly verb and noun structures. Prepositional and word-order indicator conventions.	We have to design the seats place inside, and the play-ground.
	Semantic frames	Action-centered meanings of words. Qualifiers and relations concerning participants, instruments, trajectories and strategies, goals, consequences and side effects.	How many seats do we have in the playground?
High level frames	Thematic Frames	Scenarios concerned with topics, activities, portraits, setting. Outstanding problems and strategies commonly connected with topic.	In fact I think the seats should be placed together to have better social interaction, maybe there is a round table, so three are bench chairs and one table.
	Narrative Frames	Skeleton forms for typical stories, explanations, and arguments. Conventions about foci, protagonists, plot forms, development, etc., designed to help a listener construct a new, instantiated thematic Frame in his own mind.	So we can place many seats around here in order to have a more pleasant area.

6. Results

The protocols recorded for each session were coded using the schema above to identify frame, move and reflection actions. Framing actions were then further encoded using the second schema to identify high and low level framing. Linkographs were drawn for each session.

Goldschmidt (1990) devised a measure of *link index* to measure the comparative complexity of critical moves and to identify the critical path in a linkograph. As she noted, a low index value suggests inexperience and a poor grasp of the design problem. The index does not tell us of the complexity of the links in a graph, so we have identified two additional metrics. One is the *ratio value* that tells us of the structure of the graph, and the second, *depth*, measures the continuity of design ideas across a graph. These are explained below.

6.1. RATIO VALUES

These protocols have been previously reported in Kvan & Gao (2005a) where analysis was conducted on the largest component only in each setting. For these, the depth and diameter were calculated; in that analysis, we found that the largest components in the remote settings exhibited the largest depth but not the largest diameters. That analysis, however, did not examine the largest component in its larger context of the whole protocol. The analysis technique we adopt in this study emphasizes the relation between largest component and the whole design process. To examine this, we have used two ratio values:

$$\text{Ratio value 1} = \frac{\text{the number of design activities of largest component}}{\text{the total number of design activities in the protocol}}$$

This ratio value, R1, measures the coherence of the largest component within the overall design process. If the ratio is low, the largest component represents but a small part of the overall process and hence suggests that the overall process was fragmented into many discrete and disconnected design actions. A large R1 indicates a persistency in design ideas as they are re-examined and interpreted, in which instance the largest component represents a major part of the design process thus suggesting internal coherence and continuity.

$$\text{Ratio value 2} = \frac{\text{the greatest depth in a component for the protocol}}{\text{the total number of design activities in the protocol}}$$

Ratio value R2 measures the reach and extent of revisiting of early ideas as the design progresses. Depth is a measure of the largest number of nodes linking two discrete design actions in a component and hence describes complexity of relationships between design actions (Kvan and Gao 2005a). If a protocol exhibits a high R2, ideas are closely linked from beginning to end of the design session. A low R2 indicates rapid chaining of concepts but little cross-checking to earlier intentions. Using the terminology from Vygotskii's complexes, a high R2 suggests complexes of a higher order.

Results from calculating the two R values are presented for the three settings in Figure 4; in each setting the minimum, maximum and median are indicated. We can see that the value for R1 and R2 are substantially higher in the remote setting.

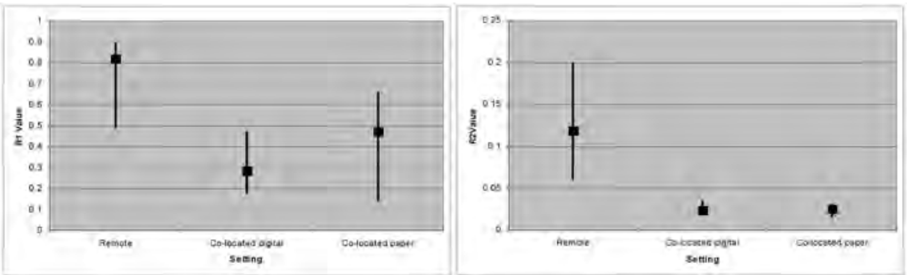


Figure 4. Results for R1 and R2

6.2. CASE STUDY

As we have reported elsewhere (Kvan and Gao 2005b), the proportions of framing found in these protocols varied significantly in the three settings (Figure 5), with the remote setting exhibiting a higher ratio of framing than the co-located settings and that the protocols from the remote setting exhibited more of both high and low level frames that the co-located settings.

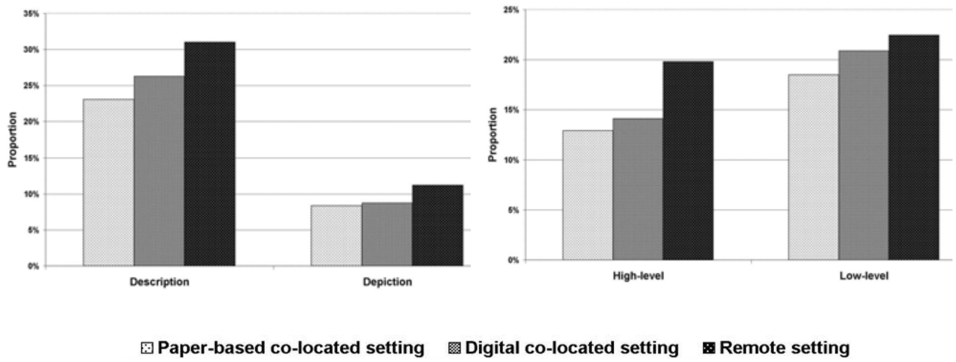


Figure 5. The comparison of the proportion of different frames of the largest components across the three settings (left: description vs. depiction; right: high and low-level of frames)

These initial findings are clarified by examination of three examples, one from each design environment, in which we can examine how a creative idea is introduced, improved and carried to later activities. Figures 6, 7 and 8 we show the linkograph for the largest component with the highest R1 value for each of the settings.

Remote setting

In this design environment, textual communication and digital drawing are main channels for design communication. The first protocol (Figure 6) shows designers' creative design ideas interlinking richly and over a considerable span of the design session. Design ideas are constructed into complexes by association and continuation of thoughts. We observed in this protocol that this pair of students continuously produces several high-level frames to correspond the first problem, like underground, open structure, evoked by the first high-level framing. Framing activities represent 39% of the actions in the component. The R2 value is 0.06, the lowest R2 of all remote protocols, indicating other protocols should yet richer complexes.

Figure 6 Highest R1 in the remote setting

Digital co-located setting

In this design environment, verbal communication and digital drawings are the primary channels adopted by designers for design communication. From the protocol (Figure 7), we observe a small amount of chaining even though this is the highest R1 recorded; framing occurs 29% of the time. The R2 value is 0.0234 which is close to the median value for this setting.

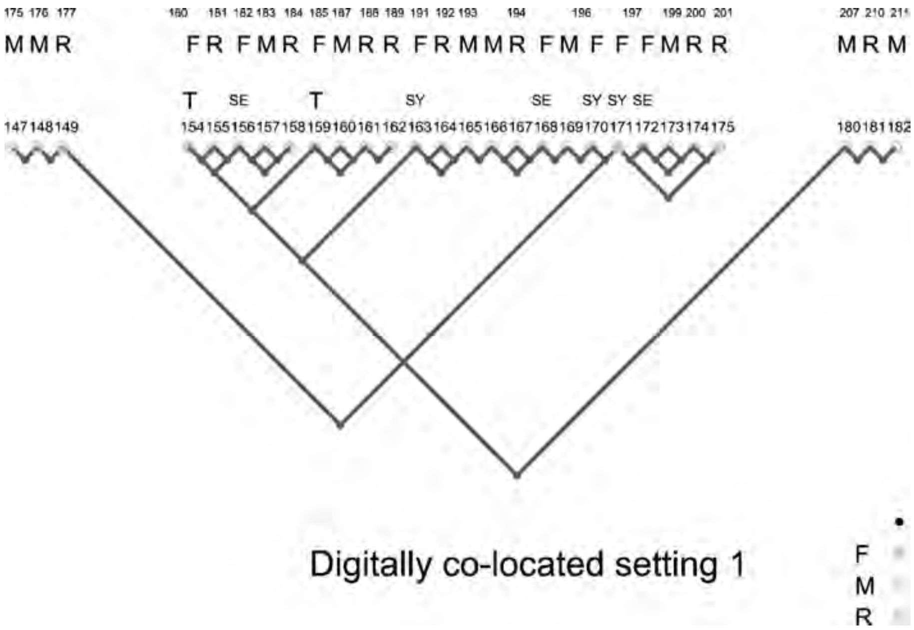


Figure 7 Highest R1 in the digital co-located setting

Paper based co-located setting
In this design environment, verbal communication and paper based drawing are main channels adopted by designers. The design engagement in this component has a short span (action 2 to action 48), Figure 8. Frames represent 28% of the actions; the R2 for this component is 0.0247, close to the median value for the setting.

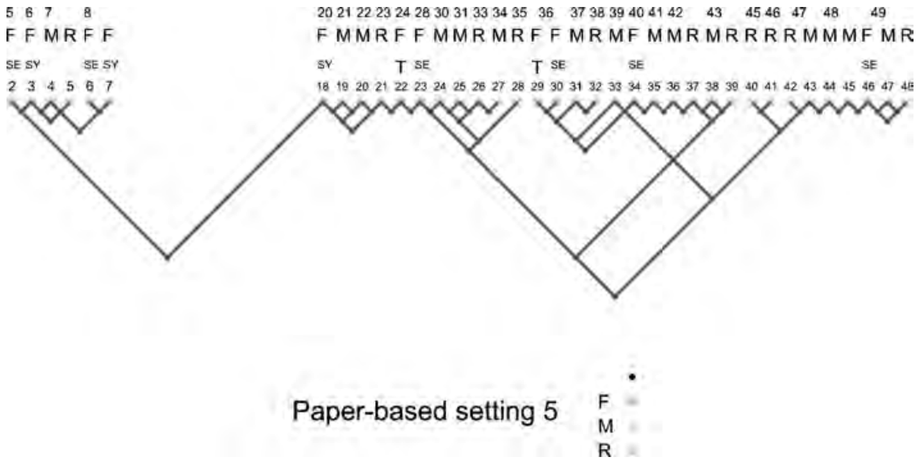


Figure 8 Highest R1 in the paper-based setting

Through comparing the content of each highest R1 of the three design environments, we find that in remote setting early designs idea lead to larger complexes with more frames than in both co-located settings. In this comparison writing communication again shows its advantage in problem framing process.

7. Discussion

The representational technique of a linkograph reveals the structure of design reasoning and is well suited for a comparative study of the design process. By linking design moves, linkography holistically describes design processes and provides graph data to analyze in order to identify the richness of design collaboration. This study has compared the problem-framing process as an indicator of the richness, since frequent engagement in framing suggests a deep engagement with the problem. Problem framing is the process of creative idea generation, which has been measured by using linkographic technique. Differentiating the modes of framing allows us to isolate further deep engagement from more procedural engagement.

We have stated in an earlier paper (Kvan and Gao 2005b) that the design activities in the remote setting demonstrated a more purposeful and richer engagement. Those in the remote setting not only engage in framing substantially more often than those in co-located settings, they also exhibit a higher proportion of higher level framing. In this paper, we have demonstrated further that the richness can be demonstrated by measuring the connectedness of design ideas as they develop.

Creative action as a process consistent with problem framing or idea improvement, developed a complex interrelationship of actions. If we observe a connection among ideas, indicating that ideas develop from one idea to a slightly different idea, i.e. connective cognition, we can infer we are observing sustained creative thinking. Using the linkograph, we have shown that sustained creative thinking can be traced through a design task, a progressive series of actions. The metric R1 shows the degree to which ideas are interlinked. The R2 metric identifies the interconnectivity in ideas. Richer creative thinking requires re-evaluation, returning to prior ideas and sometimes starting again (Scardamalia and Bereiter 2004). This will appear in our data as a higher value for R2. Multiple links, richly developed complexes, indicate higher levels of conceptual sophistication. Higher values of both R1 and R2 suggest richer and more interlinked ideas that are reengaged with greater complexity. The data from the remote setting exhibits both of these and hence we can conclude that the remote setting supports creativity well.

Idea improvement is not only the result of the interaction between cognition and representation, but also bridge previous and future ideas in form of different types of complex. From the literature, we can postulate that written communication better supports idea improvement than oral communication. Text is said to sustain the development of an idea, prolongs reflection, and facilitates cognition. We have shown that the remote setting supports more sustained creative thinking; the conversations in the chat line are more interconnected and complex constructions than those carried out verbally. The similarity of R2 values for both co-located settings suggests that the difference is in the text, not in the use of digital drawing interface. In these protocols, we observe initial ideas being developed and recorded in the remote setting, where a chat line is employed, are more persistent while in the paper-based setting the idea is developed sequentially and ideas do not chain as often to later actions (i.e. the depth is less). Ideas introduced early are picked up and developed later, an interactive cognition is developed with a consistency in pursuit. The experimental results demonstrate that writing communication with the aid of information and communication technologies could enhance people high-level design cognition and help them to produce better or more creative design performance compared with oral communication. Thus, the depth of the graphs measured is higher in the remote setting than in the co-located settings in which verbal communication dominates.

Although media richness theory proposes that a face-to-face environment can reduce task equivocality thus is a rich media, this theory is challenged by this and other studies. The comparative results show that the ratio values of remote setting are much higher that those of both co-located settings. These indicate that in remote setting design activities are not only much more holistic and comprehensive than those activities in both co-located setting, but also have stronger impact on latter activities. The results of this study indicate that writing communication, as a kind of design media, could not only deepen student design understanding and amplify human cognitive power, but also serve as chains to bridge different design concepts thus improving design ideas and letting creativity flow. Thus, we suggest that text-based collaborative systems should be considered a rich medium.

References

Bereiter, C and Scardamalia, M: 2003, Learning to work creatively with knowledge, *in* ED Corte (ed.) *Powerful Learning Environments: Unravelling Basic Components and Dimensions*, Pergamon in association with the European Association for Learning and Instruction, Amsterdam, pp. xviii, 239.

Bruner, JS: 1966, *Studies in Cognitive Growth: A Collaboration at the Center for Cognitive Studies,* Wiley, New York.

Buchanan, R: 1995, Wicked problems in design thinking, *in* V Margolin and RH Buchanan (eds), *The Idea of Design*, MIT Press, Cambridge, Mass.; London, pp. 3-20.

Chalfonte, BL, Fish, RS and Kraut, RE: 1991, Expressive richness: A comparison of speech and text as media for revision, *in* SP Robertson, GM Olson and JS Olson (eds), *SIGCHI Conference on Human Factors in Computing Systems,* ACM Press, New Orleans, Louisiana, pp. 21-26.

Corona-Martinez, A and Quantrill, M: 2003, *The Architectural Project,* Texas A&M University Press, College Station.

Daft, RL, Lengel, RH and Trevino, LK: 1987, Message equivocality, media selection, and manager performance: Implications for information systems, *MIS Quarterly* **11**(3): 355.

Dewey, J: 1930, *The Quest for Certainty: A Study of the Relation of Knowledge and Action,* Allen and Unwin, London.

Dewey, J: 1933, *How We Think: A Restatement of the Relation of Reflective Thinking to the Educative Process,* DC Heath and company, Boston.

Finke, RA, Ward, TB and Smith, SM: 1992, *Creative Cognition: Theory, Research and Applications,* MIT Press, Cambridge.

Fish, JC: 1996, *How Sketches Work: A Cognitive Theory for Improved System Design*, the Loughborough University of Technology.

Fraisse, P: 1969, Why is naming longer than reading, *Acta Pyschologica: Attention and Performance* **30** (II): 96-103.

Galaburda, AM, Kosslyn, SM and Christen, Y: 2002, *The Languages of the Brain,* Harvard University Press, Cambridge, Mass.

Goldschmidt, G: 1990, Linkography: Assessing design productivity, *in* R Trappl (ed.) *Cybernetics and Systems '90*, World Scientific, Singapore, pp. 291-298.

Goldschmidt, G: 1991, The dialectics of sketching, *Creativity Research Journal* **4**(2): 123-134.

Goldschmidt, G and Tatsa, D: 2005, How good are good ideas? Correlates of design creativity, *Design Studies* **26**(6): 593-611.

Goldschmidt, G and Weil, M: 1998, Contents and structure in design reasoning, *Design Issues* **14**(3): 85-100.

Gombrich, EH: 1982, *The Image and the Eye: Further Studies in the Psychology of Pictorial Representation,* Phaidon Press, Oxford.

Gruber, HE: 1980, Afterword, *in* DH Feldman (ed.) *Beyond Universals in Cognitive Development*, Ablex Publishing Corp, Norwoord, pp. 177-178.

Harasim, LM: 1990, Online education: An environment for collaboration and intellectual amplification, *in* LM Harasim (ed.) *Online Education: Perspectives on a New Environment*, Praeger, New York, pp. 39-64.

Kan, JWT and Gero, JS: 2005, Can entropy indicate the richness of idea generation in team designing?, *CAADRIA 2005 [Proceedings of the 10th International Conference on Computer Aided Architectural Design Research in Asia]*, New Delhi (India) **1**: 451-457.

Kock, N: 1998, Can a leaner medium foster better group outcomes? A study of computer-supported process improvement groups, *in* M Khosrowpour (ed.) *Effective Utilization and Management of Emerging Information Technologies* Idea Group Publishing, pp. 22-31.

Kvan, T: 2002, Learning through structural activity in collaborative computer aided design, *in Proceedings of the Seventh Conference on Computer Aided Architectural Design Research in Asia, CAADRIA '02,* Multimedia University, Cyberjaya, Malaysia.

Kvan, T and Gao, S: 2005a, Examining learning in multiple settings: using a linkograph to examine design learning, *in* B Martens and A Brown (eds), *Learning from the Past - A Foundation for the Future*, Springer, Dordrecht, pp. 187-196.

Kvan, T and Gao, S: 2005b, Examining the distribution of framing in design communication, *in* A Bhatt (ed.) *CAADRIA* **1**, TVB School of Habitat Studies, New Delhi, Delhi, India, pp. 458-464.

Kvan, T, Vera, A and West, R: 1997, Expert and situated actions in collaborative design, *in* P. Siriruchatapong, Z Lin and J-P Barthes (eds), *Proceedings of Second International Workshop on CSCW in Design,* International Academic Publishers, Beijing, pp. 400-405.

Kvan, T, Yip, WH and Vera, A: 1999, Supporting design studio learning: an investigation into design communication in computer-supported collaboration, *CSCL'99,* Stanford University, pp. 328-332.

Lahti, H, Seitamaa-Hakkarainen, P and Hakkarainen, K: 2004, Collaboration patterns in computer supported collaborative designing, *Design Studies* **25**(4): 351-371.

Lawson, B: 1994, *Design in Mind,* Butterworth-Heinemann Ltd., Oxford.

Lawson, B and Loke, SM: 1997, Computers, words and pictures, *in Design Studies* **18**: 171-183.

van der Lugt, R: 2000, Developing a graphic tool for creative problem solving in design groups, *Design Studies* **21**(5): 505-522.

Maher, ML and Gabriel, G: 2000, An analysis of design communication with and without computer mediation, *in* SAR Scrivener, LJ Ball and A Woodcock (eds), *Collaborative design: Proceedings of Co-Designing 2000,* Springer-Verlag, pp. 329-337.

McCullough, M: 1996, *Abstracting Craft: The Practiced Digital Hand,* MIT Press, Cambridge, Mass.

McLuhan, M: 1994, *Understanding Media: The Extensions of Man,* MIT Press, Cambridge, Mass.

Minsky, M: 1977, Frame-system theory, *in* PN Johnson-Laird and PC Wason (eds), *Thinking: Readings in Cognitive Science*, Cambridge University Press, Cambridge.

Newell, A, Shaw, JC and Simon, HA: 1962, The processes of creative thinking, *in* HE Gruber (ed.) *Contemporary Approaches to Creative Thinking: A Symposium held at the University of Colorado*, Atherton Press, New York.

Norman, DA: 1993, *Things That Make Us Smart: Defending Human Attributes in the Age of the Machine,* Addison-Wesley Pub. Co., Reading, Mass.

Olson, DR: 1974, *Media and Symbols: The Forms of Expression, Communication, and Education,* National Society for the Study of Education: distributed by the University of Chicago Press, Chicago.

Olson, DR: 1994, *The World on Paper: The Conceptual and Cognitive Implications of Writing and Reading,* Cambridge University Press, Cambridge.

Oxman, R: 2002, The thinking eye: visual re-cognition in design emergence, *in Design Studies* **23**: 135-164.

Piaget, J: 1950, *The Psychology of Intelligence,* Routledge & Kegan Paul, London.

Plocke, T: 1996, Word and picture in education, *Education for Practice 14th eCAADe Conference Proceedings* Lund, Sweden, pp. 365-370.

Popovic, V: 2004, Expertise development in product design--strategic and domain-specific knowledge connections, *Design Studies* **25**(5): 527-545.

Rusch, CW: 1970, On understanding awareness, *Journal of Aesthestic Education* **4**(4): 57-79.

Sargent, P: 1994, Design science or nonscience, *Design Studies* **15**(4): 389-402.

Scardamalia, M. and Bereiter, C.: 2003, Beyond brainstorming: Sustained creative work with ideas, *Education Canada* **43**(4): 4-7.

Scardamalia, M and Bereiter, C: 2004, Knowledge building, *in* JW Guthrie (ed.) *Encyclopedia of Education*, Macmillan reference, New York.

Schön, DA: 1983, *The Reflective Practitioner: How Professionals Think in Action,* Basic Books Inc., New York.

Schön, DA: 1984, Problems, frames and perspectives on designing, *Design Studies* **5**(3): 132-136.

Schön, DA: 1985, *The Design Studio: An Exploration of Its Traditions & Potential,* RIBA Publications Limited, London.

Schön, DA: 1987, *Educating the Reflective Practioner,* Jossey-Bass, San Francisco.

Schön, DA: 1988, Designing: rules, types and words, *Design Studies* **9**(3): 181-190.

Schön, DA and Wiggins, G: 1992, Kinds of seeing and their functions in designing, *Design Studies* **13**(2): 135-156.

Sellen, AJ and Harper, R: 2001, *The Myth of The Paperless Office,* MIT Press, Cambridge, Mass.

Shah, D, Candy, L and Edmonds, E: 1998, An investigation into supporting collaboration over the Internet, *in Computer Communications* **20**: 1458-1466.

Simon, HA: 1996, *The Sciences of the Artificial,* MIT Press, Cambridge, Mass.; London, England.

Soufi, B and Edmonds, E: 1996, The cognitive basis of emergence: implications for design support, *Design Studies* **17**(4): 451-463.

Tardif, TZ and Sternberg, RJ: 1988, What do we know about creativity?, *in* RJ Sternberg (ed.) *The Nature of Creativity: Contemporary Psychological Perspectives*, Cambridge University Press, Cambridge, pp. 429-440.

Taura, T, Yoshimi, T and Ikai, T: 2002, Study of gazing points in design situation: A proposal and practice of an analytical method based on the explanation of design activities, *Design Studies* **23**(2): 165-185.

Valkenburg, R: 2001, Schön revised: describing the social nature of designing with reflection-in-Action, *Design Thinking Research Sympoisum 5: Designing in Context,* Delft.

Valkenburg, R and Dorst, K: 1998, The reflective practice of design teams, *Design Studies* **19**(3): 249-271.

Vera, A, Kvan, T, West, R and Lai, S: 1998, Expertise and collaborative design, *CHI'98 Conference Proceedings,* Acm, Los Angeles, pp. 503-510.

Vygotskii, LS: 1965, *Thought and Language,* MIT Press Massachusetts Institute of Technology, Cambridge.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 275-300

CREATIVE ARCHITECTURAL DESIGN BOOSTED BY ITC ENHANCED INCUBATOR

How to facilitate tighter integrated collaboration to boost the emergence and diffusion of creativity.

GIANFRANCO CARRARA AND ANTONIO FIORAVANTI
University of Studies of Rome "La Sapienza", Italy

Abstract. Creativity in architecture presents quite specific features linked to the construction of spaces by means of elements that are "other": material ones. The problems arise out of the reciprocal relations – interfaces – between heterogeneous elements: interfaces between building elements, between the operators' cultures, between figurative elements, between 'form' and 'existing buildings' in the prevailing culture. Moreover, it is the work of multidisciplinary and intercultural knowledge. It is a process led by data, by the history of their evolution, while also the goals evolved, by hierarchies of authority, by increasingly rigorous rules, by delocations, by technological transfers – it is a 'complex environment'. Creativity in such an environment also, if not above all, means creativity of the team(s) and the project. We believe that the collaborative design paradigm is the most appropriate for boosting, disseminating and assessing the creative ideas arising in the course of design by the operators and users involved. It is therefore necessary to develop an overall model, or MetaSystem, that boosts to a maximum collaboration among operators both through the exchange of distributed knowledge by means of 'Intelligent Assistants', relevant to the various operators engaged in the design and building process, and through direct communication.

1. Creativity

Creativity derives from the verb to create, bring into existence, something that did not exist previously, *ex nulla re*. In its common acceptance it has been watered down to less drastic meanings; it also suggests novelty: *ex novo*. Both meanings indicate a substantial novelty with respect to the preceding actions in a given sector of human life. Creativity is a stimulus to leave aside common solutions and pre-set definitions, which form the scope of "common knowledge" in its broader meaning. In the last case it may be thought that they are inferred logically and consequentially, and thus deterministically, from the initial conditions and those premises – the context.

This further element that we have introduced – the context – in order to describe in detail, circumscribe and explain the field of the phenomenon of creativity takes on a decisive value as it reduces the data regarding the phenomenon (the variables from which it is claimed to derive the occurrence of the phenomenon itself) to two entities: the creating subject – the human side – and the context to be faced. The context has the same importance as the creating subject and can lead to creativity being favoured or hindered since, on the one hand, as we have seen, it may lead to the repetition of tried and tested solutions and conceptions; on the other, instead, it can introduce novelties, above all, if ideas from other contexts are accepted, transferred and/or adapted.

Creativity can innovate actions, solutions and conceptions so radically that the problems can be viewed in a new light: the sector will have a new point of reference.

Creativity manifests itself in two forms[1]: one, which is typical of technicians, of those who are profoundly involved in the technological aspects of a problem, that often introduce novelties in a given field of human activity, the idea is often taken from other fields[2]; the other, in which a new organization is set up on the basis of known conceptions and/or data from the field[3].

This duality of form in which creativity is expressed is found *ab initiis*, in the etymological roots of architecture as art and tectonics (see also below, section 1.1), in the never placated rivalry between designers and composers.

---

[1] Form is the correct term in this proposition as it is used unambiguously, but ambivalently. Indeed, in this case it should be understood not only as a 'modality' through which creativity is rendered explicit but also as a value in is own right, "to give connotations" – to define – to formalize, which presupposes a rationalizing activity, shared (judgment) canons. In the following we shall see how the word *form* in architecture denotes a further meaning - the language of space.

[2]For instance, the invention of reinforced concrete in which concrete and iron mimic wood and its fibers to replace planks in flower pots or boats (1848) or the 'non round wheels' of tanks or tracks; or in the microcosm-macrocosm, apple-Earth Earth-universe of Newton.

[3] For instance, the conception of structure (in an anthropological sense in accordance with structuralism) of a building by Le Corbusier in a reinforced concrete bearing skeleton and external cladding, the 'maison Domino'; or A. Einstein's special relativity starting from already largely known physical laws; or the Olivetti P101 of 1964 by P.G. Perrotto, the first computer for which the term desktop was coined.

Creativity, as we have seen, is not limited to “things”, but may be extended to include methodologies, processes, and interrelations. In the specific case of architecture it is not limited to building elements, but extends also to their realization, their modality of construction, the legislative procedures for their implementation and to their actual design.

As human history unfolds we observe that creativity, which is always the work of individuals situated in a context, has undergone sudden accelerations when the context is presented in certain conditions.

Indeed no algorithms exist to “produce” creativity, although particular conditions may arise that favour its onset and increase, that we may call ‘*incubators*’ a particular “proximity of human communities” for which it is socially significant to address abstract problems (which may or may not produce results for other human beings). Greek philosophers (420 B.C. – 330 B.C.), Italian Renaissance (1478-1515), differential calculus, Newton – Leibniz (1666-90), music – Baroque classical (1723-49), modern painting (1890-1915), Rationalism (1923– 36[4]). In all these examples the individual was able to “create” insofar as he was included in a ‘creative context’ – the incubator – . It is obviously somewhat tautological, but in all these cases in which an acceleration occurs in the “discovery of knowledge” the “proximity of interests”, often physical proximity, and emulation in a competitive context, the beginning of a favourable economic cycle, are in any case present. This is more or less what happens in nuclear fusion: both contact and critical mass are required.

1.1. CREATIVITY – PROJECT – ARCHITECTURE

It is beyond the scope of the present paper to examine the creativity issue in general or “in itself” in greater depth; nor do we wish to examine in detail the ontology of design concept that in our scientific community has been developed by Jones, Alexander, Akin, Archea, Mitchell, Negroponte, Simon, Cross, and others, but rather the *creativity – design – architecture* triangle[5].

The latter term is the one we are most interest in as architects. Just to delimit the field and to point out several peculiarities perceived by us we shall give a few relevant notes.

In a rough and ready definition, the word architecture has two roots, art and tectonics, which are closely related in the “creation” of a “space”[6] through “geometric forms” [7] constructed using materials.

---

[4] In 1923 Gropius became sole director at the Bauhaus; in 1936 that experience was lost and the first stone of the E42 in Rome brought to an end the last rational architecture-government architecture alliance.

[5] These three concepts are pertinent to the actor – process – context, par. 2.1.

[6] “Space” is the specific *object* of architecture (Zevi 1985, pp.21-32).

The two roots tell us that, as usual, it is necessarily the work of aspects that imply different manual skills; the fact that in primitive cultures a building can be made from start to finish even by a single person does not change the feature that architecture is a synthesis of different abilities. Indeed to define a space that is deemed necessary, it must be prefigured, and therefore *designed*, and built through the use of material elements, with all the aspects connected with their transport, processing and laying. Architecture as a network of different skills is confirmed by Vitruvius' definition: "Architectura est scientia pluribus disciplinis et variis eruditionibus ornata, cuius iudicio probantur omnia quæ ab cæteris artibus perficientur opera". In the first part of his definition he points out that it is a "science" supported by a number of cultures and various skills.

Therefore, architecture is a melting pot of knowledge; it is interdisciplinary by nature. It is born out of the meeting between different knowledge forms contributed by persons with different cultures and experiences and is the result of collective work among the different operators involved. Operators that are not necessarily designers in the strict sense, as in modern society the differences between roles are blurred, and they are often interchangeable in the sense that depending on the phases of the project the operators may be clients or designers. To satisfy the need for a more precise definition of these operators, who all share the fact of acting on the project according to their specific competences during the design process, they have been defined as *'actors'* by the ISO (Wix 1997). They will be referred to using this term in the present article.

Here we are concerned with investigating the relation between creativity and collaboration, as the latter is the element that characterizes today's design.

Design may be (and often has been) the fruit of individual creativity, even considering the inevitable relation between the latter and its context (which in any case is its own *incubator*).

If the work carried out among the actors takes the form of true collaboration among them, the condition required to give rise to an *incubator* is achieved, which we know is a culture medium for creativity.

Collaboration among actors, the pooling of knowledge and experience affords a two-fold advantage: design solutions are relevant, as cultural environments are contiguous and not disjoint; duplication of skills and conflicts of authority decrease as cultural environments are not overlapping.

---

[7] The latter represent a true language that expresses the spirit of the time in each period according to the community of operators interpreting it (Zevi 1985, pp. 49-99).

It is thus possible to make a more detached assessment of the work of other actors, insofar as they are not competing directly among themselves (Keil 1987).

1.2. PECULIARITY OF ARCHITECTURAL DESIGN VS. CREATIVITY

However, beyond the aspect highlighted by the contribution of different skills, often the result of the action of thousands of artist-craftsmen, as in the Gothic cathedrals, what is pinpointed by architecture?

Architecture is hard to define in essence; perhaps the most correct way of explaining what it is is through a definition given by the Arch. V. De Feo: "Architecture is identified with the history of architecture".

And the history of architecture viewed from the immanent, prosaic, aspect, as it were, neglecting the aspects regarding the aesthetics of the meaning, may be said to be an activity directed towards the construction of prototypes, an "act of faith" (Cross 1985).

These aspects link it to the other arts but again what is it that makes it so specific? The fact that it has to be the outcome of work involving many different skills requires a longer and more complex 'design' phase, although this may not be stated explicitly. Not only. In architectural design technical suitability [8] is much more important than in other arts which is the other determining element: architecture demands in-depth and effective relationships among disciplines, contexts and human factors, unlike poetry and painting.

1.2.1 Interdisciplinarity

If architecture were characterized solely by 'an activity directed towards the construction of prototypes' or by the "prevalence of technical appropriateness" [7], what would distinguish it at bottom from other types of small and very small series design, such as that of the aeronautics industry or that of Formula 1?

The fact that the its 'relations among different disciplines, contexts and human beings', compared with other sectors of human activity, share the characteristic of being hard to formalize.

Indeed all these relations: relations with the context, union of building elements, morphological relations among the elements, dialectics between

---

[8] Plato: "Architecture … the (artistic) action that produces, not the imitation of things, but the thing itself." He gives a value interpretation of it that is lower than the other arts, but greater in terms of technology "prevalence of technical appropriateness". Today we can say that the "non imitation of things" is now an acquired heritage due to all the arts, has taken on an absolute value and is the seal of each art set on the attempt to tear the 'Veil of Maya' that separates phenomenon from noumen, Schopenhauer.

operators, are in each case different. They are simply special cases of a single problem – that of the interfaces.

1.2.2 Interface with the context

One of the peculiarities of the design process in building consists of the location and, by extending this concept from the orographic and geographic area to that of temporal, cultural, technological, social, economic, ecological, etc. '*context*' [9], we may agree that design solutions previously devised for other "contexts" cannot be applied [10].

Indeed the interface with the *context* is unique, the 'boundary conditions' of a work of architecture depend not only on those mentioned earlier but also on the availability of building materials, infrastructures, town planning laws, local tradition regarding the use of spaces, changing customs, relationships with pre-existing buildings and those already planned, archaeological or historical finds, hydrogeological equilibrium and so on and so forth… There are no 'standard' situations[11] that allow situations and solutions to be reproduced: a correct architectural design makes it necessary to start from scratch.

In other words, it is necessary "to repeat the process" of how we arrived at the preceding solutions by means of new attempts to explore the "design solution space" of the new context. However, while in the past the evolution of the "context" took place as a linear progression[12], which allowed the various actors to gradually refine the building and the solutions over time – for instance the growth of the mediaeval cities or the period of the "rule of art", nowadays the transformation of the "context" is exponential [13] so that it obliges one to acknowledge various experiences and design approaches.

Once again it is "necessary to re-invent the wheel", and at each step.

---

[9] The term is used for the sake of simplicity of interpretation in its common acceptance. Perhaps 'situation' (Gero 1999, Gero and Reffat 2001) or 'condicio' (Carrara et al. 2004) would have been more cogent.

[10] Unlike the aeronautics or aerospace industries, which are also characterized by small series, e.g. the Space Shuttle, have 'standard' contexts in which the object performs its function, e.g. the upper atmosphere, or non standard conditions where standard conditions are re-established, e.g. landing fields on the Earth.

[11] Or which are re-presented in the same form, "you cannot bathe twice in the same river", Heraclitus.

[12] Knowledge growth of the individual actors of the same order of magnitude as that of knowledge of the project as a whole and that guides them.

[13] As this is a non linear phenomenon, it must be addressed using the tools of complexity.

1.2.3 Interface among building elements, Tectonics

This is a point that helps us understand the specificity of the building industry

In works of architecture, usually, complexity is found in the interface among constructive elements – the joint – between the 'parts'[14].

Two examples are sufficient to illustrate this. In masonry constructions, wall construction technology is extremely simple although making joints demands skill and knowledge to tooth together two walls converging to form an angle. The joints of the cables and struts of R. Piano's Beaubourg were 'invented' without anything material in the centre in such a way that the forces are concurrent in a point whatever their direction.

In each case the joints in architecture are generally different, between typical and market consolidated constructive elements.

In other sectors such as the aeronautics industry and mechanical engineering in general, a symmetrical approach is observed: the union of two complex 'pieces'[15] is achieved by means of simple joints.

In these, use is made of solutions acknowledged as valid and having precise, let us say, standard thermo-mechanical characteristics: flanged, bolted, bayonet, etc. The complexity of construction is shifted upstream, the processing of each piece can be extremely laborious, but it is essential for their union to be easy; and it is true that it is more appropriate to speak of assembly. The attempts to transfer these technologies unchanged to architecture[16] have all failed. Even if it were also true that the 'house' is a "machine à habiter", 'living' is certainly not a 'thermo-mechanical action'.

1.2.4 Interfacing among the persons involved.

One of the main problems in these processes lies in the different cultural baggage of the actors, in their different scientific-disciplinary background, in the different meanings and knowledge associated with the entities involved. Indeed the overall process is fragmentary because of the different actors, different phases and regulatory, environmental and cultural contexts. All this brings about inefficiency of costing and/or timing, or buildings that do not deliver the required performance.

Moreover, the need for such complex organization derives from the impossibility for the individual actor to cope with the required task in the time available.

---

[14] The name 'part' already suggests a whole from which it is conceptually separated.

[15] The term 'piece' already denotes an autonomy, a kind of completeness, of the object.

[16] Suffice it to recall Jean Prouvé's "maison tropicale", or the Dymaxion House and Wichita House of Buckmister Füller.

From the beginning of the project it is therefore necessary for the principal actors to interact amongst each and all of them[17]. In mechanical engineering the Concurrent Design paradigm has established itself. Separating design problems into independent ‘pieces', it aims at allowing simultaneity in decision-making. In designing architectural works it is necessary to consider that there is also a simultaneity of skills, which can lead to *conflicting solutions*, *selfish solidarity* or *paralyse decision-making*.

1.3. CREATIVITY IN ARCHITECTURE

Creativity is a possible way out of these oxymorons: *conflicting solutions*; as the greater the extent to which the study of the problems to improve the project is pursued by each actor, the more likely it is that his excellent specific solution in his own field will clash with other equally specific ones; *selfish solidarity,* in which each actor, despite being linked to a team whose reason for being depends solely on the successful outcome of the project, pursues his own goal; *paralyse decision-making*, indeed the more one seeks new solutions the greater the explosion of the number of their possible equivalent combinations, which can lead to the field of undecideability.

Creativity means moving outside apparently deadlocked logic, like the preceding oxymorons, of a given context in order to refer to other contexts in which such limitations have no further reason for being.

Design therefore can be the fruit of collaboration among the actors, and in the process, creativity, in its turn, will be the result of collaboration between the creativity of individual actors, their reciprocal relations, of the project.

In order to achieve a fuller understanding of the field on which we are focused, it is necessary to define creativity in architecture from three different points of view: the first is linked to ‘the solution’ (project), the second to ‘creativity as such’ (actor) and the third to the ‘design process’.

1.3.1 The ‘solution’ in architecture

As far as the first aspect is concerned it must be said that in architecture it is incorrect to speak of a ‘solution’ with reference to a design problem because, as we have seen, the problem(s) is(are) always of an interdisciplinary and intercultural nature; they must be viewed in the perspective of a design goal. However, the design goal is the *building* of the work[18] - neither the work itself, nor the peculiar ends of each actor involved.

---

[17] Obviously it is not a question of involving all the actors in all phases, but of having a qualified specific group for each phase. One possible way of identifying such a group – *the audience* – has been defined in Carrara and Fioravanti 2004, pg 432.

[18] This is the ideological position of our “Roman” school of Architecture in the Faculty of Engineering, in harmony with Brunelleschi.

In design, the actors work as a team to achieve the project and since the boundary conditions are always changing, the actor, by gaining fresh experience, changes his goals and objectives, which then modify the overall objective, which evolves over time in a non deterministic fashion.

The final object cannot be inferred from the premises and is therefore the fruit of a creative activity.

1.3.2 'Creativity' in architecture

As far as the second aspect, 'creativity *per se*', is concerned, there are two reasons that make it indispensable in designing architectural works.

The first is that in designing works of architecture, as well as building elements or parts of a building, the best solution is obtained when one attains objectives which, in different fields or at different scales, are optimal, but that could perfectly clash.

For example, in the addition to the Staatsgalerie by J. Stirling at Stuttgart (1977-83), the inclusion of the central courtyard. It, in order to have adequate dimensions (height/diameter ratio for optimum illumination, a width such as to allow an optimal placing of sculptures, a semi-circumference length in which to develop a ramp to offset the difference in level between the upper and lower entrances determined by a slight slope), clashes with the U shaped dimensions of the museum (which are then imposed by the dimensions of the building lot, the dimensions of the exhibition gallery section, the rearward position of the U shaped body with respect to the old wing and the new administrative part in such a way as again to make symmetrical and 'recenter' the new entire complex thus formed). This, as we raised earlier in section 1.2.3, is a typical interface problem between architectural elements, this time at the level of the composition of the building parts, which is solved not by giving up any of the compositive and functional prerogatives. In this, as usual, the solution is attained by deforming the points of junction and interlacing them. The solution is tertiary to the initial 'solutions' (design hypotheses), although embracing them both. The needs at a certain scale (dimensions and shape of an internal courtyard) clash with those at a different scale, in this case of a higher hierarchical order (the dimensions and shape of the entire museum complex) and are not evaluated hierarchically: for architecture they are on the same footing.

The second reason, even more specific to architecture, is that creativity is valid in itself. *Architecture is such only if it is creative, otherwise it is not architecture*. We have said that form is the language of architecture; it is immanent to it, and is not imposed from the outside.

Just as in a literary work it makes little sense to speak of 'motivations', but rather to evaluate it as such, as well as of 'repetition' as it is situated within a history of literature that is pushing towards new forms. This is the same for architecture: suffice it to think of works like the Chapelle de Ronchamps, the Sydney Opera House, the Guggenheim Museum at Bilbao in their respective contexts of sanctuaries, theatres or art centers. Not only but also, on a large scale it is possible infer what design is on a small scale: architecture is the goal pursued by the goals of individual works of architecture.

1.3.3 The 'design process' in architecture

The third aspect of why creativity is important is related to the design process. Indeed the concurrent design process, which has produced significant results in other sectors, shows its limitations when applied to architectural design, limitations due to the minimal overlapping of skills. However, one must avoid pursuing also the opposite myth: sharing all skills and/or knowledge. A vast dissemination of information (to indicate to all, all the open problems and the ongoing contradictions in the design solutions selected by each actor), does not necessarily lead to a better result. Suffice the example given by H. Simon in his *Science of the Artificial* (Simon 1996, pp. 143-144) regarding the number of telex machines in the State Department offices in the United States: an information overload leads only to unmanageable decisions. This observation indicates the essence of the problem: the importance of the context in identifying which opportunities/constraints must be selected and activated by which subjects. This is obviously, as one would say in philosophical terms, a question of 'degree'.

How necessary is it to filter the exchange of information and knowledge among the actors, and where must the selection be made?. And again, for each design phase, what skills are necessary for sharing, and to what degree, how can creativity be transferred, and how can conflicts be reduced? Clearly no single answer can be given to these questions, which must be examined case by case. Also here however we can glimpse the importance of creativity.

The process is not predefined in areas of competence; we have only a trace obtained from previous experience on to which to graft a variable geometry [19] of skills/actors.

---

[19] Variable geometry of aircraft wings (first operational example: General Dynamic F111 A, 1967) is a typical example of creative design, as in the Staatsgalerie of Stuttgart: retain both *forms* (open wings and delta wings) by means of compenetration (part of the wing enters the cockpit).

2. Architectural design today – complexity

Architectural design as a collective process consists of the intervention of and interaction among many professionals, as well as, indirectly, by the action of non professionals. Architectural design must be situated within the broader construction process in building which leads to the construction, restructuring and finally the demolition of the building asset.

Architectural Design must be considered as a 'process' subdivided into 'phases' each of which involving certain actors who have their own specialist skills, although all, to varying degrees, are aware of a shared "knowledge base" that allows them to interact.

In this sense the project is the outcome of *collective decisions* and in any case hierarchically managed, as the case may be, by one or more of the actors involved, Figure 1.

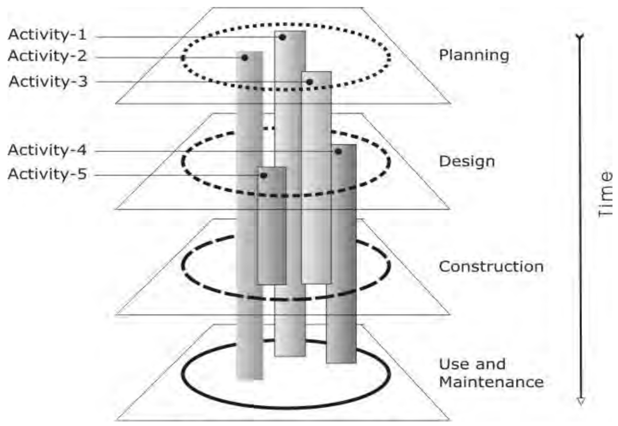


Figure 1. Phases of construction process.

The design of an architectural work is a process that in the industrialized countries, has gradually become more complex under the growing complexity of the architectural product, the number and different specializations of the 'actors' involved, the increasing demands of regulatory, procedural and technical prescriptions and the increasing lack of time, Figure 2.

This means that often in current professional practice the first solution is given priority, as it is deemed an acceptable basis for subsequent developments. Any 'creative' hypotheses arising out of the exchange of different knowledge and skills among actors are neglected as they would initially involve longer times or greater design costs, but would eventually give rise to a more sustainable architectural work. Precisely at a key moment in the design approach when it would be more suitable to explore different solutions one imposes self limitations.

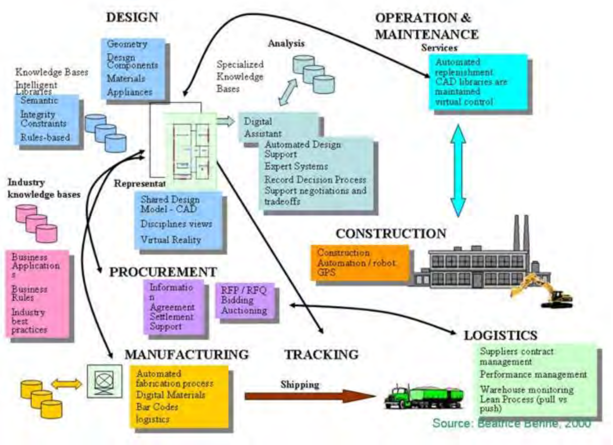


Figure 2. The "usual" model of design.

To avoid these drawbacks and to formulate and compare different design hypotheses within the limits set by the action chronogram it is necessary to make use of other forms of design process management which will facilitate matters and save time without limiting the creativity of the other actors .

The attempt to find more efficient systems for managing design complexity has attracted the attention of the scientific community for a number of years and had led to the introduction of methods and techniques of project planning and control in industrial, mechanical and manufacturing design.

Nevertheless the peculiarities of architectural design, linked as they are to a definite contextualization of place and user, render these techniques and methods of project management ineffective.

The characteristic of design in architecture, as we have already seen, is embodied in its multidisciplinary and interdisciplinary nature, and the consequent complexity of the design problem, is independent of the project dimensions and the involved disciplinary areas. Complexity is also due to the different forms in which it is expressed as a function of the regulatory procedures, which vary from one country to the next.

In this the field has aroused interest in the study of forms of *collaborative design* that pursue a greater involvement of the actors in the design process to interact in a *direct*, logically (not necessarily temporally) *simultaneous*, and *multiple* fashion in the decision-making process of the project in its various phases and on its various scales.

2.1. COLLABORATIVE DESIGN AND CREATIVITY

As stated earlier, the best way to boost creativity is to train and involve as a team a group of actors to reproduce an ‘incubator’. The design paradigm that comes closest to these intentions is the Collaborative one where several actors are involved in a project from the outset, work in close contact ‘project-wise’ (not necessarily from a physical point of view thanks to the development of ICT tools), and are involved in more than one project at the same time. In this way they:

- acquire and transfer knowledge and experience in one’s own field in different contexts;
- learn about new opportunities/needs of different disciplines;
- bestow experiences, opportunities/needs on the other actors of different disciplines.

This confirms what was stated in section 1.2; we are dealing with a context in which “symmetry of ignorance” is valid, which in this way is used in a positive fashion. The latter aspect opens up the horizon to possible new solutions through the transfer of ideas from one discipline to another, and to the application of technologies in areas that differ from the original one: the technology transfer.

Through the collaborative design a ‘virtuous circle’ is set up among the various actors in the project. This contributes to enhancing their own knowledge, from which three consequences derive.

The first is that it allows greater awareness to be attained in design choices, increases the exploration of design solutions in terms of quantity and quality, improves the project and the product. This consequence is strongly related to sections 1.3.1 and can have a positive influence on these aspects. As far as the ‘solution’ – the architectural process – is concerned, Collaborative Design makes it possible to publish the different *solutions* proposed by the various actors, to become familiar with them and thus to compare them. This can happen both by means of meeting physically and through ‘virtual arenas’, with the participation of experts as well as using specific ICT tools to enhance collaboration, as we shall see below. Not only; it also has a positive influence on the awareness by individual actors of the evolution of the *project* given that the meetings and the actual decisions taken are made known to the actors involved.

The second, more interesting one, is that the creativity of the individual actor is shared with others and the needs/opportunities of the other disciplines, often creative, learned by the actor, bring about new solutions in one’s own field. This second consequence is related to section 1.3.2, and actually entails a greater overall awareness of the reasons underlying the various design hypotheses being developed by the various actors. It gives rise to both a less conflictual trade-off, as each is more highly motivated to verify the creative design solutions of others in one’s own area, and to a more rapid emergence of opportunities/constraints.

The third, related to section 1.3.3, is that time and/or costs are reduced, as well as process efficiency increased. As far as the 'design process' is concerned, also in this case Collaborative Design will have significant knock-on effects on creativity, as it represents a precondition for it. Having to define/redefine the competences of the various actors before/during the design process will ensure a continual verification of the goodness of the most suitable work flow "in real time" among the design and construction activities and resources envisaged, of their modification and/or consolidation, and of the different modes of sub-contracting and funding used to implement them under pressure from new design hypotheses. In this way it will be possible to hypothesize, define and verify various process scenarios emerging from the creativity of the various actors.

For each actor, at every moment, the project is the 'design solution' proposed by him in the 'space of the design solutions of his own context'.

As there are several actors who vary during the design process and the procedural rules consist of specifications for the various phases of the process, we can claim that also the 'design solutions spaces' vary over time.

The overall building project is given by the intersection in the 'design solutions space' of those deriving from the *operating context* 1.3.1, those proposed by the *actors* 1.3.2 and those defined by the *process rules* 1.3.3, Figure 3.

This intersection may prove to be an empty set and so no solution will exist, or else, in the 'design solutions space', the solutions defined above are partially overlapping and so a more or less shared set of solutions exists.

Collaborative Design may be viewed as a procedural modality that modifies the 'design solutions spaces' of the individual 'actors', pursuing their harmonization and innovation until a more extensively shared and advanced intersection has been constructed. Creativity succeeds in overcoming the stated oxymorons by satisfying the various needs thanks to the contribution of actors and highly evolved ICT tools in an *incubator*.

2.2. COMPUTER ENHANCED COLLABORATIVE ARCHITECTURAL DESIGN

In the last few years groups of researchers have undertaken research aimed at identifying and proposing more advanced ICT methods and techniques to improve the efficiency of architectural design by means of the collaborative method Design (Woo et al. 2001; Kvan 2000; Gross et al. 1998; Jeng and Eastman 1998; Kolarevic et al. 2000).

In order to manage these problems effectively using specifically designed tools, two paths were followed: on the one hand, to continue to develop the existing process and product methods so far used to tackle them, and on the other to develop new and innovative tools for managing the process.

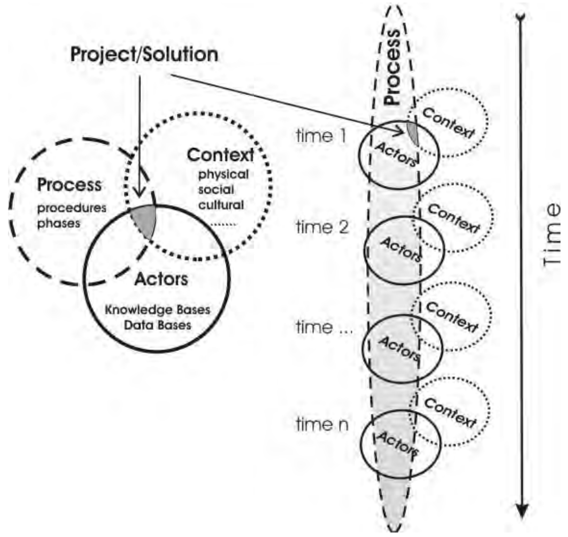


Figure 3. The project as an intersection set of "Design workspace" of the actors, the context and the process.

The former includes the evolution of the normal commercial CAAD systems (Laiserin 2000; Laiserin 2001), as typical ones of graphics aided (AutoCAD, Microstation, …) and integrated or parametric ones (Architectural Desktop, Revit, AllPlan, Triforma, Project Bank, …), in the other alternative Knowledge Engineering based approaches have been proposed by several researchers (Björk, 1999 and 1993; Carrara and Kalay 1994; Eastman and Siabiris 1995; Jacobsen et al. 1997; Papamichael et al. 1996; Kavakli 2001).

The latter systems have several models of the design process, but they are similar ones because they use a single Knowledge Base or Data Base. Because of the uniqueness, the pre-established cataloguing of the Building Organism, its components and the process, as far as sections 1.3.1 and 1.3.3 are concerned, reveals that these models are insufficient owing to the peculiar nature of architectural design and as regards section 1.3.2 – the architectural composition is not taken into consideration at all.

More precisely, the gaps in the software system supporting building design were identified as: the rigidity of the Data Bases, which do not allow inconsistency, the difficulty of having coherent KBs of the various actors, the incongruity of multi-semantic objects, the synchronicity of the process itself in which the IT objects referring to a process of architectural and building design are simultaneously modified by several actors.

We claim that these critical aspects of the design process are not accidental, sporadic or occasional but part and parcel of architectural design itself. In Collaborative Design these aspects are enhanced owing to the closer relations between actors, activities and resources.

Several research teams are moving to bypass these limitations (Reffat and Gero 2000; Kalay 2001; Eastman 1998; Turner 1997; Rosenman and Wang 2001; Carrara and Fioravanti 2002), albeit with different objectives and following different methods.

3. An overall model of the design process to boost creativity

To develop suitable methods, technologies and tools to enhance Collaborative Design in an innovative way using the timing and hierarchy deemed most suitable by the group of participating actors, with a high degree of interdisciplinarity, the correct use of the most advanced methods and technologies, and which allow the creative ideas of each actor to be collected and exploited, we propose a different overall model of Process/Product/Construction, the philosophy of which is alternative to those illustrated in section 2.2.

3.1. THE MODEL AND INTELLIGENT ASSISTANTS

The model, in order to order to bring about a decisive improvement in design processes, possesses Knowledge Bases and/or other semantically significant instruments; otherwise it would allow only relatively difficult exchanges of data to be achieved, and with problems of communications protocols. In this case no IT assistance would be available and each actor would have to face up to the different design solution directly, in order to associate it with meanings to detect any differences, suggestions and/or design contradictions.

In this model the actors are helped by relatively ‘Intelligent Assistant’, I.A., capable of providing support in relatively complex tasks. At the extreme limits we could have, on the one hand, an I.A. that completely replaces an actor, and on the other, a simple interface that allows an actor to interact with the MetaSystem and, through this, with the other actors.

The aim is for each actor to be free to choose the customary tools that he considers most appropriate in his professional field.

Each I.A. thus consists of an interface that, as well as interacting with the MetaSystem, also allows interaction with its customary applications software and, if present, its own inference engines, its own Knowledge Base, its own Relation Structures, its own Data base, its own graphics primitives, and so on.

The model possesses the following duality: distributed I.A.s and a central I.A.; it must be a distributed structure to simulate the presence of numerous independent actors, but at the same time it is centralized for the consistency of data of the building project.

3.2. CHARACTERISTICS OF THE MODEL

This one is based on mimicking what happens in professional best practices, in which not only are data and prescriptions exchanged but above all intentions. In this way, phase by phase, Figure 4, shared design objectives are extracted from the opportunities/problems (Rosenman and Gero 1996; Carrara et al. 2004).

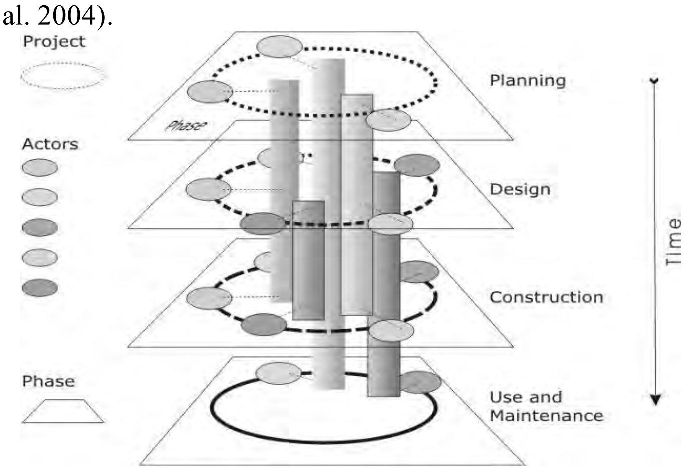


Figure 4. Actors and Context in the phases of design process

The attainment of such an objective involves a whole series of inter-coordinated sub-objectives. Therefore the fundamental problems underlying this model, to which the respective sub-objectives refer, involve:

- representation of the object, the validity of which must be guaranteed in the Shared Project as well as in that of the various actors;
- the need to have simple objects-agents (both logical and ICT) for the purpose of easy management, but at the same time that can be 'enhanced' with new characteristics inside the KBs of the specialists' IAs;
- 'translatability' and 'interpretability' of the object in the actors' various semantic universes;
- verification of local and overall performance with immediate identification and explanation of conflicts;
- the hierarchy of authority, individual property, versioning, privacy;
- the dissemination of creative ideas and of opportunities/constraints combined with the ease with which suggestions and new design proposals can be pooled.

Overall, the difficulties involved in managing this process may be divided into two categories: those deriving from a *general model* that is insufficient, and those referring to the *formalization of information* exchanged among the various actors.

3.3. THE MODEL AND MANAGEMENT OF COMPLEXITY IN THE DESIGN PROCESS

As far as the first difficulty is concerned, the *general model* was inadequate to represent the complexity of the design process. It was not simulated correctly as it was simplistically reduced to a single actor or specialist team and a single KB (exhaustively defined in Carrara and Kalay 1994; Maher et al. 1995; Schmidt RF and Schmidt M 1996; Kim et al. 1997), also because the aspects regarding procedures, timing, decision-making hierarchies, intellectual property, etc. were not taken into sufficient consideration.

A *Project* may be considered a structured set of operators, activities and resources provided with organizations and aims.

In a Project each operator has his own working area characterized by a time period, by a field of action that he can manage, by choices that may be subjected to the approval of other experts, by decisions that he can take, by a hierarchy of authority, by a degree of autonomy with respect to the other operators, by limited resources that he can draw upon: we have called all this the "design choice workspace", or *Design Workspace* (DW) for short.

3.3.1 'Shared'/'Private' Workspace

We believe that the working method in the design process subtended by the intrinsic nature of Collaborative Design is based on the division of design activities into two types of *Design Workspace*: on the one hand, a large number of *'Private'* type PDWs, specific to each team involved (e.g architectural team; electrical engineering; bearing structure, energy, economic and financial, etc.); on the other, a *Shared Design Workspace* (SDW) common to all the teams where the various choices are combined into a synthesis.

We successfully proposed a design process model in which numerous Intelligent Assistants (IAs, sec. 2.1.), engage in dialogue through the metaphor of a 'Private Design Working Space', PDW, and a 'Shared Design Working Space', SDW (Carrara and Fioravanti 2001; Carrara and Fioravanti 2002), Figure 5.

3.4. THE MODEL AND ITS FORMALIZATION

As far as the second difficulty is concerned, the *formalization of the information* exchanged, the problem of its correct simulation remains open insofar as the models proposed by the scientific community have become radicalized into two positions, both inadequate.

In the first the simplification, the 'semantic impoverishment' of the information exchanged, necessarily leads to incomprehension among the actors and an iatrogenous effect owing to an excess of low level information exchanged, which is both the cause and the effect of the potential of the new IT means, Figure 6.

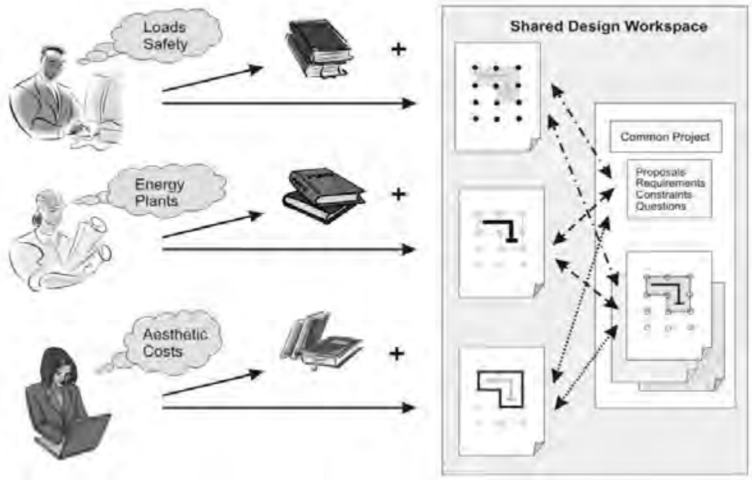


Figure 5. The 'Private Design Workspace' 'Shared Design Workspace' dialectics.

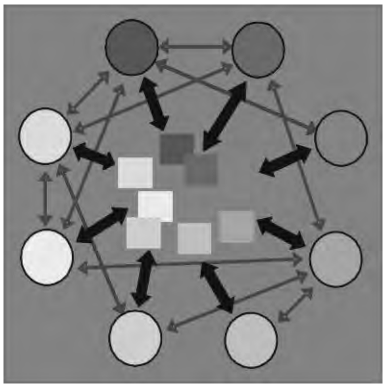
Each actor who produces drawings and documents, is confronted exclusively with his/her own direct interlocutor, and has no tools that allow him/her to disseminate and explain his/her design intentions, nor does he/she provide automatic explanations of failure to satisfy one's own constraints with respect to modification of the *project* performed by other members of the SDW.

The process, like the management of collaboration, takes place sequentially and at the same time in random fashion. No tools exist that can allow knowledge and creativity to be disseminated.

One development of the preceding model is when Collaboration becomes Concurrent, an attempt to pool one's experience at the same moment, both through working meetings and IT tools, but it is laborious to achieve through lack of ontology and semantics included in the information, and the need to synchronize the meetings, Figure 7. Making a comparison is as though, on the same marble block, several sculptors are trying to sculpt simultaneously, each with their own intentions. Not only, but also the design solutions are eventually relatively non-creative, as the working meetings are necessarily limited in their frequency and the number of actors.

In the second position, the 'semantic richness' of the information exchanged by all the actors leads to a formalization that is so exhaustive as to be practically unmanageable, Figure 8.

Therefore we have defined a new model that is both an object and an objective of the research, which makes it possible to share the respective knowledge, verifies the compatibility of the design solution in the course of its development, and transmits formalized and non formalized information, Figure 9.



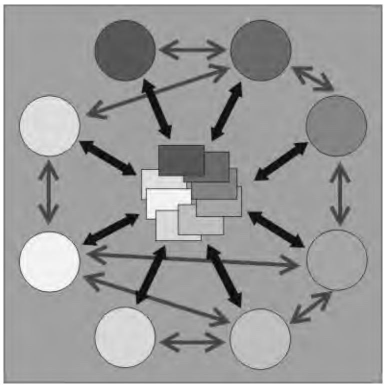
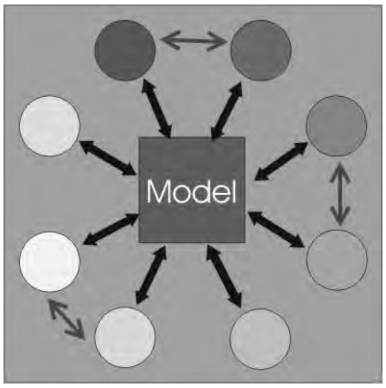


Figure 6. "Usual" model of distributed collaborative design.
Figure 7. 'Progressive' model of distributed collaborative design.



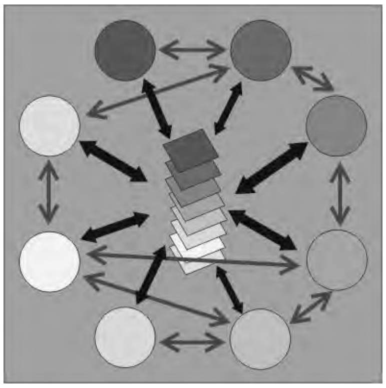


Figure 8. "Utopian" model of distributed collaborative design.
Figure 9. 'Synthetic' model of distributed collaborative design.

By taking account of the different points of view of the actors, this model allows a holistic approach to be made to the opportunities/problems; it is also flexible enough to allow new actors, new characteristics and/or ICT object constraints representative of the building components and the design process to be taken into account (Cheng 2003; Ren 2004).

The general aim is to enhance the design developing suitable tools for boosting integrated Process/Product Collaborative Design activity, by means of an effective and innovative representation of building entities in the broad sense (building components, requirements, methods, processes, etc.), by providing immediate explanations of constraints and meanings, by allowing dynamic annotations (agents) between the internal representation (used by each actor in his own specialist field) and the external one.

One typical aspect of Collaborative Design is the de-hierarchization and breakdown of the process: every aspect of the process is both central and peripheral vis-à-vis the others (for instance, as in 1.3.2).

One possible way out of the dilemma illustrated above between 'semantic poverty' and 'all comprehensiveness', consists in having available the strictly necessary information and knowledge among the actors, the other specialist knowledge, which is not strictly necessary for the other actors remains confidential.

3.5. FORMALIZATION OF LOGICAL OBJECTS

At this stage it is necessary to draw attention to two conceptual design 'layers': that of project, information and knowledge exchanged among the actors, and that of the 'logical objects' representing and conveying them.

With reference to the dilemma in section 3.4, relations between the two 'layers' likewise give rise to two correspondence paradigms.

In the first paradigm, which refers to the *semantically poor* product/product model, an identity correspondence exists between a design product/process model and the underlying ICT logical object.

In this case, current design, the entities involved are generally represented by often dimensionless symbolic graphic signs and by often jargon filled technical reports; neither entity has any *intrinsic meaning*; they have some only in the scientific and professional context in which they are situated; therefore, the only way to give them meaning is by an accompanying informative-explicative attachment (Carrara et al. 2004; Drakos and Knox 2004). Each of the abovementioned entities corresponds to a specific logical objective, which has very little, and often no, meaning, even though it may be provided with an excellent figurativeness. In this case it is the exclusive task of the actor to 'translate' meanings, perceive differences among different versions, carry out comparisons among different solutions, and point out conflicts and contradictions.

In the second case, which corresponds to the *semantically all-comprehensive* model, the model of a unique process/product, inclusive of all the characteristics, attributes, behaviours of all the entities – in a word, the semanteme – of which it is composed. The corresponding logical object is plethoric and at the same time fragile for such a difficult task: however foresightful and exhaustive one is, gaps emerge during the design work, making it necessary to redefine the initial logical object. Or else conceive of logical objects that can be enriched with semantemes at will, during the design work, and thus, in the case of distributed KBs and DBs, there would be huge problems of synchronization, communication and consistency as all the semantemes in all the KBs and DBs would have to be replicated. Or even again, wanting to enrich logical objects at will with a multi-model representation (Roseman and Gero 1997), that is, one that is specific to each logical object according to the actor, would lead to a Babel of different models with logical coherence problems.

In the perspective towards which we are moving our model ranks third after the preceding ones: it is made to correspond to a “virtually rich” logical object: the part common to the actors is reduced to a minimum, the coordinates, the links with other involved actors, the versions (Carrara and Fioravanti 2004). All the semantemes are linked only to the logical object according to the context, the participating actors, the authority hierarchy, the design phase while remaining within one’s own specific KB and/or DB. There are therefore no replicas of semantemes of a logical object belonging to the IA of one actor, in an IA of another actor.

This is made possible both by the choice of subdividing the ‘design solutions working space’ into ‘Private’ and ‘Shared’, and by the definition of a new type of Perspective/Filter that “translates” a logical object from the IA of an actor, into the Common IA and vice versa. The Perspective/Filter behaves differently in the two directions: when the logical object is published it will be “simplified” in the SDW (shared design solutions space); conversely, when it is ‘privatized’ in the PDW (private design solutions space) it will be ‘enriched’ with all the semantemes specific to the actor’s IA. One assumption of the model is that each actor continues to work with his customary quantities, functions, algorithms, programs, tools (physical, geometric, legal, etc.), and has his own specific representation of complexity. He wants to resolve as quickly as possible design contradictions in his own PDW, the merits of which others do not want to go into, Figure 10, and at the same time enhance his I.A. with new rules, new design experiences and new knowledge which are to be used as creative ideas for other projects.

Our model, on the one hand, is not intended to obstruct the usual way of proceeding of each actor towards his/her possible ‘private’ solutions; on the other, it wants in addition offer the chance of ‘real time’ verification of any contradictions to which his solution would lead vis-à-vis the opportunities/constraints defined by the others, facilitate creativity by pooling one’s own knowledge and propose alternative hypotheses using a whiteboard

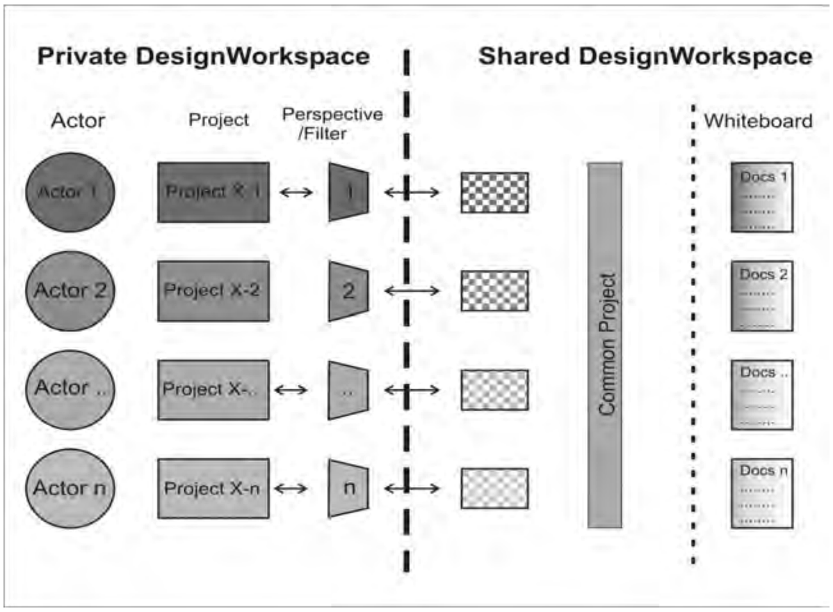


Figure 10. The actors relate their own Private Project and their own skills with the other actors through the Perspectives/Filters.

The notifications exchanged in the SDW are of two kinds: automatic, which are triggered by the daemons and the procedural attachments, and manual, i.e. messages included by the actors on a whiteboard. In this way a more exhaustive exchange of knowledge is obtained which includes both the formalized aspects and the no-formalized ones The latter can then be formalized by means of conventions among actors using XML.

Let us define for each instant the building's 'Common Project', the central and unique core of information and knowledge shared by all the actors and indivisible property, a kind of 'highest common denominator' among the projects of the various 'actors'; 'Shared Project', the union set resulting from the combination of the 'Shared Specialist Projects' and , 'Common Project'.

In this way what are virtually available in the SDW are shared parts of the project that are owned by actors, and that, as well as avoiding the ineffective simulation of a centralized model, also make it possible to safeguard non secondary design aspects such as privacy, intellectual property, the history of project versions, long term ease of use of its own customary tools.

Indeed, inside each PWD the solutions are perfectly coherent and consistent; those chosen by the actor and "translated" for the SDW are not used to replace any version of the Common Project, but simply "published", that is, they launch the verification of the constraints active in that particular instant. *If* these constraints are respected and *if* the other actors at that time are empowered to allow it, the CP is released in a new version.

4. Conclusion

The structure of the model based on the separation of the PDW from the SDW, as postulated, allows the design process to be managed also in the presence of partial and contradictory design solutions. Thanks to this separation, each actor can have fun producing new, non conventional design hypotheses that may be tested in his own PDW and in the SDW.

The model allows the other actors to visualize each partial solution ‘published’ so as to have not only his/her solution but rather the verification of the active constraints, the explanation of why some may not be respected, the possibility, stimulated by the proposed solution, of activating new ones.

The activated constraints, the messages exchanged and the error warnings ‘disturb’ the SDW, causing conflicts, arousing curiosity, and potentially promoting creativity. The proposed model can thus boost both the ‘pruning’ of unsuitable solutions of the branches of the ‘graph’ of the SDW solutions, as well as the ‘grafting’ of innovative proposals onto the same graph.

The model is therefore a promoter of ‘perturbations’ of the status of the design solution (which in any case take place, albeit postponed in time as collective awareness, when it is perhaps too late to find a remedy) as well as a promoter of creativity, disseminating and acquiring creative ideas by triggering an *incubator* among the actors in order to find a new point of synthesis.

It must be stressed than an *incubator* (i.e. Collaborative Design reinforced by ICT) is not only a stimulus to the introduction of imaginative hypotheses but above all guarantees the affordable feasibility of such hypotheses, as it has to pass the test of being judged by a multicultural environment: creativity = radical innovation + feasibility.

Acknowledgements

Many of the topics treated in the present paper have been discussed in detail and “collaboratively” shared with Prof. Y. Kalay of the University of California at Berkeley, to whom the authors express their heartfelt thanks.

The research was funded by MIUR (Ministry of Education, the University and Research): Project of Research of National Interest 2002: “An integrated Product/Process model of support to collaborative design in building".

References

Björk BC, 1992: A unified approach for modelling construction information, *Building and Environment* **27**:173-194.

Björk, BC: 1989, Basic structure of a proposed building product model, *CAD* **21**: 71-78.

Carrara, G, Fioravanti A: 2004, How to construct an *audience* in collaborative design - The relationship among which actors in the design process, *in* Rudiger, B, Tournay, B and Orbaek, H (eds), *Architecture in the Network Society*, eCAADe, pp. 426-434.

Carrara G, Fioravanti A and Nanni U: 2004, Knowledge Sharing, not MetaKnowledge. How to join a collaborative design process and safely share one's knowledge, *Intelligent Software System for the New Infostructure*, Focus Symposium and InterSymp-2004, Baden-Baden, pp. 105-118.

Carrara G and Fioravanti A: 2002, 'Private space' and 'shared space' Dialectics in collaborative architectural design, *Collaborative Decision-Support Systems*, Focus Symposium and InterSymp-2002, Baden-Baden, pp. 27-44.

Carrara G and Fioravanti A: 2001, A Theoretical model of shared distributed knowledge bases for collaborative architectural design, *in* JS Gero and K Hori (eds), *Strategic Knowledge and Concept Formation III*, Key Centre of Design Computing and Cognition, University of Sydney, Sydney, 129-144.

Carrara G, and Kalay YE: 1994, Past, present, future: process and Knowledge in Architectural Design, *in* Carrara, G and Kalay, YE (eds)*, Knowledge-Based Computer-Aided Architectural Design*, Elsevier Science Publishers BV, Amsterdam, pp. v-vii, 147-201, and 389-396.

Cheng N-Y: 2003, Approaches to design collaboration research, *Automation in Construction* **12**(6): 715-724.

Cross N: 1985, L'architetto automatizzato, *Liguori S.r.l.*. Italiano edition of *The automated architect*, Pion Limited, 1977.

Drakos N and Knox RE: 2004, You need more than e-mail to share tacit knowledge, http://www4.gartner.com/DisplayDocument?id=450075.

Eastman CM and Siabiris A: 1995, A generic building product model incorporating building type information, *Automation in Construction* **3**(4): 283-304.

Eastman CM: 1998, special issue: TeamCAD Workshop, *Automation in Construction* **7**(6).

Gero, JS: 1999, A new model of designing which includes its situatedness, *in* Gu, J and Wei, Z (eds), *CAADRIA'99*, Shanghai Scientific and Technological Literature Publishing House, Shanghai, China, pp. 235-242.

Gero JS and Reffat RM: 2001, Multiple representation as platform for situated learning systems in designing, *Knowledge-Based Systems* **14**(7): 337-351.

Gross MD, Yi-Luen Do E, McCall R, Citrin WV, Hamill P, Warmack A, Kuczun KS: 1998, Collaboration and coordination in architectural design: approaches to computer mediated team work, *Automation in Construction* **7**(6): 465-473.

Jacobsen K, Eastman C and Tay SJ: 1997, Information management in creative engineering design and capabilities of database transactions, *Automation in Construction* **7**(1): 55-69.

Jeng T-S, Eastman CM: 1998, A database architecture for design collaboration, *Automation in Construction* **7**(6): 475-483.

Kalay YE: 2001, Enhancing multi-disciplinary collaboration through semantically rich representation, Porter, WL and Goldschmidt, G (guest eds), Special Issue: Design Representation, *Automation in Construction* **10**(6): 741-755.

Kavakli M 2001, NoDes: kNOwledge-based modeling for detailed DESign process – from analysis to implementation, *Automation in Construction* **10**(4): 399-416.

Keil JM: 1987, *Il mistero della creatività*, McGraw-Hill Libri Italia srl, Milano. Italian edition of *The creative Mystique – How to Manage It, Nurture It, and Make It Pay*, 1985, John Wiley and Sons, Inc.

Kim I, Liebich T and Maver T: 1997. Managing design data in an integrated CAAD environment: a product model approach, *Automation in Construction* **7**(1): 35-53.

Kolarevic B, Schmitt G, Hirschberg U, Kurmann D, Johnson B: 2000, An experiment in design collaboration, *Automation in Construction* **9**(1): 73-81.

Kvan T: 2000, Collaborative design: what is it? Martens, B (guest ed.), eCAADe, *Automation in Construction* **9**(4): 409-415.

Laiserin J: 2000, Collaborative AEC design, *CADence* **15**(11): 10-17.

Laiserin J: 2001, AEC collaboration, *CADence* **16**(6): 10-17.

Maher ML, Balachandran BM, and Zhang Dong M: 1995, *Case-Based Reasoning in Design*, Lawrence Erlbaum, NJ, USA.

Papamichael K, La Porta J, Chauvet H, Collins D, Trzcinski T, Thorpe J and Selkowitz S: 1996, The building design advisor, design computation: collaboration, reasoning, pedagogy, *ACADIA*, Tucson, Arizona, pp. 85-97.

Reffat RM and Gero JS: 1999, Situatedness: A new dimension for Learning Systems in design, *Architectural Computing from Turing to 2000*, eCAADe, Liverpool, pp. 252-261.

Ren Z and Anumba CJ: 2004, Multi-agent systems in construction – state of the art and prospects, *Automation in Construction* **13**(3): 421-434.

Rosenman MA and Gero JS: 1996, Modelling multiple perspectives of design objects in a collaborative CAD environment, *Computer Aided Design* **28**(3): 193-205.

Rosennam M and Wang F: 2001, A component agent based open CAD system for collaborative design, *Automation in Construction* **10**(4): 383-397.

Simon HA: 1996, *The Sciences of the Artificial*, third ed., MIT Press, Cambridge, MA,

Schmidt RF and Schmidt M: 1996, *Computer aided concurrent integral design*, *in* Schmidt RF and Schmidt M (eds), Springer-Verlag, Berlin-Heidelberg, Research Reports Esprit, *Project 5168 CACID Volume 1*, ISBN 3-540-60480-4.

Turner JA: 1997, Some thoughts on the existence of a generic building object, *in* Junge, R (ed.), *CAAD Futures*, pp. 533-552.

Woo S, Lee E and Sasada T: 2001, The multiuser workspace as the medium for communication in collaborative design, *Automation in Construction* **10**(3): 303-308.

Wix J: 1997, ISO 10303 Part 106, BCCM (Building Construction Core Model) /T200 draft.

Zevi B: 1985, *Saper veder l'architettura,* G. Einaudi Ed., Italy; in English, 1993, *Architecture As Space: How to Look at Architecture*, Da Capo Press. Ed.

CREATIVITY AND COMPUTERS

On creative engagement
Ernest Edmonds and Lizzie Muller

Tales of the unexpected: Understanding emergence and its relationship to design
Martyn Evans

Computational support for personally-creative designs
Daryl Hepting

Modes of engineering design thinking
Pertti Saariluoma, Kevali Nevala and Mikko Karvinen

Methodologies for understanding social creativity during collaborative design activities
Elisabeth Sylvan

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 303-318

ON CREATIVE ENGAGEMENT

ERNEST EDMONDS AND LIZZIE MULLER
University of Technology Sydney, Australia

Abstract. The paper is concerned with the design of interactive art systems intended for display in public locations. It reviews approaches to interactive art systems and discusses the issue of creative engagement with them by the active audience. An approach to elaborating a model of creative engagement is described and exploratory work on its refinement is reported.

1. Introduction

There is a growing field of interactive visual art that is currently being shown in public galleries and museums. Such work is also finding its way into cafes and bars as well as private homes. For the designers of such systems, the questions relating to audience engagement are critical but, at this time, not particularly well understood. The paper reports on work that addresses this problem.

The work described in this paper begins with a model of creative engagement based on three attributes. At the top level, the attributes are characterized first as *attractors*, that is, those things that encourage the audience to take note of the system in the first place, second, as *sustainers*, that is those attributes that keep the audience engaged during an initial encounter, and third, *relaters*, aspects that help a continuing relationship to grow so that the audience returns to the work on future occasions. In the area of museum studies a number of research projects have looked at these issues in the broader context of audience behaviour in museums. We are able to draw upon this work to provide a starting point.

In order to investigate the problem, the Powerhouse Museum Sydney and Creativity and Cognition Studios (CCS) have created *Beta_space* an experimental environment where the public can engage with the latest research in art and technology. *Beta_space* shows interactive artworks in development by CCS researchers and collaborators. The works may be at different stages, from early prototype to end product. In all cases, engagement with the public provides critical information for further iterations of the artwork or of the research. The name ‘beta’ refers to a new piece of software or hardware that needs testing and feedback from its users to help the project team to eliminate design and engineering errors. *Beta_space* is a working environment and a laboratory yielding valuable research outcomes. The paper reports on the results of investigations into creative engagement using *Beta_space.*

An evolving interactive art system by the first author and Mark Fell, *Absolute_4.5*, has been used as the subject of this investigation. The parameters of behaviour of the work have been varied and refined whilst it has been in *Beta_space.* As a result, we are elaborating our model of creative engagement, described in terms of characteristics that offer a positive influence. The paper concludes with a description of the emerging model and speculation about the more general applicability of the ideas that have been developed.

2. Interactive Art Systems

When we look, read or listen we know that we are engaged in an active process even if we do not physically move at all. Perceiving art is an active constructive process. In this sense, and in others, the audience is engaged in a creative pursuit as well as the artist. This was quite a hot topic in art during the 20th century and it was particularly of concern in the late 1960s. The interest was partly political. It seemed to many inappropriate for artists to play the role of the all-knowing creative being handing down his or her work for the pleasure and education of passive masses. Artists holding this view wanted to give the audience their own part of the creative action, not just in their perceptual mechanisms but also as an explicitly recognized part of the creative process. Apart from this ‘political’ view, it was also current wisdom that engagement and interaction had a positive part to play in any creative activity. Thus, participation in art was considered to be important. Learning by doing, interactive science exhibitions and so on were very popular concepts. However, notwithstanding ‘Happenings’ and exhibitions that invited the audience to play, participation was much easier to promote than to achieve. This is where the computer came in.

If we view the computer as a real-time control device and given that we can specify rules for how it is to respond to external stimuli, it can be seen to put behaviour into effect by taking in sense data and controlling output devices such as video projectors and speakers. The work done in Artificial Intelligence and on Robotics in simulating intelligent thought was an important inspiration for this kind of work. The interest of computer people in writing computer programs that simulated human thought and controlled robotic devices, caught the public imagination and is a common topic in science fiction. Artists have also found such possibilities exciting and examples can be seen as far back as the 1968 Institute of Contemporary Arts exhibition, Cybernetics Serendipity in London. The technical issues are well reviewed in Barr et al (1990).

Theoretically, Cybernetics and General System Theory offered interesting ideas about how computational systems could be used to model and implement animal-like behaviour (von Bertalanffy 1968). These fields seemed interesting, therefore, in the development of engaging participative artworks. The computer offered something quite new in respect of enabling interactive artworks to be made. This new opportunity did not depend on agreeing with the form of Artificial Intelligence that believes that the programs can stand as some kind of scientific theory of human thinking, but some of the techniques developed in those studies are certainly valuable. The questions come down to quite normal ones for the artist. How is the artist think about and make the work? How is engagement enabled and how is audience interest sustained? How is one to make interaction meaningful? What makes interaction meaningful and how does that influence our understandings of ourselves?

In 'Interactive Video Constructs', the artwork reacts to events detected by sensor systems (Edmonds 2005). An image analysis system that analyses the scene as the pictures are captured is incorporated into the generative program. The performance of the work, i.e. the generative path that it takes, is then reactive to what participants are doing. A *Video Construct* is searching through a set of rules and, as it does so, it generates the sequence of images that form the output of the work. Each image represents the state of the search at that moment. In the earlier systems, the sequence of states was entirely determined by the 'search strategy' used by the software to explore the rules (Edmonds 1993). In the interactive case, however, the 'search engine', that automatically operates the search strategy, has available to it a stream of data that is a coded, or symbolic, representation of the behaviour of the viewer. This data modifies parameters in the search and leads to a perceived sense of reaction by the system to the participant. Because these Interactive Video Constructs are described within the computer by a set of rules, it is possible to add an extra computer program, often called a software agent. This 'agent' uses the history of interactions between participants and the work to modify the generative behaviour by changing the rules or changing which rules are used. By recording and analysing the interactions, the software agent 'learns' from experience about human reaction to the artwork. The Video Construct changes its behaviour in the light of its experience with human participants interacting with the work. As it learns it changes the way that it develops rather than simply changing the stimulus-response rules that govern its behaviour. In summary, the 'Learning Interactive Video Construct' is an art system that evolves in response to participant interaction with the work. This learning process is postulated as a significant possible approach to retaining engagement over time.

3. Categories of Interaction in Art

As discussed be Candy and Edmonds (2002) we can envisage several situations that characterize the relationship between the artwork, artist, viewer and environment. The core categories devised by Cornock and Edmonds (1973) are applicable to current examples of interactive artworks. They were defined then as: *static, dynamic-passive, dynamic-interactive* and *dynamic-interactive (varying)*. We can now elaborate on those descriptions and bring them up-to-date as follows:

[1] Static

The art object does not change and is viewed by a person. There is no interaction between the two that can be observed by someone else, although the viewer may be experiencing personal psychological or emotional reactions. The artwork itself does not respond to its context. This is familiar ground in art galleries and museums where art consumers look at a painting or print, listen to tape recordings and talk to one another about the art on the walls and, generally speaking, obey the command not to touch.

[2] Dynamic-Passive

The art object has an internal mechanism that enables it to change or it may be modified by an environmental factor such as temperature, sound or light. The internal mechanism is specified by the artist and any changes that take place are entirely predictable. Sculptures, such as George Rickey's kinetic pieces that move according to internal mechanisms and also in response to atmospheric changes in the environment fall into this category (Rickey, 1979). The viewer is a passive observer of this activity performed by the artwork in response to the physical environment.

[3] Dynamic-Interactive

All of the conditions of the dynamic passive category apply with the added factor that the human ‘viewer’ has an active role in influencing the changes in the art object. For example, by walking over a mat that contains sensors attached to lights operating in variable sequences, the viewer becomes a participant that influences the process of the work. Motion and sound capture techniques can be used to incorporate human activity into the way visual images and sounds are presented. The work ‘performs’ differently according to what the person does or says. There may be more than one participant and more than one art object. An example of this work is the Iamascope, a work which includes a camera looking at the viewers and is connected to a controlling computer. The work reacts to human movement in front of it by changing a kaleidoscope-like image and making music at the same time in direct response to the viewer's movements (Fels and Mase, 1998). Another example is the interactive video construct discussed above.

[4] Dynamic-Interactive (Varying)

The conditions for both 2 and 3 above apply, with the addition of a modifying agent that changes the original specification of the art object. The agent could be a human or it could be a software program. Because of this, the process that takes place, or rather, the performance of the art system cannot be predictable. It will depend on the history of interactions \with the work. In this case, either the artist from time to time updates the specification of the art object or a software agent that is learning from the experiences of interaction, automatically modifies the specification. In this case, the performance of the art object varies, in addition to case 3, according to the history of its experiences.

When defining these categories, Cornock and Edmonds proposed that rather than talk about ‘artworks,’ it was helpful to think in terms of ‘art systems’ that embraced all of the participating entities, including the viewer. It follows from this that the role of the artist is not so much to construct the artwork, but rather to specify and modify the constraints and rules used to govern the relationship between audience and artwork as it takes place in the world. In the paper by Candy and Edmonds (2002), four art systems, each exemplifying one of the categories above, are described. These are examples of an important strand of the future development of approaches to making interactive art. They are also all examples of human collaboration and of inter-disciplinary partnerships in practice.

4. Studying situated interaction

To begin to understand interactive art, we must begin to question how interactivity as a medium produces meaning. Some of the most important work in this area has been done in the context of Human-Computer Interaction. One of the most significant explorations of the meaning-producing capacity of computer-based interactivity is Lucy Suchman's *Plans and Situated Actions* (1987). Suchman applies Garfinkel’s ethno-methodological approach to the problem of accounting for purposeful action and shared understanding between humans to the problem of understanding and designing for human computer interaction (Garfinkel 1967).

Suchman critiques the cognitivist conception of meaningful action, which posits planning as a primary activity, and instead locates the source of meaning in situated action itself. In so doing she moves away from a causal, goal oriented idea of interactivity towards a notion of interactivity in which action is central and goals are emergent. Human actors “achieve” meaning in their encounters with interactive artefacts through action.

This achievement is absolutely rooted in the contingent resources of the context, which are brought into being by the situated action that requires them, and, as a result "… the significance of artefacts and actions, and the methods by which their significance is conveyed, have an essential relationship to their particular, concrete circumstances." It is the infinite potential of these contextual resources that stymies attempts of the planning model to create taxonomies, or general rules, for the interpretation of action.

Suchman locates the generation of meaning not just in interactivity in an abstract sense but in situated interactivity. This has significant methodological implications for understanding interactive art, necessitating a form of accountability to the actual lived experience of audiences. We can therefore build on the conclusion of the last section to say that research in interactive art need not only engage the public, but engage the pubic on their terms in the real-world situations where interactive art is experienced. The site of exhibition can be seen therefore not as an auxiliary space for understanding certain aspects of an artwork, such as its social or practical implementation, but the central site for interactive art research; the necessary starting and finishing point for any study that aims to understand how meaning is produced by an interactive artwork.

Some of the methods for achieving Suchman's goals have been evolving through a series of artist-in-residence research projects in the UK and in Australia in which the concept of *Studio as Laboratory* has been developed (Candy and Edmonds 2002; Edmonds et al 2005). They key point has been that, for the artist, it is of little interest to evaluate the work once it is finished and delivered into the gallery. That is too late. The investigations have to take place as part of the development process that the artist is engaged in. This process, with its increasingly collaborative nature, was the focus of the UK studies and from that emerged an important concern for and problem with interaction. Where is the audience in the studio? That is the nub of the issue that led to the development of the initiative described in the next section. In this innovation the studio as laboratory, has been taken out of its private space and into the public arena.

5. *Beta_Space*: Concept and implementation

In November 2004, the Creativity and Cognition Studios at the University of Technology, Sydney (CCS) and the Powerhouse Museum, Sydney launched an initiative that sought to realise the concept of research studio in a public place in a very particular way, through the participatory qualities of interactive computer-based art. *Beta_Space* is an experimental exhibition area within the Powerhouse, which extends the interactive-art research studios of CCS into the public context. *Beta_Space* shows interactive artworks at different stages, from early prototype to end product, Figure 1. It is the principal site of CCS research into the audience experience of interactive-art. *Beta_Space* is a practical solution to two areas of need: the needs of practice-based researchers in interactive art to engage audiences in their research, and the needs of the museum to provide current and dynamic content to their audience in the rapidly changing field of information technology. Based within the area known as Cyberworlds, the permanent Information Technology exhibition at the Powerhouse Museum, *Beta_Space* aims to respond to the needs of practice-based researchers in interactive art to engage audiences in real-world settings by developing the concept of the museum as public laboratory.

Figure 1. Beta_Space in the Powerhouse Museum, Sydney with Iamascope

The initiative is based on the idea of a flexible, dynamic exhibition space showing work at various stages of production, with exhibits lasting between one week and three months. The space is constructed to allow maximum flexibility with a basic but adaptable technical set up. Its name derives from the software development practice of releasing new applications and products to the public before they are completed in order to gather feedback and improve their quality. The name signals that *Beta_Space* is a site for experimental work-in progress, and for working in partnership with audiences.

Realising the vision of the public laboratory requires collaboration between the cultural and the academic research spheres. *Beta_Space* has been a truly collaborative venture between the Creativity and Cognition Studios and the Powerhouse Museum in Sydney at all levels, from conception, through technical implementation and now in the ongoing programming, design and installation of exhibits, Figure 2. Both partners have different, complementary aims for the initiative that are explained in more detail below.

Figure 2: Active involvement in Beta_Space

From the point of the Powerhouse *Beta_Space* provides an experimental approach to the problem of how to exhibit Information Technology in an authentic, dynamic and satisfying way. In an exhibition such as Cyberworlds, it is necessary to provide contemporary computing experiences that are unlikely to be available elsewhere. Museums are under pressure to provide hands-on experiences of *future* computing that will remain in the future for the duration of the exhibition (Kittler 1996; Schubert 2000).

Developing partnerships with research groups is one solution to this seemingly impossible task. However there is a need to think carefully about the difference in cultures and requirements between academic and cultural institutions, and how to accommodate those differences in effective partnerships. Issues include the instability and fragility of research based innovations that often need frequent maintenance and attention. Continuity of expertise and interest can also be a problem as research groups move on from individual technologies quickly because of the rapid turnover of post-graduate researchers. After one or two years it is very possible that the research group with whom the museum has made a partnership no longer has the expertise or interest in the technology they have installed. Academic researchers also have a different way of judging success and failure in experimental technologies, in which problems and failures can produce some of the most interesting results and advances. For the museum on the other hand, such breakdowns are difficult to accommodate in an exhibition setting, and compromise the quality of visitor experiences.

The *Beta_Space* initiative offers two solutions to these problems. Firstly and most importantly it is focused on audience experience rather than technology. *Beta_Space* is about interaction, and issues such as robustness, usability and audience satisfaction are therefore central to its research aims. Secondly *Beta_Space* does not provide a fixed technological exhibit, or even a fixed technical delivery system but rather a research rationale and a shared commitment backed up by flexible resources. Issues of obsolescence, continuity of expertise and maintenance are avoided as *Beta_Space* is designed to respond to the changing needs and interests of both the museum and the research group.

6. Engagement

> "What I dream of is an art of balance, of purity and serenity devoid of troubling or depressing subject matter, an art which might be for every mental worker, be he businessman or writer, something like a good armchair in which to rest from physical fatigue." (Matisse 1908).

Matisse is referring to one kind of engagement: an engagement that a museum can encourage by providing interesting displays and comfortable armchairs. By contrast, the interactive artist and the modern museum are involved in a process of engaging the audience in an active and observable way.

A key feature of much of today's art is interaction: the interchange and exchange between art systems and people (Cornock and Edmonds 1973). The advent of digital technology has dramatically changed this and today one of the main concrete concerns is interaction. Because we still read books and magazines our experience of time-based and interactive art is often through still images and we can hence be tempted to compare such work with earlier paintings. Nothing could be more misleading. In interactive art, the complexity, the key experiences, the value is surely embedded in the interaction itself, not in still frames. That is the concrete reality of such art. The essence is the lean, economically realized, process of interaction.

Interaction is not material. It is experienced, perceived and understood, but we cannot touch it. It is a somewhat difficult concrete reality to deal with, but it is the concern of many artists today. The questions we ask ourselves include, for example, the nature of engagement in an interactive art system. How do we explore engagement and its impact on our sense of ourselves and of our relationships with the world around us? We ask about complexity in the context of time and interchange. We try to find what can emerge perceptually beyond and over an interaction as specified in concrete terms.

We can consider engagement in a number of different ways and here we define three primary categories. The first is *attractors*, things that encourage the audience to take note of the system in the first place. They have *attraction power* (Bollo and Dal Pozzolo, 2005). In a busy public pace, be it museum or bar, there are many distractions and points of interest. The attractor is some feature of the interactive art system that is inclined to cause the passing 'audience' to pay attention to the work and at least approach it, look at it or listen for a few moments. This is obviously a crucial factor in enabling an interactive experience to even have a chance of happening.

Next come *sustainers*, attributes that keep the audience engaged during an initial encounter. These have *holding power* and create museum *hot spots*, in Bollo and Dal Pzzolo's term. So, presuming that the attractors have gained attention it is necessary to start to engage the audience in a way that can sustain interest for a noticeable period of time. The behaviour of the work needs to be interesting. The problem is identifying just what **is** interesting in interactive experiences. That is one of the main tasks that *Beta_Space* and its related methods tackle.

Finally, there are *relaters*, aspects that help a continuing relationship to grow so that the audience returns to the work on future occasions. These are factors that enable the hot spot to remain hot on repeated visits to the exhibition. A good set of relaters meet the highest approval in the world of museums and galleries.

7. Absolute_4.5 in *Beta_Space*

One of the early experimental works installed in *Beta_Space* was *Absolute_4.5*, by the first author and sound artist Mark Fell. This is a 'dynamic-interactive art system'. They were commissioned to make a large interactive work for the White Noise exhibition at the Australian Centre for the Moving Image (ACMI), Melbourne (Edmonds and Stubbs, 2005) and *Absolute_4.5* was used as part of the development process in the manner discussed above.

The work *Absolute_4.5* is displayed on a back-projected video wall, with sound relayed over a pair of audio monitors. It is a generative piece which is written using Max/MSP/Jitter software running on an Apple Mac computer. This is a graphic programming environment for sound, image and interaction, providing an ideal system for exploring the correspondence between sound and image. In this work, which is part of a series, the artists/programmers use predefined colours and two-dimensional bars specified as co-ordinates. These correspond to synthetic sounds that occupy temporal rather than spatial positions.

The software consists of several discreet processes. These are grouped together into four sections, 1 – pattern generation, 2 – sensor analysis, 3 –

image display, 4 – audio output. The sensor data modifies the pattern generation process and, between them, a sequence of number pairs is generated. The image display section waits for a list of two integers, the first integer relates to a position, and the second a colour. The audio output again waits for the same two integers, yet here treats the first as a position in time not space, and the second a sound.

Given this flexibility, several different pattern-generating modules can be written which explore the outcome of different algorithmic processes. In this case an algorithm generates a list of 8 numbers each element of which counts from 0 to 3. These elements are connected in series, so that as one element reaches the maximum value, the next one counts up 1. The outcome of this is a series of absolutely linked color bars and a shifting musical pattern.

Beta_Space is equipped with a grid of pressure sensitive floor pads under the carpet in front of the screen and these were used to detect the position of people in the space and hence to influence the behaviour of the work. In order to conduct the initial investigations a simple interaction algorithm was employed. The two key numbers that drive the work were associated with each of the two axes of the grid (across the screen and perpendicular to it). In crude terms, the activity of the different aspects of the work was made to increase as someone walked (a) towards the screen and (b) away from the entrance to the space, i.e. to the left of the screen. In implementation terms this was specified by two simple numerical tables. In each case an extra value was available to correspond to the case when no floor pad was active: when nobody was in the space.

The range of behaviours was wide. In the least active state several seconds could pass without any sound or image change. In a museum context, five or ten seconds can be quite a long time. In the most active states, however, the sounds were intense and very busy and the image was equally intense in very rapid, almost flashing, changes. The question was, how to orchestrate these shifts in relation to the floor pad sensor data in order to obtain the greatest likelihood of engagement. This was studied by a series of explorations with staff and visitors to the Powerhouse. Observation and post-hoc interviews were used and they alone provided sufficient feedback for considerable progress to be made in the development of *Absolute_4.5*.

The question of *attractors* was quite interesting from the start. The initial decision was to make the null state (no presence detected) very busy and to almost stop the work as soon as someone ventured into the space. The attraction power was, in this way, very strong. However, from the wider perspective of the museum it was too much. The attraction power of this exhibit had to be balanced with the attraction power of other exhibits within its context. So, during the installation process, a careful exploration of the options was made and a busy, but not frenetic, rest state was determined.

The extreme slowing of the work on entry to the space was a clearly positive initial sustainer. It caught the attention and caused a certain puzzlement about what next. The initial transformation along each axis was linear. It turned out that this meant that the exciting behaviour (particularly the frenetic sound) was only reached gradually and the tentative visitor often never evoked it at all. The solution was to replace the linear functions by an inverse exponential one. This did the trick. Once this change was made another sustainer factor was able to come into play more successfully. On one axis, perpendicular to the screen, a reasonably obvious change in speed was apparent. On the other axis, however, a more subtle change in the image patters emerged. Thus the audience had something that they could readily grasp together with something rather difficult to pin down. This two pronged approach seems to be a valuable one in creating sustainers.

8. Absolute_5 in *White Noise* at ACMI

Absolute_5, the ACMI commissioned work for its White Noise exhibition, occupies a much larger environment than *Absolute_4.5* and, in certain respects uses different technology. It also uses a single large projection screen, but instead of floor-pads, the sensors consist of three cameras and image analysis systems. The sound has been extended to eight channels which are realized through eight suspended speakers that form a space in front of the screen. Two of the cameras analyze the movement pf people in this space in terms of simple general parameters such as the total amount of movement. The third camera covers the entrance to the space and is used to trigger a direct response as people arrive at the work and hence provide the attractor. The lessons of *Absolute_4.5* are applied in the context of its 'beta-testing' in order to ensure the quality of the final work. This is a specific process that illustrates the importance of the approach for interactive art systems.

Absolute_4.5, in itself, did not tackle the issue of relaters beyond its intrinsic interest. However, initial experiments are underway in two respects. Firstly, as mentioned above, arranging for the work to 'learn' or modify its behaviour as a result of experience is under investigation. Secondly, a networked approach that connects *Absolute_4.5* to *Absolute_5,* Figures 3-6. The method is to have each of the two remote works influence one parameter of the other. Thus, the activities of the audience in Melbourne can change the colour space employed in the work in Sydney in real time. This investigation is around the concept of an interactive experience that is different in some way each time that it is entered into. The changes are not random, although perhaps they might be thought to be, but are influenced deterministically by people out of sight in another city.

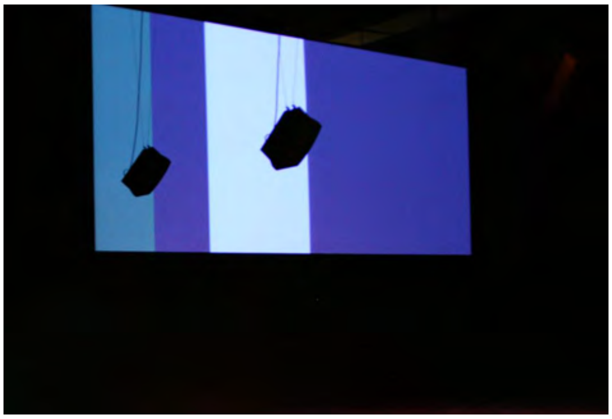


Figure 3. Absolute_5 from outside the space, showing speakers

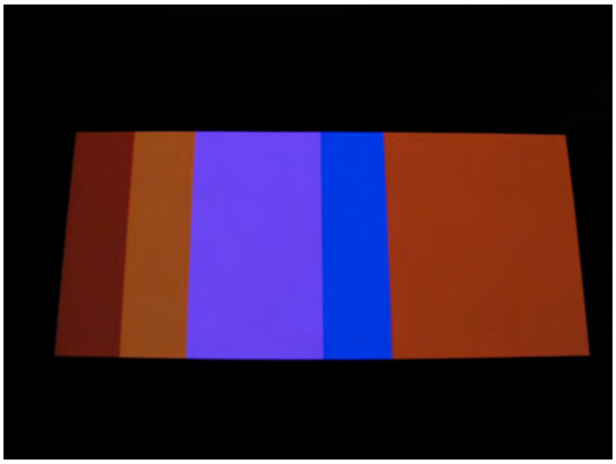


Figure 4. Absolute_5 looking up to the screen

From these studies we begin to see some approaches being developed that can elaborate our model and provide set of principles for building successful *attractors, sustainers* and *retainers* in public interactive experiences. The initial power of attraction is a question of appropriate differentiation from the context, so not an intrinsic property of the work itself. The holding power, on the other hand, is very much to do with the behavioural patters of the work and it has been suggested that a combination of easy to grasp patterns and slightly obscure ones is the basis of the way forward. For relaters, it seems likely that an evolving behaviour can be positive: however, we need to explore this issue much more before we can begin to articulate a clear set of principles.

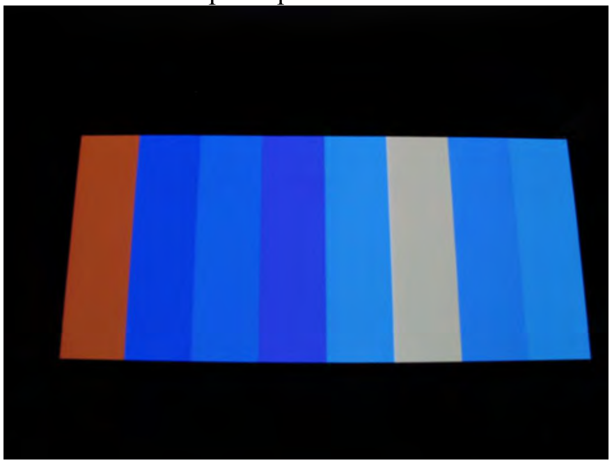


Figure 5. Absolute_5 looking up to the screen

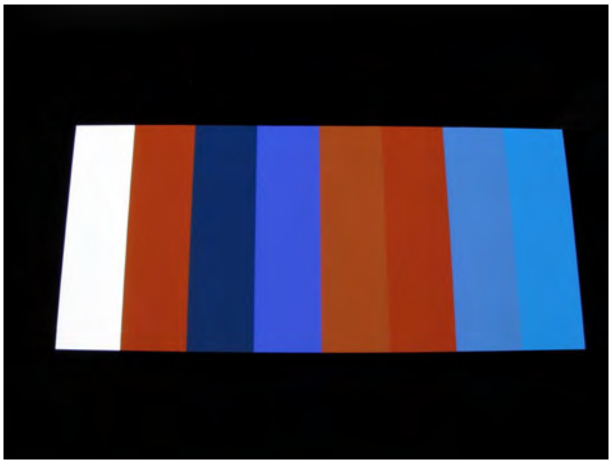


Figure6. Absolute_5 looking up to the screen

9. Conclusion

The paper has discussed an important current problem in the area of interactive experience design and described an approach that is being taken to address it. The approach is to extend the Studio as Laboratory concept by taking the experimental studio into a public space and, hence, enhance the creative process of developing such systems by enabling explorations with real audiences involving themselves with the works in realistic contexts.

Experiences with the development of an interactive artwork using the approach were described and the model illustrated in terms of the key issue of the audience's creative engagement with such works. It is proposed that this approach can offer a realistic and viable method for conducting research into the difficult and rather elusive problem of designing for creative audience engagement with interactive art systems.

Acknowledgements

The authors are extremely grateful to the team who enabled, constructed and realized *Beta_Space*: not least, Matthew Connell, Alastair Weakley and Greg Turner. Shigeki Amitani and Brigid Costello have made very valuable contributions to the evaluation work and Mark Fell has been a crucial partner in the making of Absolute_4,5 and its related works. Linda Candy has made valuable comments on much of the work and on this paper.

References

Barr, A, Cohen, PR and Feigenbaum, E (eds): 1990, *The Handbook of Artificial Intelligence*, Addison-Wesley New York.

Bertalanffy, L von: 1969, *General Systems Theory: Foundations, Development, Applications,* George Braziller, New York,

Bollo, A and Dal Pozzolo, L: 2005, Analysis of visitor behaviour inside the museum: An empirical study, *Proc 8th Int. Conf. on Arts and Cultural Management*. Montreal, Canada. July.

Candy, L and Edmonds, EA: 2002, *Explorations in Art and Technology*, Springer-Verlag, London.

Cornock, S and Edmonds, EA: 1973, The creative process where the artist is amplified or superseded by the computer. *Leonardo* **16**: 11-16.

Edmonds, EA: 1993, Knowledge based systems for creativity, *in* JS Gero and ML Maher (eds), *Modeling Creativity and Knowledge-Based Creative Design*, Erlbaum, Hillsdale, New Jersey, pp 259-271.

Edmonds, EA: 2005, *On New Constructs in Art*, Artists Bookworks, Sussex, UK.

Edmonds, EA, Weakley, A, Candy, L, Fell, M, Knott, R and Pauletto, S: 2005, (to appear) The studio as laboratory: Combining creative practice and digital technology research, *IJHCS*.

Edmonds, EA and Stubbs, M (eds): 2005, *White Noise*, ACMI, Melbourne Australia.

Fels, S and Mase K: 1998, Iamascope: A musical application for image processing, *in Proceedings of the Third International Conference on Automatic Face and Gesture Recognition*, Los Alamitos, Calif.: IEEE Computer Society Press.

Garfinkel H: 1967, *Studies in Ethnomethodology*, Englewood Cliffs: Prentice-Hall.

Kittler, F: 1996, *Museums on the Digital Frontier. The End(s) of the Museum*. J Hanhardt. Barcelona.

Matisse, H: 1908, Notes of a painter, This translation printed in Herschel B Chipp, *Theories of Modern Art* (Los Angeles: University of California Press, 1968).

Rickey, G: 1979, *A Retrospective.* New York: Guggenheim Museum,.

Schubert, K: 2000, *The Curator's Egg: The Evolution of the Museum Concept from the French Revolution to the Present Day*. One-Off Press, London.

Suchman, LA: 1987, *Plans and Situated Actions: The Problem of Human-Machine Communication*, CUP, Cambridge, UK.

Paper to appear in *Journal Visual Communications* **5**(1), February 2006.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 319-331

TALES OF THE UNEXPECTED: UNDERSTANDING EMERGENCE AND ITS RELATIONSHIP TO DESIGN

MARTYN EVANS AND RACHEL COOPER
University of Salford, UK

and

NICHOLAS HALL
University of Central Lancashire, UK

Abstract

This paper considers how user adoption and design envisioning contribute to the recognition and interpretation of emergent properties within the design life cycle. This life cycle encompasses not only the actual design activity but extends into consideration of user adoption and consumption. The stages in this life cycle can be identified as: pre-design emergence; design activity; post-design emergence. The value to the designer of an enhanced awareness, and ultimately understanding of emergence and emergent properties is considered, and the way in which designers may engage with emergent properties discussed. Models of these engagements are presented. An awareness of the implications of emergence may provide opportunities for designers to develop intuitive and simplified methods of engaging with complex systems and technologies. The paper uses a case study, of the ubiquitous mobile phone, to illustrate the role of emergent properties to design activity, user behaviour, and user adoption patterns

1. Introduction

The pace we lead our life, the technology that supports it, and the corresponding pressure on our time, results in a society that is dependent upon complex systems which are made up of multiple components or entities. These systems, and their interaction with the world around them, often gives rise to unpredictable, unexpected and unprecedented properties. These properties cannot be attributed to a single entity within the system, but the collective interaction of the system as a whole. This phenomena is termed emergence, and the resulting attributes emergent properties.

Designers do not understand emergence. They are not aware of it. They do not need to be. It is not part of their vocabulary. If you ask a room full of designers, a minority will have heard of emergence and emergent properties. An even smaller minority will be able to articulate a clear understanding. This identifies a problem. Designers use emergence. It informs design activity. The manner that users (ab)use products and services in a way that was not intended, considered or expected, informs subsequent design activities. This pattern of unexpected use and adoption can actually trigger New Product Development (NPD) by providing insight into unexplored areas.

Understanding the nature of this adoption allows designers to formulate user insights that in turn assist in the development of new products and services. The recognition of actual user adoption, as opposed to intended, desired or predicted user adoption, is key to utilising emergence in a design context. Identifying and acknowledging the way that users actually use products and services, and incorporating this information into future scenarios of use is intrinsic to the design activity. Thus, it may be claimed that designers engage with emergence as an integral element of their design activity.

2. Definition of Emergence

Before developing the theories within this paper, a consideration of emergence in broad terms is necessary. Numerous definitions and interpretations of emergence prevail, we offer the following:

Emergent properties are those features of a system that cannot be anticipated or understood by a complete analysis of the system. When the whole is greater than the sum of the parts, indeed, so great that the sum far transcends the parts and represents something utterly new and different, we call that phenomenon emergence (Johnson 2003).

The hallmark of emergence is much coming from little, with the behaviour of the whole being much more complex that the behaviour of the individual elements or agents. Emergent behaviour occurs without direction from a central executive but is the result of uncovering quite unexpected possibilities via collective interactions (Holland 1998).

An emergent property can appear when a number of simple entities or agents operate in an environment, forming more complex behaviours as a collective. The property itself is often unpredictable and unprecedented, and represents a new level of the system's evolution. These behaviours are not a property of any single such entity, nor can they easily be predicted or deduced from behaviour in the lower-level entities. An entity is something that has a distinct, separate existence, though it need not be a material existence (nationmaster.com 2005).

3. Design and Emergence

In the context of design, emergence can be described as unexpected properties that evolve during the use of products and services that include user interaction. The system with which interaction occurs represents a level of adaptability or series of ways in which we can determine the same result. No one approach is paramount, rather a multiplicity of approaches are adopted dependant upon the users cognitive responses.

A number of stages in the relationship of design and emergence have been identified, with these forming a Design and Emergence Spiral, Figure 1. The stages in this spiral are represented as: pre-design emergence; design activity; and post-design emergence.

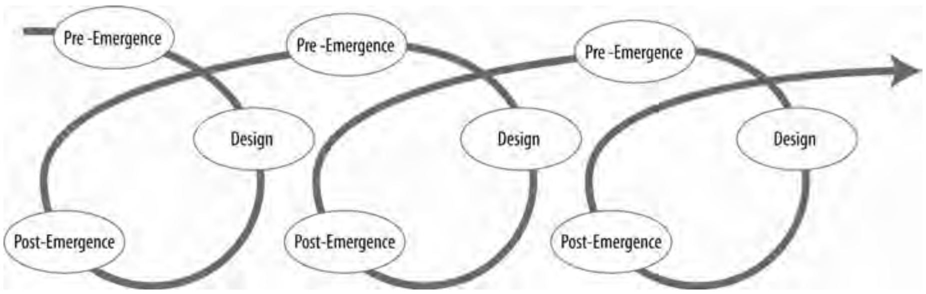


Figure 1: Design and emergence spiral

The design and emergence spiral provides a generic model of the design and emergence interface. The user/designer relationship is central to this interaction. A feedback loop between post and pre-design emergence stages allows user behaviour to inform design undertakings. The designer utilises this information to explore potential behaviour patterns and ultimately design opportunities. The following provides a more detailed consideration of design and emergence in the form of the Design and Emergence Cycle, Figure 2.

The interrelationship of design end emergence is comprised of the following stages:

- Pre-Design Emergence: where potential user behaviour and adoption patterns are envisioned by the designer in the form of future scenarios
- Design Activity: where design opportunities and explored and developed in relation to specific contexts

- Post-Design Emergence: where actual user behaviour and adoption patterns are studied by designers and utilised in the development of future strategies

The above stages form a Design and Emergence Cycle. This will be considered in more detail.

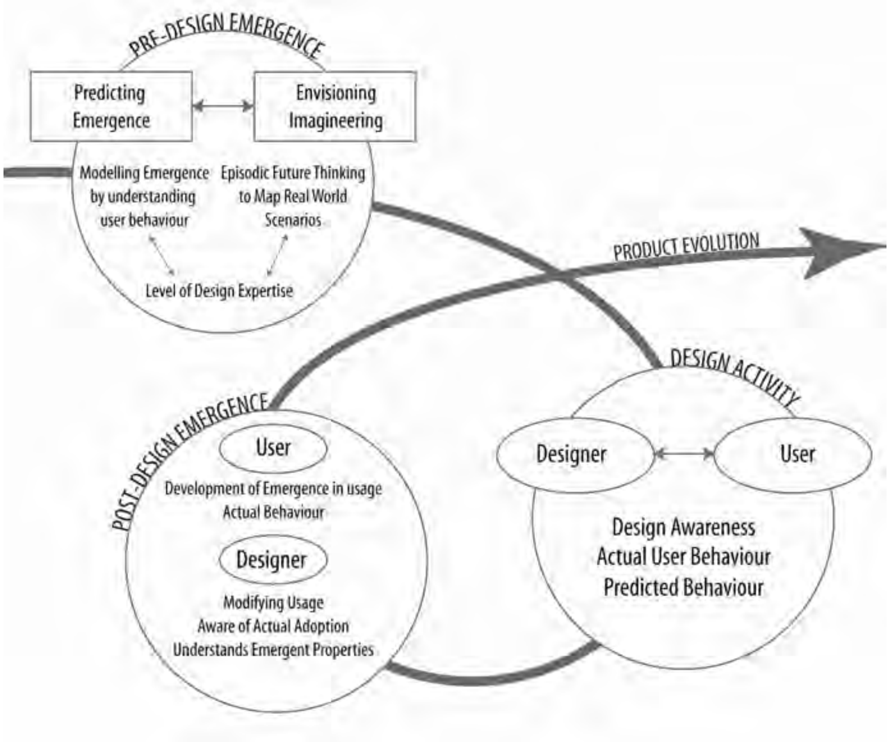


Figure 2: Design and emergence cycle

4. Pre-Design Emergence

Designers attempt to predict expected and unexpected behaviour within specified contexts, and utilise this information within subsequent design undertakings. The likelihood that unexpected behaviour will occur is explored by modelling emergent properties via an understanding of user behaviour and adoption patterns. The understanding of user behaviour is based upon a prediction of how a product or service is likely to be adopted. These predictions are informed by experience of adoption patterns and the outcome of tailored research undertakings.

Designers envision future scenarios as part of their design activity. The envisioning process is informed by the creation of simple (or complex) visions of future scenarios. Consideration is given by the designer to preferred and possible user behaviour in a given context. This may include multiple (ab)uses of a proposed product or service. Here the designer is considering possible user behaviour and adoption patterns. These patterns are the designer's vision of what is likely to occur. These activities are undertaken before the design activity stage is commenced. We call this stage Pre-Design Emergence.

4.1. THINKING ABOUT THE FUTURE: FORECASTING

Designers utilise many approaches to consider, develop and evaluate potential futures. These approaches are collectively known as forecasting.
Forecasting approaches are employed across all design domains and include methods such as backcasting, cross-impact matrices, Delphi surveys, scenario building, trend analysis, visioning, and time line extrapolations (Slaughter 1996).

Thinking about the future events and their consequences is described as prospective thinking (Atance and O'Neill 2001). This is defined as how we remember to engage in an intended action at a specific point in the future, for example remembering to give someone a message. The process of using prospective thinking can be split into three stages:

(1) The development of a plan
(2) Remembering that plan
(3) Remembering at to execute the plan in the future

Within the context of this paper we will predominately be considering the development of a plan (1).

In the context of design and emergence, effective prospective thinking allows the pre-experience of a future event. Designers project themselves into the future, pre-experiencing an event or situation before it has occurred. This process is called Episodic Future Thinking (Atance and O'Neill 2001; 2005).

4.2. EPISODIC FUTURE THINKING

Episodic Future Thinking is defined as projection of the self into the future to pre-experience an event. It used to envisage future scenarios, and plan for them accordingly. The use of episodic future thinking is based on experience of similar events and the knowledge we may have gained from that experience. Humans have the ability to re-experience situations and project them into the future, applying them to events that we perceive to have similarity (Atance and O'Neill 2001; Atance and O'Neill 2005).

To understand how the experience gained from an event is utilised in episodic future thinking, we must consider how human memory functions. Human memory can be split into two distinct systems: Episodic and Semantic Memory (Tulving 2001):

- Episodic Memory: the system that allows us to remember personally experienced events, and to travel back in time to re-experience those events
- Semantic Memory: is our knowledge of the world, with respect to memories related to the self

The distinction between semantic and episodic memory can be described as the difference between knowing information explicit to one's existence, such as the name of the school you attended (semantic memory), against a memory specific to a particular experience or episode you recall at school, such as embarrassing situation during your school life (episodic memory).

4.3. THE USE OF EPISODIC FUTURE THINKING IN PRE-DESIGN EMERGENCE

Designers create visions of possible futures, using episodic future thinking as a method of pre-experiencing future events. This allows designers to consider a multitude of possible futures or scenarios. In this context, scenarios are a descriptions of events that might possibly occur in the future (Cornish 2004), or descriptive narratives of plausible alternative projections of a specific part of the future (Fahey and Randall 1998). Scenarios allow consideration of the prospective actions of potential users, rationalising solutions in real world contexts. By carefully developing scenarios that envisage user behaviour, designers have a tool that assists in the identification of potential emergent properties before design activities have been commenced, i.e. pre-design emergence.

4.4. THE EFFECTS OF EXPERTISE ON EPISODIC FUTURE THINKING

Insight into how successfully designers can consider future user scenarios to map emergent properties can be gained by analysing the content of scenarios which people generate before making their prospective plan. Several scenarios may be created, analysed (Atance and O'Neill 2001).

Scenarios can be considered in terms of possible, probable and preferred future states (Horton 1999). The key to the development of appropriate user scenarios is experience, and the development of expertise in specific knowledge and expertise domains relevant to the design task. Domain specific knowledge plays a significant role in the design of products and services, distinguishing the novice designer from the expert. Two distinct types of expertise can be identified: (1) Routine Expertise and (2) Adaptive Expertise.

Routine Expertise allows the ability to use knowledge to solve familiar problems quickly and accurately, where as Adaptive Expertise allows the utilisation of knowledge, adjusting to varied circumstances, and applying new procedures. Designers use Adaptive Expertise: using both creative and analytical ability to extract, conjugate and apply knowledge.

Table 1 shows the distinction between novice and expert designers in terms of articulating modes of knowledge.

TABLE 1. Levels of Expertise in Designers

Novice Designer	Expert Designer
Weak goal limited strategy Smaller informational gathering Weak domain specific knowledge A lot of assumptions Limited experience General strategies very weak	Rich content of goal-limited strategy Large informational gathering High level of domain specific knowledge Few assumptions High level of experiential knowledge Developed general strategies

An experienced designer demonstrates adaptive expertise. They are proficient at engaging with episodic future thinking due to an enhanced level of understanding of given contexts. This experience provides user scenarios that are informed and appropriate to a given situation. These scenarios consider emergent properties during their development.

5. Design Activity and Emergence

An examination of the design development cycle allows an understanding of how emergent properties can be incorporated into design activities. The identification of emergent properties, and their incorporation as constraints, can provide more effective design approaches. The design development cycle is thus (Kryssanov et al 2001):

(1) Identification of user's needs – generation of basic user scenarios
(2) Conceptualisation of design requirements to meet the needs identified
(3) Transformation of requirements into performance and function specification. Detailed user studies
(4) Elaboration of cost, resources and other critical elements

(5) Mapping and converting the specifications into feasible design solutions
(6) Development of more detailed user scenarios from design solutions presented, prediction of emergence
(7) The optimisation of solutions
(8) Prototyping and testing
(9) Manufacture of product
(10) Implementation of various control, logistics and marketing procedures
(11) After sales services and maintenance
(12) Obtaining and utilising feedback concerning products utility, operation and market value. Identification of user initiated emergence
(13) Product re-development - design evolution

During the design development process, research is used to determine what the problem is, which of the ideas proceed and how they are rationalised, given constraints identified. In short, the designer uses information which allows them to draw a mental picture of the current situation, a complex vision, considering many aspects factual and perceived; experiential and domain specific.

This approach assists the designer in an understanding of the triggers within the design decision making process and supports the development of the design to an optimal state. This process is iterative, as in general, each stage is intended to be an improvement.

Using the design development process, the designers task is to produce a solution to a given problem, beginning by understanding of user needs and identification of market opportunity (1). The information gathered and initial research and information that can be used to generate initial user scenarios and begin generation of realistic concepts (2). As the concepts are rationalised through constraints identified, such as materials and manufacture (3,4,5) and more detailed research is gathered via user studies, the development of more detailed user scenarios can be produced (6). By using an informed or 'real world' visions of user scenarios which feed into the design process, the designer can imaginer the use of complex systems and develop an understanding of potential emergent properties, leading to improved final designs (8,9). Analysis of actual user behaviour and usage is monitored post-design, identifying apparent emergent properties that may be useful in product re-development, developing improved solutions (13). It is a cyclic process of continual product evolution, particularly relevant to sustained product development.

The identification and utilisation of emergent properties both pre and post-design, can enhance the usability of complex, increasingly integrated technologies by simplifying interaction systems or creating more intuitive use.

6. Post Design Emergence

User behaviour and adoption patterns do not always follow the projections or expectations of the designer (or user). A multiplicity of expected and unexpected uses are undertaken by the designer in the development of a product or service during the pre-design emergence and design activity stages. When a product or service has been developed and is experiencing 'consumption', analysis of user behaviour is possible. This analysis allows the designer to identify actual user behaviour and adoption patterns. This will identify use (and abuse) of the product or service and will include patterns that were not anticipated in any former stages. We call this Post-Design Emergence.

Where user behaviour has not followed the projected path of use, an analysis of the underlying reasons for the deviation is possible. This is retrospective (as opposed to prospective) and may uncover the reasons for this deviation. The difference between forecasted user patterns and actual user patterns is called Forecast Deviation. There are often a number of reasons for this deviation (as opposed to a single reason) and the interaction of these reasons can contribute to this change. Holland describes this in terms of the behaviour of the whole being more complex than the behaviour of the individual parts, or as he indicated, much coming from little (Holland 1998).

The analysis of actual user behaviour or 'reality' can be assistive in developing future strategies. This may require additional design activities (in terms of new product development) or revisions to existing offerings due to the knowledge gained in the Post-Design Emergence stage.

7. Case Study: The Secret Life of the Mobile Phone

To understand the effect of emergent properties within everyday culture, the following is a case study of the mobile phone: a product that has exhibited identifiable emergent properties during its life cycle.

The development and consumer take-up of the mobile phone has a long and protracted history. This paper does not intend to provide a critique of this history, but looks at the numerous developments in relation to unexpected use and proliferation of the consumption of the mobile phone.

The history of mobile communication extends beyond the recent introduction of what we think of as a mobile phone. Numerous 'wireless' attempts were made in the last century to provide users with mobile communication. They were often limited, cumbersome, usually expensive and ultimately unsuccessful (Rheingold 2002).

In the early 1990s, technical trends, especially miniaturisation, led to a qualitative change in mobile terminal design (Agar 2003). Mobiles became small and light enough to routinely carry round. New designs attracted new customers, and the mobile became less a business tool as originally envisaged, and much more an everyday object. In addition to technological developments, an important factor in the take up of mobile phones was their cost. In the UK competition between mobile network suppliers, keen to ensure they secured business from customers brought prices down. The mobile became affordable: no longer was it a status symbol – signifying privilege and wealth – but instead the universal accompaniment of (particularly) the young and old (Katz and Aakhus 2002; Agar 2003).

One of the most identifiable presences of emergence in mobiles, in terms of unpredicted user behaviour and adoption, was in fact an afterthought – text messaging, or SMS (Short Messaging Service) as it is officially known. When the first text message was sent in 1993 by Nokia engineering student Riku Pihkonen, the telecommunications companies thought it was not important. Like many technologies, the power of text was – indeed the power of the phone – was discovered by users. In the case of text messaging, the users were the young in the West and East (Agar 2003).

The unprecedented consumer take-up of text messaging surprised the telecommunication companies. Until 1998 the service was free but in September 1998 the traffic threatened to overwhelm the normal mobile voice system. It was at this point that a tariffing system was introduced.

The development of a dedicated text language is perhaps one of the biggest changes mobiles have brought. The language – Textsperanto – the amalgam of abbreviated words, acronyms and coded punctuation that teens developed so that they can fit more words into their space-limited text messages was designed to be impenetrable to adults (Aldridge 2004). Dedicated dictionaries have been developed to assist users understand the multitude of coded exchanges utilised. As a SMS test message contains only text, and the maximum length of a message is only 160 characters, teens have developed an abbreviated language to make maximum use of precious character space (Kasesniemi and Rautiainen 2002).

A number of interrelated factors contributed to take-up of text messaging and the resulting phenomenon. By far the largest single group of text message users are the youth (and in particular teen) market, who have inextricably integrated mobile phones into their lives (Ling and Yttri 2002; Aldridge 2004). They use their mobiles for security, spontaneous coordination of everyday events, interaction, and as a status symbol. SMS is employed for social and emotional communication. The pre-paid or pay-as-you-go system has greatly fostered mobile use among youth. In this system payment is made in advance for telephone access. Once the allotted sum has been consumed, one cannot call out to other (non-emergency) numbers although calls and text can be received for a certain period. Text messaging is generally cheaper then voice calls and so is quite popular among cost-conscious teens who pay for their own mobile use. Each message is unit priced and is usually two to three times cheaper than voice calls especially when calling another network (Kasesniemi and Rautiainen 2002).

The widespread adoption of mobiles points to the importance of availability for teens. Unlike adults, who often feel stressed by the mobile's impact resulting in them being 'constantly available', teens thrive on access and interaction. To receive a message is a conformation of one's membership in a group (Ling and Yttri 2002). Teens feel that accessibility is an important factor of their social life. To be available to friends and to know what one's peers are doing is central. Adolescence is a period in life where the focus is upon peers rather than parents and family. The mobile provides a personal communication away for the eyes and ears of parental view (Agar 2003).

As mobile technology has developed, so has the ways that consumers utilise these new features in a manner not intended by the developers. A by-product of Bluetooth, a short distance wireless communication system, has been the proliferation of Bluejacking. Bluetooth enabled devices can send things like phonebook book contacts, pictures and notes to other Bluetooth enabled devices. Using a phone with Bluetooth, you can create a phonebook contact and write a message, e.g. 'Hello, you've been bluejacked', in the 'Name' field. Then you can search for other phones with Bluetooth and send that phonebook contact to them. On their phone, a message will popup saying 'Hello, you've been bluejacked'. Most victims they will have no idea how the message appeared on their phone (bluejackQ.com 2005). This form of emergence is undesired as well as unpredicted.

Enhancements in mobile phone technology have spawned a host of new and sophisticated forms of bullying. In the latest craze, happy slapping, youths use their mobile phone's video streaming function to film attacks on innocent bystanders. As a result, following a number of playground incidents, schools in the UK have imposed a total ban on camera phones. The development, part of a larger trend in cyber bullying, is increasing due to the ease of greater dissemination of the abuse. The use of mobile to send abusive text messages has also been identified. Some schools have installed a confidential mobile number for pupils to report bullying by text message (Hoare 2005).

The development in mobiles has been greeted with numerous unexpected and unpredicted consumer application of the available technology. The case study has identified a number of occurrences of unexpected user behaviour and adoption patterns. This information is identified in the Post-Design

Emergence stage but is utilised in subsequent stages including Pre-Design Emergence and Design Activity.

8. Concluding Remarks

Emergence has an important role in design. This is demonstrated by the possibilities made available by the recognition and utilisation of emergence properties in design undertakings. An enhanced awareness and understanding of the role of emergence in design provides the designer with a powerful design development tool. This tool is particularly appropriate for fast moving consumer markets that exhibit complex interactions where unexpected and unpredicted properties are common place.

The difference between forecasted user patterns and actual user patterns is Forecast Deviation. This allows analysis of unexpected properties and adoption patterns and provides information that may inform strategy and NPD activities. The awareness of actual, as opposed to projected user behaviour patterns is important to effective management of the design life cycle. The primary role of the mobile phone, for example, was to enable voice communication while mobile. This has developed greatly into a communication device that enables a multitude of 'communications'. The way that users have adopted mobile phones has been instrumental in subsequent design activity. Strategic direction has been influenced by the role of the user in this process.

The presence of emergent properties within a given system changes the status of that system. It is an evolving system where the behaviour of the whole is much more complex that the behaviour of the individual elements. The interactions within the system contribute to its evolution. These interactions are said to be synergetic – the whole being more than the sum of the parts.

The role of episodic future thinking is central to considering proposed user behaviour patterns. The pre-experiencing of events and situations is valuable to designers as it allows multiple scenarios to be modelled, developed and evaluated. Within pre-design emergence, episodic future thinking is an effective tool for the consideration of possible user behaviour patterns. This provides opportunities to develop intuitive interaction approaches as the mindset of the user is being (pre)experienced.

References

Agar, J: 2003, *Constant Touch: A Global History of the Mobile Phone,* Cambridge, Icon Books.

Aldridge, J: 2004, I'll Give You a Bell, *The Observer 'Review'*, London: 1-2.

Atance, C and O'Neill D: 2001, Episodic future thinking, *Trends in Cognitive Science* **5**: 533-539.

Atance, C and O'Neill D: 2005, The emergence of episodic future thinking in humans. *Journal of Learning and Motivation:* 126–144.

bluejackQ.com: 2005, What is Bluejacking? Accessed: 03 June 2005.

Cornish, E: 2004, *Futuring: The Exploration of the Future*. Maryland, World Futurist Society.

Fahey, L and Randall R: 1998, *Learning From The Future*, John Whiley & Sons.

Hoare, S: 2005, Danger: Cyber torturers online, *The Guardian: G2,* London: 11.

Holland, J: 1998, *Emergence*: *From Chaos to Order*, St. Ives, Oxford University Press.

Horton, A: 1999, Forefront: A simple guide to successful foresight. *Foresight: The Journal of Future Studies, Strategic Thinking and Policy*: 05-09.

Johnson, S: 2003, *Emergence: The Connected Lives of Ants, Brains, Cities and Software*, Penguin Books Ltd.

Kasesniemi, E and Rautiainen P: 2002, Mobile culture of children and teenagers in Finland. *Perpetual Contact: Mobile Communication, Private Talk, Public Performance* J Katz and M Aakhus, Cambridge, Cambridge University Press: 170-192.

Katz, J and Aakhus, M (eds): 2002, *Perpetual Contact: Mobile Communication, Private Talk, Public Performance*, Cambridge, Cambridge University Press.

Kryssanov, V, Tamaski, H, et al.: 2001, Understanding design fundamentals: How synthesis and analysis drive creativity, resulting in emergence, *Artificial Intelligence in Engineering* **15**: 329-342.

Ling, R and Yttri, B: 2002, Hyper-coordination via Mobile Phones in Norway. *Perpetual Contact: Mobile Communication, Private Talk, Public Performance*, J Katz and M Aakhus. Cambridge, Cambridge University Press: 139-169.

nationmaster.com: 2005, Encyclopedia: Emergence, Accessed: 24 May 2005.

Rheingold, H: 2002, *Smart Mobs: The Next Social Revolution*, Cambridge, MA, Basic Books.

Slaughter, R: 1996, How to develop a social foresight capacity, *Future Visions: Ideas, Insights, and Strategies*, H Didsbury (ed.), Maryland, World Futurist Society: 88-100.

Tulving, E: 2001, Origins of autonoesis in episodic memory, *in* H Roediger, J Nairne, I Neath and A Surprenant (eds), *The Nature of Remembering: Essays in Honor of Robert G Crowder,* American Psychological Association: 17-34.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 333-348

COMPUTATIONAL SUPPORT FOR P-CREATIVE SOLUTIONS

DARYL H HEPTING
University of Regina, Canada

Abstract. One can distinguish ideas that are historically creative (H-creative) and novel to society, and those that are personally or psychologically creative (P-creative) and novel only to their creator. Many current computational approaches to support creativity and innovation have focused on H-creativity. However, P-creativity is more important to individuals and potentially more valuable to society. In the end, the society whose citizens are supported in finding P-creative solutions is more likely to see H-creative solutions from those citizens. This paper discusses the design of a software system that is focused on the support of P-creative solutions and the democratization of creative thinking. The system allows an individual to work on a problem in his or her own terms of reference, by constructing a conceptual space that the system then populates. The user interface provides each individual many options for organizing this conceptual space in meaningful ways, without imposing a heavy cognitive burden. Four sample implementations are presented and the results of several usability studies are summarized.

1. Introduction

The assessment of creativity for a particular design or solution can be a difficult task. Although Boden (1995) makes the distinction between H-creativity (historical) and P-creativity (personal or psychological), the designer is likely to first be concerned with whether his or her solution satisfies the expressed need. Some of these solutions, according to Gero (1995), will be exceptional while others will be routine. Shneiderman (2000), with his *genex* framework, would direct computational support towards creation of the exceptional, and possibly H-creative, designs.

However, creativity at the psychological level is very important because one invents things for oneself. Wessel and Wright (2001) echo this sentiment with respect musical synthesis: a low entry fee with no ceiling on virtuousity.

Ideally, computer support for design and problem-solving will minimize the gulfs of execution and evaluation and provide users with the ability to interact directly with their designs in a representational mode that is most appropriate (Paivio 1986). In the second option, the user will strive to become an expert in the software tool. However, it may be difficult to maintain expertise in all the facets of the software's operation that are required to realize solution alternatives. And, immersion in the command syntax of a tool may affect one's view of the semantic aspects of the problem.

A powerful tool is required to support the user both in creating an acceptable solution alternative and in its modification, which is related to one's ability to evaluate and compare different solution alternatives. Regardless of the expertise one has with respect to the syntax of the tool or to the semantics of the problem, generating solution alternatives can be difficult. As Bertin (1983) indicated, "to construct 100 DIFFERENT FIGURES from the same information requires less imagination than patience."

This paper describes an augmented system, called *cogito*[1], which enables combinatory play for users to explore and navigate complex (design) problem spaces.

2. Background

This work draws from several diverse sources for its foundation. This section first presents the background that inspired the *cogito* system and then reviews other work done in support of creative designs. A variety of application areas considered and illustrated with examples.

Figure 1 shows a sample visual representation where the parameters include plot-type, colour, data, and sorting. A user may understand each value for each parameter, yet he or she has likely been unable to assess each combination, each point in the conceptual space. P-creative solutions may exist within these unexplored alternatives. Although it is feasible to identify a parameter and change its value in order to change the design, one must know the permissible values and keep a record of which have been used in which combinations, if the activity is to be something more than random.

When potential solutions are realized, as in Figure 1, they are interpreted and evaluated for effectiveness. Although a pattern may be clearly visible

[1] The name of the system, *cogito* is taken from the Latin verb "to think", which etymologically means "to shake together". This is done to acknowledge the role of the combination of ideas in various models of human inventive thought.

here, there are many questions that need to be answered before deciding if this solution is optimal for any particular application.

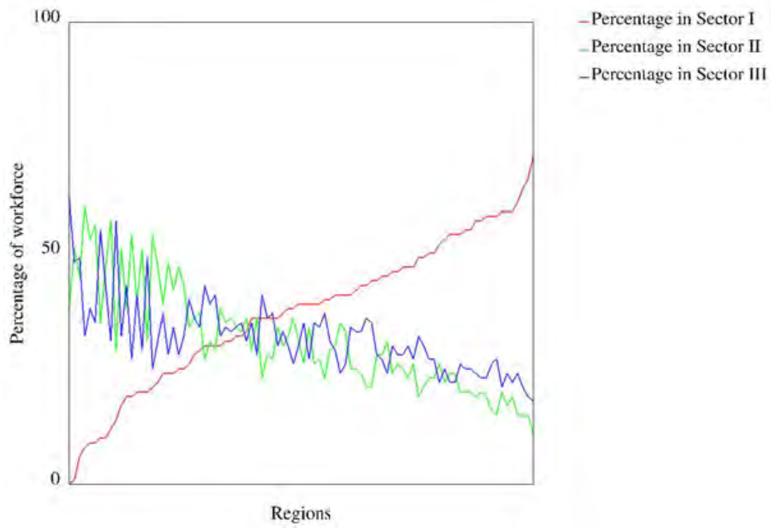


Figure 1: A sample visual representation design that illustrates the description of each design as the combination of values, one from each parameter.

Bertin (1983) contends that meaning can be communicated fully through the graphic and its legend. The more widely accepted view is that communication and interpretation occur, or are influenced by things, outside this realm. Casner (1991) argues that one must always consider the task when assessing any visual representation. Furthermore, it is important to understand that each viewer is unique in terms of the experience brought to the interpretation of any visual representation. Although some have suggested the use of "efficiency" as a means for choosing a visual representation, it cannot be generalized beyond a single user.

Many augmented systems require an initial, at least partial, specification of a design. Yet, the initial specification can be difficult if one is unfamiliar with the range of available options. Local searches using gradient-based methods are useful to refine a particular design, but they may trap the designer near a local maximum. Genetic algorithms are very effective at searching an entire space in a global fashion, and they permit what Gero (1995) has called *emergence* (of unexpected designs): their combination of pieces from different known solutions may lead to something unknown. Interactive, computer-aided, searching of a large space has been available since Dawkins (1986) released *The Blind Watchmaker*. Sims (1991) presented a method for the use of artificial evolution in computer graphics that employed both a genetic algorithm (Goldberg 1989) and genetic programming (Koza 1992). Both of these "genetic" methods work by simulating the cellular-level processes of cross-over and mutation. The former does this as a means to search a space whereas the latter works to transform the space itself. For Sims, the goal was to evolve images and textures. However, because it is surprising to see images from different generations with no apparent connection between them, it can work to defeat the user's control. Todd and Latham (1992) also discussed a genetic approach to the generation of new images, theirs being more restrictive by not including genetic programming. Boden (1996) argues that the latter is more relevant to artistic creativity because it allows a more deliberate and disciplined exploration of alternatives. Shneiderman (2000) also focuses on the evolutionary creativity found in an iterative process, which he calls *genex* (generator of excellence).

Vass et al. (2002) study creativity by constructing a problem-solving environment (PSE) that supports flow "being completely involved in an activity for its own sake" (Csikszentmihalyi 1996), and evaluating PSEs on that basis. The design of the *cogito* system, described next, was influenced by the same inquiry about what things support creativity.

3. Tool Design

The human-computer symbiosis first proposed by Licklider (1960) had the goals of bringing the computer into the "formulative parts of technical problems" which might be too difficult for humans alone; and to create a direct link between human and computer which would enable the computer's involvement in "real time" situations. The design of this software is based on five principles, described in this section, that are all facilitated by the parameteric representation of conceptual space. There is agreement between these principles, the activities that support the different generator-of-excellence phases (Shneiderman 2000), and other problem-solving models. Ultimately, this work is concerned with empowering the user to work with problems in their most appropriate representational mode. Broadly, this means working visually with data plots. In terms of textual interfaces, though, it means choosing and naming parameters (or dimensions) of a conceptual space in the most appropriate way for individual users (for example, in the description of recipes or cleaning products with environmental impacts).

3.1. SUPPORT THE DESIGNER IN INTERACTING DIRECTLY WITH SOLUTIONS

Although a user may have excellent semantic knowledge in relation to the problem, he or she may have poor syntactic knowledge in relation to the tool

(Shneiderman 1992). Requiring that a user upgrade his or her syntactic knowledge of a tool may not be a good solution.

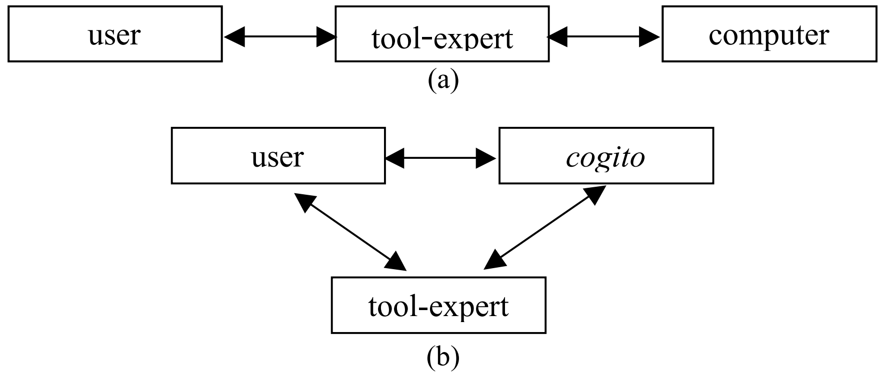


Figure 2: In (a), the user's access to the computer is mediated by the tool-expert. However, in (b), the user has direct access to the cogito software, and so fewer syntactic issues are anticipated.

There is increasing evidence, in part reported by Fallshore and Schooler (1995), which indicates that attempts to verbalize descriptions of such non-reportable phenomena may overshadow the original information. For example, verbalizing the appearance of a previously seen face interfered with the ability to later recognize that face from a group of similar ones (Schooler and Engstler-Schooler 1990). Likewise, the verbal specification of a desired solution alternative may ultimately impede access to it when the language of the user does not match the language of the tool. Remaining in the perceptual domain of images for visually-oriented tasks may alleviate this problem (Hepting and Arbuthnott 2003). More generally, this suggests that representation modality be matched to the problem so that the need for syntactic knowledge can be minimized. In the area of decision support, users may have a more satisifying experience if the information is organized and named in ways that they would choose.

Simultaneous display of multiple solution alternatives is essential because it permits the user to see what is possible within the space and it facilitates navigation amongst alternatives, which is done by mouse clicking. In order for the user to concentrate on the semantics of the task, the interface must be simple, yet sufficiently powerful. The *cogito* system does this by presenting the user with a selection of solution alternatives, realized from potential solutions in the conceptual space, as illustrated in Figure 3. For example, a cook could conceptualize an American-style appetizer with beans as the main ingredient. At least one such a recipe does exist in the collection: “opposing-sides two bean dip”, which is then realized in the top left display cell. This interface, inspired by Sims (1991) and Dawkins (1986), presents the user with a sample of what is available in the space. The user sees the current space, with the current organizational view (examining American-style appetizer recipes by their main ingredient), one screen at a time.

Figure 3: The cogito interface used for browsing a recipe collection. Each of the recipes shown is from cuisine “American” and course “Appetizer”, but the ingredients are varied.

3.2. SUPPORT THE USER IN CHOOSING AND COMBINING SOLUTIONS

Any visual representation arising from data visualization is a combination of values to encode which data to depict, by what means to depict the data, which colours to use, and so on. In the general problem-solving case, identifiably desirable features may be spread over a number of combinations. A mechanism that permits combination would allow these features to be examined or explored more closely. Such an operation would very tedious if done manually but it is easily accomplished within *cogito*. Crossover is used to compute the subspace of alternative solutions that are consistent with the selections. The new subspace is sampled in the same way as the original: potential solutions are partitioned according to values of a parameter or parameters and then a representative potential solution from each partition is realized and displayed to the user. From the display in Figure 3, if the user selected "opposing-sides two bean dip" and "scallops on skewers with carrot sauce", the system would create a subspace of alternative American-style Appetizer recipes that shared the same characteristics as the selected alternatives (beans and cook, fish and grilled) as well as combinations of these: beans and grilled, fish and cook – if they exist in the collection. The cook could explore a wider range of recipes by indicating that similar recipes would be permitted (not matching on all parameter values). For example, an American-style recipe with beans and bake (differing on only 1 parameter value) would be considered similar.

3.3. SUPPORT THE USE OF HEURISTIC SEARCH TECHNIQUES

Researchers have observed that, especially in design, problems and solutions co-evolve. One usually does not, perhaps cannot, have a clear statement of the problem without an idea of the solution. The advice is to begin, regardless of whether one is actually at the beginning. One's ability to explore the space from that starting point may affect his or her satisfaction upon completion. This searching permits an interactive articulation of the design, which has some similarity to participatory design (Muller and Kuhn 1993) or evolutionary project management (Woodward 1999).

According to Simon (1977), one may think of the search within the conceptual space for a solution as an instance of problem-solving. Even for small problems with relatively few alternatives, an exhaustive evaluation is almost always completely impractical. Instead, humans rely on heuristic search methods that are not likely to find an optimal solution, however judged, but rather to find acceptable (or *satisficing*, after Simon (1977)) solutions in a reasonable amount of time. In general, these search heuristics can be of two sorts. If the problem is well-understood, local search techniques may be employed effectively. If the problem is new, global search may be fruitful. Csikszentmihalyi and Sawyer (1995) also distinguish between problem-solving and problem-finding. One begins problem-finding with a less-clear problem at the beginning, and it can take longer to get through. Problem-finding has been connected to creative productivity and it may be distinct and more difficult than problem-solving.

Csikszentmihalyi and Sawyer (1995) trace many of the current three-stage models to the evolutionary epistemology of Campbell (1960). In these schemes, variations are created, then selected and possibly retained. Behind the flexible visual interface of *cogito* is an architecture that supports the problem-solving process of combination, selection, and retention. Combination is done by both user and computer: the user constructs the conceptual space and the computer samples the space to realize potential solutions for display in the interface. Selection is done by the user, who can interactively articulate his or her requirements in a powerful way (Wegner, 1997). The user indicates desirable parameter values or complete solution alternatives by selection (done by clicking directly on the desired cell). Once the user is satisfied with the selections made on a particular space, a new space consistent with those selections is generated by a genetic approach that performs crossover operations amongst selected combinations. Final solutions that meet the needs of the user are retained.

In this way, the space of all available solution alternatives can be navigated to achieve effective results. The possibility that the selected alternatives will come from combinations generated outside the user's experience is a very powerful aspect of this approach. It is therefore much more likely those fruitful combinations will be explored using this system.

In general, many existing software systems either limit user involvement and exploration by assigning search tasks solely to the computer, or encourage involvement by providing tools to support programming and ignore the issue of exploration. Spreadsheet interfaces (Jankun-Kelly and Ma 2001) are powerful, but they are also limited by the fact that they require manual specification of the two parameters that are used for searching at any time.

3.4. SUPPORT THE DETERMINISTIC MANIPULATION OF THE CONCEPTUAL SPACE

One's conception of the conceptual space relating to a problem may change considerably over time. According to Perkins (1995), a problem space can appear either as clue-rich (homing) in which the solution is evident, or clue-poor (Klondike) in which the solution must be found by prospecting. Before redesigning or respecifying a conceptual space, the designer may wish to restructure and reorganize alternatives in the space in an attempt to increase understanding and to find a transformation of the space from Klondike to homing. Choosing to view or organize the current space by a different parameter can do this: for visualizations, to look at alternatives based on "plot-type" or "data" or "colour" (with reference to Figure 1). The manipulations are deterministic because genetic programming is not used to increase the size of the space of available solutions.

Boden (1996) also discusses conceptual spaces defined by stylistic conventions, and how to expand those spaces with three rules: "drop a constraint", "consider the negative", and "vary the variable." On the one hand, constraints may be necessary when the design space is large. However, to constrain or to rely on examples too much might lead one to fixate too soon on an ineffective design (Smith 1995). Schank and Cleary (1995) made the following comments regarding computer systems: "We are not proposing that people simply loosen the constraints they use when searching for and applying knowledge. A system [person] that worked in this way would not be creative but would instead progress from schizophrenia (as it leaped from one random idea to another) to catatonia (as it found itself buried under a combinatorial avalanche of attempts).”

Figure 5 illustrates how organization is done within *cogito*: the conceptual space shown in (a) can be organized according to each axis. This affects how alternatives are presented to the designer through the interface. It provides, through views, the means to structure and examine the space according to a range of criteria. Successive generations can be used to either narrow or expand the search space, depending on the needs of the designer. The system does support “vary a variable” by allowing some or all values of a parameter to be returned to consideration when the designer might say “I like everything except the colour.”

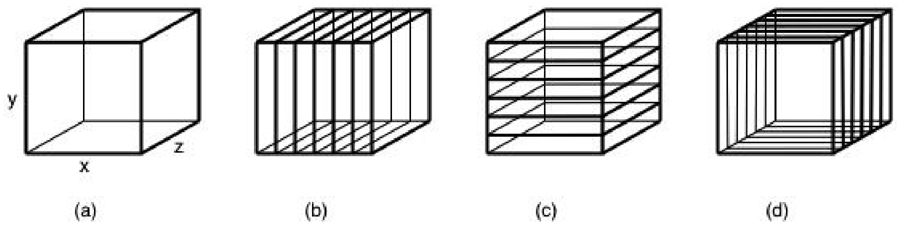


Figure 5: Consider a conceptual space parameterized by x, y and z as shown in (a). Figures (b)-(d) show how this space can be partitioned according to each of the parameters (first x, then y, then z).

3.5. SUPPORT COLLABORATION AND SHARING OF IDEAS

The computer is well-suited to provide the external memory necessary to support decision-making processes that rely on the evaluation of a number of different alternatives, so that the user can know which potential designs have been realized without being responsible for the bookkeeping.

Both problem-solving and problem-finding are social activities, to which many people can contribute (Csikszentmihalyi and Sawyer 1995). Yet, if novel designs are discussed too early, the group may discourage them. A record of exploration and of design rationale can help make these arguments more clear. According to Fischer and Boecker (1983), “design is concerned with how things (“artifacts”) *ought to be*, in order to attain goals and to function.” As the solution evolves, it is desirable to keep a record of changes.

4. Results

The function of the *cogito* system is separate from any application that may be written for it. Therefore, the interface presented to the user is always the consistent interface of the *cogito* system itself. This section describes results obtained with different applications written for the *cogito* system interface.

4.1. INFORMATION VISUALIZATION

An information visualization application was developed to explore how people would go about selecting a two-dimensional data plot in order to answer some specific questions about the data being plotted. Figure 1 was created using this application. The conceptual space was defined by the author and it allowed users to manipulate data plots according to plot-type, data, data-sorting, and colour (for example). A user study was devised to test two variations of the interface: verbal-sequential (one alternative at a time) versus visual-simultaneous (several alternatives displayed at once) that respectively provided primarily-global and primarily-local searching and navigation capabilities. The two interfaces are shown in Figure 6. Over the course of two studies, fifty-seven undergraduate participants were asked to perform tasks using only one of the interfaces. Each participant was given a pre-task questionnaire, a training task with a simple *cogito* application, a main task with the *cogito* application, and a post-task questionnaire. The task involved creating two-dimensional plots based on data about the French economy from the early 1960's (Bertin 1983, page 100). For each département in France, there was information about the workforce (in thousands of workers) for each of the three sectors (primary, secondary, and tertiary) in the economy; the total workforce (the sum of the three sectors); and the percentage of the workforce in each sector. The questions posed were chosen to emphasize the three different types of reading one might use with a graph, identified by Bertin (1983): elementary, where one is interested in a specific fact; intermediate, where one is interested in characterizations of facts; and overall, where one is interested in relationships between different characterizations.

The data, in this case the percentage of workforce in each of three sectors, provided the necessary inputs to allow participants to use the tri-linear plot (bottom of Figure 6). A point that had values of 33.3%,33.3%, and 33.3% would lie in the middle of the triangle. If any of a point's values was 100%, it would lie at the corresponding vertex of the triangle.

A between-subjects design was used to gather qualitative data about the participants' impressions of the tasks they completed. It was found that users did not always find that the conceptualization of the problem (in terms to plot-type, data, colour, etc.) was not always liked. Therefore, performance from users was likely influenced by this potential mismatch.

With respect to the interfaces, participants liked the speed with which they could manipulate alternatives (bottom, Figure 6) by selecting items from option menus. The participant comment "having the ability to play with the data, and see it in ways that were meaningful to me – and being able to build that meaningful representation" was indicative. These participants also missed the opportunity to see multiple plots at once.

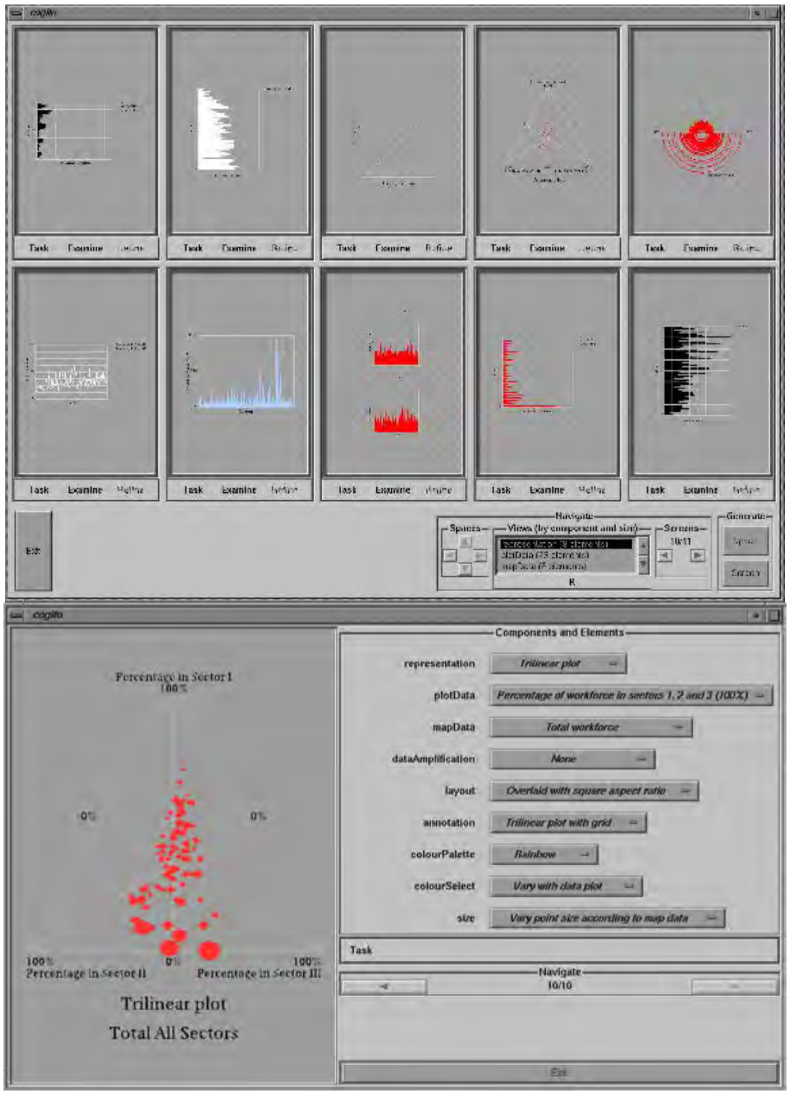


Figure 6: The global (top) and local (bottom) search interfaces for cogito. These interfaces were used in a study of the cogito software. The examples shown are from a data-plotting (information visualization) application.

However, there were many positive comments: “It seems to be a very good program for someone like myself, with little graphical software knowledge to use. It is easy to learn which would allow more time to focus on the data that the graph represents and less on actually making the graph.” Users of the simultaneous-visual interface (top, Figure 6) also liked the organizational capabilities: “the way it organizes information trees, the hierarchy allows easy access to previous choices, the way many graphs are different options displayed at the same time lets it be easy to see which one is best for analysing data.”

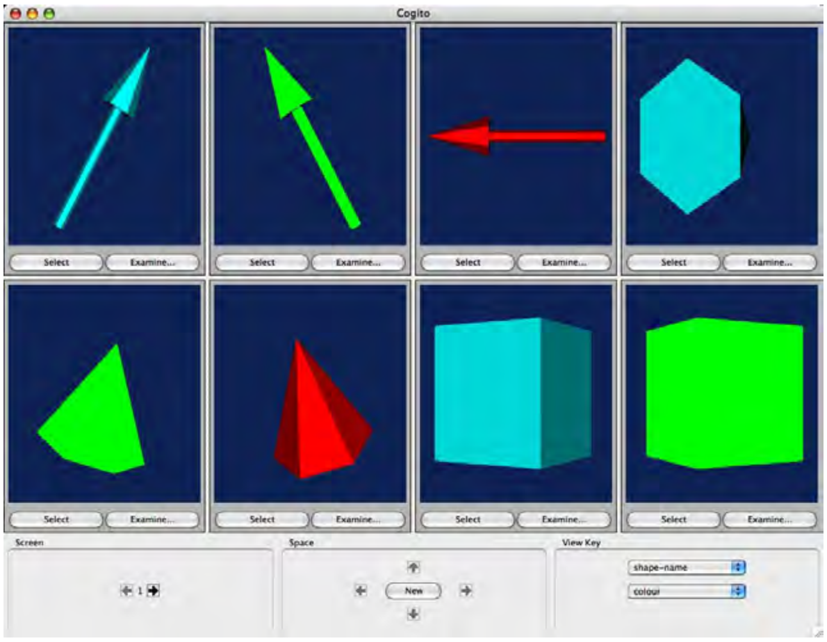


Figure 7: The cogito interface exploring outputs from an application which uses the visualization toolkit (vtk).

Overall, participants were not overwhelmed when dealing with a large space and that both local and global search features were appreciated. Although this global search interface may have a steep learning curve, it is also very novel. Further studies will be needed to better test for creative outcomes. However, that participants were not overwhelmed with the number of available alternatives may indicate the presence of flow (Csikszentmihalyi 1996), in that people were able to stay focused their task, despite having over one million potential solutions in the conceptual space.

It seems that *cogito* can provide the basis from which p-creative, and h-creative, designs (or choices or discoveries) may come.

A separate application programming interface (API) has been developed so that a variety of applications can be written to use the system user interface. This approach was adopted in order to provide easy access to the common capabilities for navigating and exploring a conceptual space.

Figure 7 shows *cogito* being used to explore alternatives generated by an application written using the visualization toolkit (vtk), developed by Schroeder et al. (1996). The programming, as described below, that is required to interface with the application's syntax is done separately from the user's interactions and is hidden from the user.

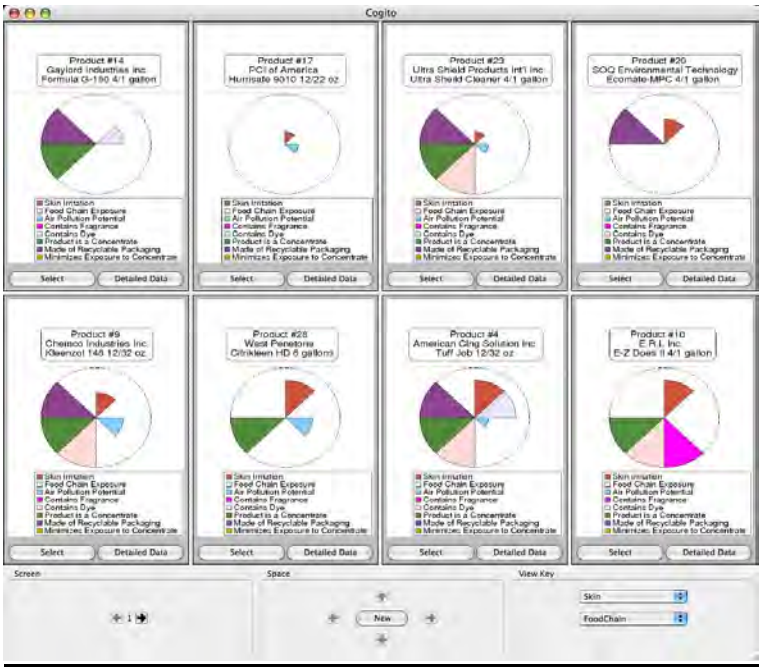


Figure 8*:* The cogito interface used to provide decision support for environmetally-preferable purchasing.

4.2. ENVIRONMENTAL DECISION SUPPORT

Figure 8 shows a decision support system for environmentally-preferable purchasing. It involves access to a database, and as such is different from the aforementioned applications (Figure 6 and 7). The database will not generally contain records for all possible combinations of parameters. For each product, there are eight attributes that are used to quantify environmental impact. This application has been studied in relation to more traditional web-based decision support alternatives, with positive results. Maciag et al. (2005) examined how people relate to the information presented through these attributes and explored ways that the presentation could be personalized without significant overhead.

4.3. RECIPE BROWSING

A recipe-browsing application, shown in Figure 3, was built for the *cogito* system. It is similar to the Environmental Decision Support in that it accesses a sparsely-populated database. For example, recipes do not exist for every combination of ingredients. Therefore, the application retrieves whatever available records match the current query and employs a concept of similarity to retrieve close matches when no or very few exact matches exist. A user study was conducted of the recipe browser using 20 undergraduate participants. The participants were asked a variety of questions involving 1, 2, and 3 parameter values (relating to cuisine, ingredients, season of year, and cooking method – for example). Comments were very positive, especially related to the ability to find interesting recipes (for example): "I like the idea of this software a lot. It would help me getting rid of leftover ingredients. I think the layout is good, and once learned, very fast, powerful and easy to use."

5. Conclusions

The prototype *cogito* system was implemented based on the design principles described herein, and various user studies of the software with different applications have validated those principles. The result that users were not overwhelmed by the size of the conceptual space presents significant encouragement for the architects of tools who seek to put the designers at the centre of the decision-making process regarding their own solutions. The development of the *cogito* system as a flexible interface to a wide range of applications is an important aid to personal creativity and understanding.

Although here is presented a single idea of how a user may proceed with the help of a programmer, there may be cases when users need to add to a conceptual space without a programmer so the means to enable that will require further development.

Acknowledgements

I thank the University of Regina and the Natural Sciences and Engineering Research Council (NSERC) of Canada for financial support. This work was begun as part of my dissertation and I thank Bob Russell, Dave Fracchia, John Dill, and Joe Marks for their valuable guidance. My colleague, Katherine Arbuthnott has helped me to define new directions for this work.

Students Timothy Maciag, Yuancheng Liu, Matthew McKague, Paul Schmiedge, and Orland Hoeber have helped with implementations, proof-reading, or both.

References

Baecker, RM, Grudin, J, Buxton, Greenberg S: 1995, *Readings in Human-Computer Interaction: Toward the Year 2000*, Morgan Kaufmann Publishers, San Francisco.

Bertin, J: 1983, *Semiology of Graphics: Diagrams, Networks, Maps*, University of Wisconsin.

Boden, MA: 1996, Creativity, *in* MA Boden (ed.), *Artificial Intelligence: Handbook of Perception and Cognition*, Chapter 9, Academic Press, Second Edition.

Campbell, DT: 1960, Blind variation and selective retention in creative though as in other knowledge processes, *Pyschological Review* **67**(6): 380–400.

Casner, SM: 1991, A task-analytic approach to the automated design of graphic presentations, *ACM TOG* **10**(2).

Csikszentmihalyi, M: 1996, Creativity: *Flow and the Psychology of Discovery and Invention,* New York.

Csikszentmihalyi, M and Sawyer, K: 1995, Creative insight: The social dimension of a solitary moment, *in* RJ Sternberg and JE Davidson (eds), *The Nature of Insight*, MIT Press, pp. 329–364.

Dawkins, R: 1986, *The Blind Watchmaker*, WW Norton and Company, New York.

Fallshore, M and Schooler, JW: 1995, The verbal vulnerability of perceptual expertise, *J. Exp. Pysch: Learning, Memory and Cognition* **21**(6).

Fischer, G and Boecker, H-D: 1983, The nature of design processes and how computer systems can support them, *in Integrated Interactive Computing Systems*, North-Holland, pp. 73-86.

Gero, JS: 1995, Computers and creative design, *in* M Tan and R Teh (eds), *The Global Design Studio*, National University of Singapore, pp.11-19.

Goldberg, D: 1989, *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley.

Haber, RB and McNabb, DA: 1990, Visualization idioms: A conceptual model for scientific visualization systems, *Visualization in Scientific Computing*, IEEE Computer Society Press, pp. 74-93.

Hepting, DH: 2002, Towards a visual interface for information visualization, *Proc. 6th International Conference on Information Visualization*, IEEE, pp. 295—302.

Hepting, DH: 2003, Interactive evolution for systematic exploration of a parameter space, *in Proceedings of ANNIE*, ASME Press, pp. 125—131.

Hepting, DH and Arbuthnott, KD: 2003, The implications of verbal overshadowing for computer interface design, *Computer Science Tech Report CS-2003-10*, University of Regina, Canada,

Jankun-Kelly, TJ and Ma, K-L: 2001, Visualization exploration and encapsulation via a spreadsheet-like interface, *IEEE Transactions on Visualization and Computer Graphics* **7**(3): 275-287.

Kelly, G: 1955, *The Psychology of Personal Constructs,* Norton.

Koza, JR: 1992, *Genetic Programming: On the Programming of Computers by Means of Natural Selection*, MIT Press.

Larkin, J and Simon, H: 1987, Why a diagram is (sometimes) worth ten thousand words. *Cog. Science* **11**: 65–99.

Licklider, J: 1960, Man-computer symbiosis, *IRE Trans. Human Fact. Elect.*, 4–11.

Maciag, T, Hepting, DH and Slezakm D: 2005, Personalizing User Interfaces for Environmental Decision Support Systems, *Proc. Web Intell. Rough Set WS.*

McCormick, BH, DeFanti, TA and Brown, MD: 1987, Visualization in scientific computing. *Computer Graphics* **21**(6).

Muller, MJ and Kuhn, S: 1993, Participatory Design, *CACM* **36**(6).

Norman, DA: 1988, *The Psychology of Everyday Things*. Basic Books, New York.

Paivio, A: 1986, *Mental Representations: A Dual-Coding Approach*, Oxford Univ. Press.

Perkins, DN: 1995, Insight in minds and genes, *in* RJ Sternberg and JE Davidson (eds), *The Nature of Insight*, MIT Press, Cambridge, pp. 495–533.

Petchenik, BB: 1977, Cognition in cartography, *in* L Guelke (ed.), *Cartographica: The Nature of Cartographic Communication*, Univ. Toronto Press, Monograph 19.

Rosson, MB and Carroll, J: 2002, *Usability Engineering: Scenario-Based Design*.

Schank, RC and Cleary, C: 1995, Making machines creative, *in* SM Smith, TB Ward, and RA Finke (eds), *The Creative Cognition Approach*, MIT Press, pp. 229–247.

Schooler, JW and Engstler-Schooler, TY: 1990, Verbal overshadowing of visual memories: Some things are better left unsaid, *Cognitive Psychology* **22**:36–71.

Schneiderman, B: 1992, *Designing the User Interface*, Addison-Wesley.

Schneiderman, B: 2000, Creating creativity: User interfaces for supporting innovation, *ACM TOCHI* **7**(1): 114-138.

Schroeder, WJ and Martin, KM and Lorensen, WE: 1996, The design and implementation of an object-oriented toolkit for 3D graphics and visualization, *in Proceedings of Visualization 96*, pp. 93–100.

Simon, H: 1977, *Models of Discovery*, Reidel.

Sims, K: 1991, Artificial evolution in computer graphics, *in* RJ Beach (ed.), *Computer Graphics:* SIGGRAPH '91 Conference Proceedings, ACM Press: 319–328.

Smith, SM: 1995, Fixation, incubation, and insight in memory and creative thinking, *in* SM Smith et al. (eds), *The Creative Cognition Approach*, MIT Press.

Springmeyer, RR, Blattner, MM and Max, NL: 1992, A characterization of the scientific data analysis process, *in* AE Kaufman and GM Nielson, (eds). *Vis '02.*

Todd, S and Latham, W: 1992, *Evolutionary Art and Computers*, Academic Press, London.

Vass, M, Carroll, JM and Shaffer, CA: 2002, Supporting creativity in problem solving environments, *Proc 4th Conference on Creativity and Cognition*, pp. 31—37.

Ware, C: 1993, The foundations of experimental semiotics: A theory of sensory and conventional representation, *J. Vis. Languages and Computing* **4**:91–100.

Wegner, P: 1997, Why interaction is more powerful than algorithms, *CACM* **40**(5).

Wessel, D and Wright, M: 2001, Problems and prospects for intimate musical control of computers, *Proceedings of the 1st Workshop on New Interfaces for Musical Expression (NIME01), ACMSIGCHI* electronic proceedings.

Woodward, S: 1999, Evolutionary project management, *IEEE Computer*, pp. 49-57.

Winograd, T: 1996, *Bringing Design to Software.* Addison-Wesley.

Winograd, T and Flores, CF: 1985, *Understanding Computers and Cogniton*. Ablex.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 349-364

THE MODES OF DESIGN ENGINEERING THINKING

P SAARILUOMA
University of Jyväskylä, Finland

K NEVALA
University of Oulu, Finland

and

MIKKO KARVINEN
*VTT, Technical Research Centre Finland
Finland*

Abstract. In this paper, we have separated four different types of thought processes, which occur during engineering design. We have used data which we have collected during research into a large scale industrial design process, i.e., the design of the extended nip press (ENP) in paper machines. By means of interviews and documentary analyses, we have collected a picture of this complex design process. In it we have noticed that there are qualitatively different modes of thinking, which may be used to elaborate classical phase models of human thinking. We suggest that the human thought process entails such modes as apperception, restructuring, reflection and construction. After that we discuss the functions of the modes in design thinking research as well as the relations of content-based analysis to computational modeling and to capacity-based psychology.

1. Introduction

1.1. RESEARCH ON DESIGN ENGINEERING THINKING

Engineering thinking with its variations is one of the most challenging problems of today (e.g. Norman, Cubbitt, Urry and Whitaker 2000; Petroski 1997; Shigley and Mitchell 1960/1990; Vincenti 1990). Traditionally, the focus has been on the technological contents of design, i.e. on applying the so called engineering sciences, special technologies and practices. Systematics (e.g. Pahl et al. 2003; Lindemann 2005, Suh 1990) and promotion of engineering creativity (e.g. Altshuller 1999) were developed in the last part of 20th century.

During the same time period another way of thinking has been gradually developed by cognitive scientists (Simon 1969, Akin 1980, Dym 1994, Cross et al. 1996: Kavakli and Gero 2003, Ehrlenspel 2003, Visser 2003, Tversky 2003). This approach is characterized by a more objective stance towards human research and active use of psychological concepts.

In this paper, the main attention is focused on analyzing the mental contents of designers thinking (Saariluoma, 1990, 1997, 2001, 2003). This is why this kind of research can be called content-oriented or content-based (Saariluoma 2001, 2003). One could naturally characterize this approach with such expression as the psychology of mental contents.

1.2. CONTENT-BASED THOUGHT RESEARCH

The value of mental contents as a problem has been intuitively known for some time. It has already been seen by Newell and Simon (1972) and Fodor (1990) and has repeatedly called the attention of philosophers and cognitive scientists to such research. Nevertheless, it has been important to look for conceptual clarity in the foundations of content-based thought research (Helfenstein, and Saariluoma, in press; Saariluoma 1990, 1997, 2003).

The term content-based refers to the nature of argumentation. Content-based psychology addresses questions which can be studied and explained in the terms of mental contents. Much of the research in thinking has been capacity-oriented; concentrating mainly on the constraints of thought (Anderson, et al 1984; Johnson-Laird 1983; Kavalki and Gero 2003). Nevertheless, in the terms of this highly successful tradition, it has been very difficult to investigate the functions of mental contents in thinking and design. The reason is that the notion of human beings' limited capacity does not provide a good conceptual platform to consider mental contents.

One may naturally argue that content-based thinking is a variation of computational thinking. Newell and Simon (1972), for example, suggested that computer simulations provide sufficiently powerful approach to investigate human thinking. This naturally referred also to design thinking and therefore we have to consider whether computational modeling can answer to all important questions in analyzing design thinking.

In content-based psychology, we are interested in what types of mental contents may explain the essential aspects of the visible behavior (Saariluoma 1990; 1995; 1997; 2001; 2002). Design is a typical problem for content-based research. Problems such as the nature of the content structures in architectural design or in organizational thinking have been investigated (Saariluoma 2002; 2003; Saariluoma and Maarttola 2001; 2003). It has been shown that some structural elements such as functional reasons have a central role in a designers' way of thinking. Here, we shall specifically address on phases or modes of thinking as well as the differences content-based analysis and computational or capacity based approaches to design thinking

1.3. THE PROBLEM OF THE MODES OF DESIGN ENGINEERING THINKING

The modes of engineering thinking present a typical problem, in which content-based analysis might be helpful. Thinking is a process, in which the mental representations of designed objects and the state of a plan constantly evolve. This means that the information content of the representations keeps changing. Therefore, we need a clear conception of the movements in the way designers' think.

One way of conceptualizing the movement of design thoughts is to look for differences between various thoughts. Classic psychological phase models offer one possibility for understanding the modes of design thinking. Dewey (1910) suggested a five-phase model, in which he followed the classic pattern of geometrical argumentation. A somewhat different phase-model was suggested by Wallas (1926). He argued that thinking entails such dynamic phases as incubation and illumination. Finally, Newell and Simon (1972) argued that thinking follows phases of generating and testing. The problem with these studies is that they are generated on small laboratory problems and it is unclear whether they are fully applicable to large scale engineering design thinking. The latter is not a matter of a few minutes or hours but rather years and decades.

2. Research domain

Our investigation focuses on a very large scale industrial design process, namely paper machine design. This is an important subject for investigating design thinking as we do not have very much psychological knowledge about such processes. The artifact is very complex and the technical demands are high. The process of paper making includes a number of complex physical and chemical phenomena, and therefore, it is necessary that a reader with no previous experience on the subject has some idea about the key issues. For a detailed overview on papermaking technologies see Gullichsen and Paulapuro (1998-2000).

Due to the fact that it would have been too complicated to consider the design of a whole paper machine, we have concentrated on one part of it. This was the extended nip press (ENP) for paper machines, Figure 1, which has been an important technological breakthrough in paper machine technology during the last century.

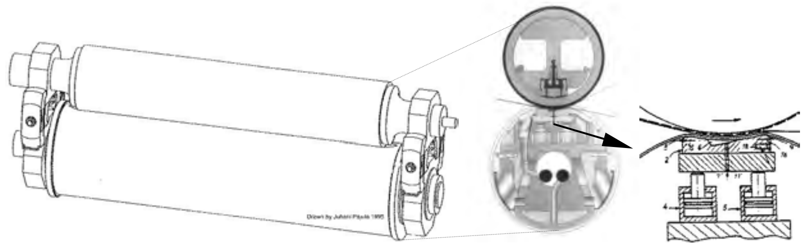


Figure 1. An extended nip press (ENP) for paper machines. It provides a wider contact zone (i.e. the nip) between two rolls and consequently a longer press impulse on the fast running paper. The lower roll has a flexible mantle, which is pressed by the upper roll against a contoured "press shoe" inside the lower roll. Sources: Patent publications (Finland 1995; PCT 1993a) and the publication of 10th Valmet Paper Machine Days (1996).

3. Method

3.1. GENERAL METHOD

A reconstructive analysis, as we see it, is qualitative, which is natural as we are interested in the contents of the thoughts (for qualitative analysis e.g., Dey 1993; Denzin and Lincoln 1994). The data for reconstruction was collected in repeated interviews of the actively involved engineers and the analysis of documentations, i.e. relevant documents and patents. The organizational documentation, e.g. drawings and patents provided us with knowledge about the cul-de-sacs, hypothesis and final solutions, which could then be compared to the interviews. This part of our work was rather analytic, because we looked for significant features in the design process.

In the next stage, the active reconstruction of the thought process was carried out. The most relevant information received in document analyses and interviews were synthesized. The focus on the investigation was to separate the major types of thought processes in the materials and to get an idea about the dynamics of thinking in design. Therefore, we concentrated on the shifts on the focus in thinking. A more detailed disquisition of the whole reconstruction process is given elsewhere (Nevala, in press).

This type of reconstructive research is rare in the psychology of thinking. It combines four important methods of present-day qualitative analysis. They are a case study, biographical method, documentary analysis and historical social science (e.g., Hodder 1994; Smith 1994). Nevertheless, our approach is not the first of its kind. A classic example in the psychology of thinking is provided by Max Wertheimer (1945) in his classic study on productive thinking.

3.2. RESEARCH DESIGN

The obtained material includes 17 hours 50 minutes of individual and group interviews, large assortments of related organizational documents and nearly a hundred patent publications.

Data analysis: In data analysis for reconstructive research, we have separated the indicative elements from the total mass of data (Duncker 1945; Ericsson and Simon 1980; 1984; de Groot 1965; Saariluoma 1990; 1995; Wertheimer 1945). By an indicative element, we mean observational elements which may have an argumentative value.

4. Results

4.1. THE FOUR MODES OF THINKING

In our analysis we found evidence for four qualitatively different modes. We termed them apperception, restructuring, reflection and construction.

4.2.1. Apperception

In earlier content-based research, on thinking, the difference between perception and the construction of mental representations or apperception has become evident (Helfenstein and Saariluoma, in press, Saariluoma 1990, 1995, 2003, Saariluoma and Hohlfeld 1994; Saariluoma and Maarttola 2003). This is a classic difference, which was originally made by Leibniz (1704) and Kant (1781) among others (Stout 1896; Wundt 1880). The content-analysis of mental representations during various thought processes has shown that people incorporate non-perceivable kinds in the content of representations. Typical examples are such notions as possible, infinite, tomorrow; force, mass, friction and electrons. This means that the origin of mental contents cannot be solely in perceptual processes.

CASE 1: The need for making use of the already known invention of the extended nip press was connected to the strategic decisions of considerably increasing the running speed of paper machines.

(T10, 00:09:51[1]): *... On the other hand, at that time the speed was increased. Actually that was why it [the extended nip press] became interesting… When I came here in 1979, I came to the project for increasing the speed… The idea came from outside Valmet… It lead to the approach of increasing the speed, in other words we saw the problems in increasing the speed and tried to search for the solutions… There was the question of supporting the paper web, but at the same time it was seen that when increasing the speed the dry content [of paper] goes down. So increasing the pressing time was a natural idea.*

[1] Position on the CD of the interview recordings: track 10, 00 h, 09 min, 51 sec.

Explanation: In 1970s, in the papermaking industry, a search for technology, which could make it possible to significantly increase the running speed of the paper machines, had been started. One of the many ideas involved, which the product development engineers created, included the possibility of extending the press zone of one press nip.

Later on, the importance of the extended nip was reinforced in the minds of the engineers by the delivery of a “shoe press” into a board machine by the American Beloit Corporation in 1981. This invention was explicated by Justus and Cronin (1982).

In the example, the designer concentrates on some aspect of the manifold of possibilities. Evidently, there is very little perceivable in this representation. The plan was to make a machine with double the speed, but such a machine could not be seen, because there was no machine built. The above representation is thus fully conceptual. For this reason, it is logical to use the notion of apperception. The example also illustrates how apperception focuses on the contents of mental representations.

CASE 2: The content elements of mental representations in design are normally integrated into sense making or senseful wholes (Saariluoma 1990, 1995). In the current interviews, this character of mental representations was explicit. The systems of reasons could be constantly seen. A good example is presented in Figure 2. It concerns the mental representations of the hydrostatic pressure pockets

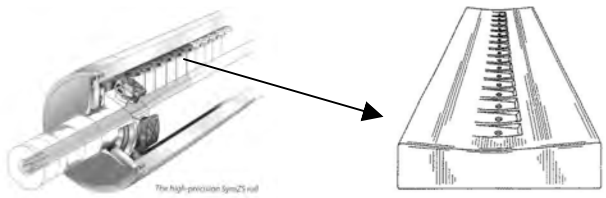


Figure 2. Pressure pockets of the SymZ-roll were transformed to hydrostatic pressure pockets of the so called hybrid (i.e. hydrostatic-hydrodynamic) press shoe.

(T8, 00:24:26): *... This is good in that way that there is no friction here. It is on the oil cushion… The nip [pressure] curve in a hydrodynamic press shoe always becomes by physical laws this kind… We thought that it would be convenient if the nip curve could be adjustable… These were the two reasons…*

Explanation: The main reason for inventing the pressure pockets was to decrease the friction of the press shoe, but it also gave the possibility of adjusting the pressure conditions, i.e., the pressure curve along the shoe. An earlier model for this solution was provided by the existing SymZ-roll.

Discussion

The self-consistent structures of representations are a major characteristic of the apperception mode. This means that there is a reason for each element for being incorporated in a representation (Saariluoma 1990, Saariluoma and Hohlfeld 1994, Saariluoma and Maarttola 1993). This property gives mental representations their sense-making or senseful structure (Saariluoma 1995, Saariluoma and Maarttola 2003).

4.2.2 Restructuring

In an empirical analysis, the intuitively emerged apperceptive representation seems to fluctuate and change. These changes from one apperceived representation to another can be called restructuring (Köhler 1930, 1956, Wertheimer 1945). Restructuring the mental representation is triggered by the information, which is considered inconsistent in the apperceptive representation. This means that the subject sees it impossible to reach the goal.

CASE 3: The quotation in CASE 1 one continues as follows:

At the same time it was seen that putting nip after nip would be a rather expensive solution, but if it were possible to handle the situation by lengthening the nip, so why not…

Obviously, the engineers were dissatisfied with the natural idea of increasing the number of nips to increase the press impulse, Figure 3. Consequently, they rejected this idea and searched for a new. They restructured their mental representations as the solution would not work.

CASE 4: The reason for restructuring can be the falsifying information induced by the professional knowledge of the designer and the comparison of a hypothetical solution to the problem situation.
(T4, 00:02:50): *... Here again… two static pressure pockets. This is one of these propositions of the belt extorted press nip constructions [which do not work in reality]…*

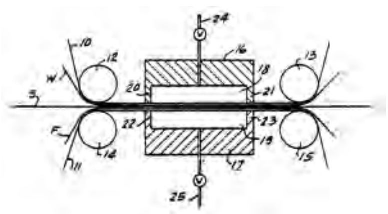


Figure 3. Extended press nip according to patent publication USA (1974).

Explanation: The engineer could conceive without calculation that it is not physically possible to achieve the pressure necessary for an extended press nip by the means of two belts and two pressure pockets only. Mechanical means in maintaining the pressure is also needed. Consequently, all these kinds of constructions were abandoned and more consistent representations were sought. This made it necessary to restructure the prevailing representation. It was put aside and a new apperceptive process constructed a new representation.

Discussion
Restructuring is a qualitatively different mode from apperception. One could characterize restructuring as the process of realizing the fatal inconsistency in the prevailing representation (hypothesis), abandoning it and starting the construction of a new representation. When in apperception we are interested in the way functional reasons bind the elements of the structure into a coherent whole, the major characteristics of restructuring is some inconsistency, which makes the hypothetical solution impossible to realize or non-purposeful to apply (e.g., for economical reasons).

4.2.3 Reflection
When we follow the development of design process as a whole, it is possible to find a new mode of thinking. Clearly, designers have several hypotheses, which are mutually inconsistent in content. It is possible to think, for example, that the flexible belt is either of fiber reinforced polyurethane or of metal, but it is impossible to think of it both at the same time. The shifts in apperception and restructuring seem to lead to a higher level mode in thinking. This is the movement from one possible solution to another (de Groot 1965; Saariluoma 1995).

CASE 5: Figure 4 illustrates a set of alternative apperceptive representations in how it would be possible to connect the flexible belt to the end plates of the roll in a reliable way. The restructuring modes follow each other. The designer's thinking moves from one way of solving a problem to another. This series of alternatives, picked up from a patent publication, documents the movements of thoughts of the design engineer.

In this case, alternatives are mutually exclusive. This means that only one of them can be applied.

Discussion
The crucial difference between reflective and apperceptive modes can be found in the focus. When the apperceptive mode focuses on one single and consistent representation, in reflection the focus is on the comparison between several alternatives which are essentially inconsistent.

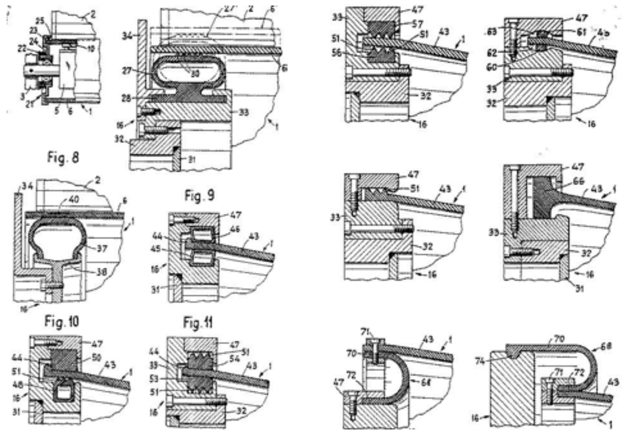


Figure 4. Alternative designs for mantle-end plate fastening in the flexible roll of an ENP-unit. According to patent publication (Germany 1985).

This is why it is conceptually a different mode than the first two and can be called reflection. Perhaps, the dominant characteristic of reflective thinking is where to go in the "forest" of possibilities. It is essentially the selection between various possible ways of acting.

4.2.4 Construction

Finally, our results suggested that design engineering thinking has a constructive character. This means that element after element is incorporated into the final design. The elements are combined and included in a harmonious whole. Analysis of our research material shows how the designers construct the whole; step-by-step and problem-by-problem.

CASE 9: (T4, 00:14:44) ... *We got thicker felts and ZS-roll… So we had to do something to the third press in order get the felt change in order…*
Again (T4, 00:16:10) ... *I think that it was some machine in Rauma, where we built the first cantilever press section…*
(T4, 00:21:35): ... *[Cantilevered press means that] this felt can be pushed as a tube into the press … The felt can be as thick as needed…*
(T4, 00:23:35): ... *Then the latest one is the jointed felts. ... Damn simple frames… … the felt is not an endless loop, the ends will be joined together… The new felt will be drawn in by ropes ...and somewhere here joined. It can be used also in old machines, when thicker felt is needed. ... Nowadays the joint is so good that it does not differ from the rest of the felt.*
(T4, 00:53:48): ... *What it [the dry content of paper] depends also significantly on is the felt type… especially in the extended nip press. In the beginning there were completely wrong types of felts. When the right types of felts were found, the dry*

content rose significantly and the running speed could be increased… The extended nip was an invention which caused many changes in the press section…

Explanation: These quotations represent good examples of the series of consequences to the mental representations of the design engineers caused by the demand for increased running speed of the paper machines and the emergence of the extended nip press. A thicker felt was needed. The felt changing procedures were necessary to change. At first the whole construction of the press section was redesigned to a cantilevered model, where the stiff felt could be changed. This was a rather expensive construction, but was an established solution for over two decades. However, modern technology allows for the use of joints in the thick felt. The felt can be threaded into the press and then the ends are joined, without the expensive cantilever constructions.

The content structure of the constructive mode of thinking is evidently different from apperception, restructuring and reflective thinking. In constructive thinking, the elements of the final design are organized into a self-consistent form. The resolved sub-problems find their places in the plan. This means that the content of the constructive representation is consistent as in apperceiving, but simultaneously it also contains a large set of supplementary elements.

These examples only represent a very small part of the total set of solved problems. Nevertheless, it gives an idea to what sort of things must be bound together in constructive thinking.

Discussion

Typically, in the constructive mode the hypothetical but already working solutions find their place in the whole in what the engineers are building. In principle, constructive mode gives the “eventual”[2] form to the design solutions. It forms the realizations of the design ideas and makes the realization of design ideas possible to begin. When something has got the form that can be incorporated into the final plan, it has its form and place in the whole. It need not be changed but in rare cases we can think that the problem has been solved in this respect.

Construction differs essentially from restructuring and reflection, because it produces integrated representations. It does not focus on inconsistencies. It differs from apperception because of its focus. When apperception entails one sub-problem and a suitable solution to it, construction integrates large

[2] Quotes are used around “final” and “ultimate”, because such attributes can be given to engineering solution only in relative sense. Improvements are on the way all the time.

groups of solutions together. For this reason it is normally impossible to keep all the elements in mind. It is necessary to move the focus between the elements to find a place for all of them. In this way, construction exceeds the limits of apperceptive representations

5. General discussion

We have addressed two different questions here. Firstly, we have considered the phase structure of design thinking from the contents point of view. Secondly, we have focused on developing the analysis of design thinking from the contents point of view. To the very end we shall briefly discuss about the modes or phases of design thinking and secondly the relations of computational and content-based analysis of human thinking.

We have suggested a model with four different modes. Apperception means activation of one pre-dominant mental representation. It entails information about problem situation, goals of design and some unified model for solution. Restructuring is a qualitatively different mode from apperception. It is the process of shifting one representation to another. Apperception is a transiently stabile state but restructuring is a fast change for one way of representing the problem to another.

The need for restructuring is always based on some inconsistency in the prevailing mental representation. In protocols, subjects often refer to the reasons, why they have to abandon their earlier hypothetical solutions. They say that the original way of thinking did not work for some reason. This forces them to abandon one representation and use some other way of thinking as the basis of the solution process. Normally, the alternative representations are mutually incompatible, so that selecting one means that the other one cannot be selected, because the essential elements have different contents and roles in the total representation. The reasons for changing thinking to the restructuring mode differ from detailed physical facts to the normative rules of the organization culture. The reflective process of thinking means that the new hypotheses generated by restructuring processes will be assessed. It is possible to see in the interviews and documents how design engineers' minds have alternated between various possibilities. They have looked for the optimal way of solving the problem. They have to choose between alternative problem and solution representations. They have to compare them and make choices.

Finally, one must incorporate the selected solution to the whole. One must decide how the solution is connected to the whole. Above all, one must decide that there is no need to continue looking for new solutions in the particular issue. For example, the designers were finally happy with the form of the hydrostatic pressure pocket and they accepted that this is a satisfactory solution for this sub-problem. The acceptance makes the constructive mode different from others.

The abstraction of modes is a small detail in the whole of paper machine design process, but it makes understandable some discontinuities in the whole. Modes provide a logical framework for investigating different types of stages and phases of the designers' thoughts. The model makes it understandable, how and why people shift their focus during problem solving processes independent of the specific contents. The presented system is analogous with the stages found in analyzing a chess players' thinking (Saariluoma 1995). This suggests that the modes are not only specific to paper machine design.

An interesting aspect of content-based design analysis is its relation to computational modeling. As is well known, computational thinking is based on Turing's (1936; 1950) famous insights about human mind as a computational device. In this device, a set of inherently meaningless symbols are manipulated by a set of functions. Naturally, a human designer could be seen in this light. They could be seen as symbol manipulating devices (Newell and Simon 1972).

A crucial question we have in individuating content-based approach is to define its differences to computational models of designers. Can we make a difference between content-based and computational analyses of designers' minds? Here, we like to raise one meta-scientific point of view, which supports the idea that contents cannot be expressed by means of computational theory languages. If we are right, this means that content-based analysis is a theoretically independent way of thinking.

It is naturally possible to construct computational models of human thinking. Chess playing programs may serve as examples (for a review, see Saariluoma 1995). The crucial question is, whether we can justify these models on computational theory languages only, or do we need more powerful content-based languages and theory constructions to decide whether a computational model makes sense or not.

The difficulty with computational approaches is that when the machines are abstracted, some essential aspects of mental contents are lost. This is the only way to make such abstractions. It is naturally possible to get meanings back to symbols by means of interpretation. The only problem is that there is no way to justify the interpretation on computational grounds. To justify the interpretations we need to have a non-formal theory language. From our point of view, this kind of theory language is what content-based design analysis should be able to work out.

It is possible also to suggest that a working computational model describes the minimal conditions for a thought process (Newell and Simon 1974). This is also problematic, because modern chess machines or pocket calculators are able to perform like human beings but the way they operate does not teach us anything about human thinking. The way they operate is too far from the way human mind operates. A behaviorally working simulation model is not sufficient justification for internally plausible model. We have to have a content-based justification.

In sum, we are able to construct simulation models which imitate the content aspects of human mind, but we cannot justify those models on formal grounds only. For this reason alone, it is necessary to develop content-based theoretical concepts and analysis of human mentality. The structure of design processes we have abstracted here is a typical example of a problem, which cannot be coped on computational models. The differences between the phases are in the mental contents. On formal level, they are equivalent.

Another natural explanatory language for the modes in design thinking is provided by the limited capacity of the human working memory (Miller 1956, Simon 1974). We know that the capacity of human information processing system is connected to thinking (Anderson et al 1983). Working memory capacity sets limits to the sizes of mental representations. Consequently, it is rational to divide big problems into parts and sub-problems. However, capacity based approaches cannot really explain the differences in contents as one can fill the limited capacity with any information contents as long as they do not surpass the limits. This means that the capacity-based theory language is not sufficiently powerful to express differences in mental contents, which is crucial in the phenomena of mental contents and respectively content-based analysis.

One may naturally be skeptical and ask why we are interested in modes. One answer is practical. We work to reconstruct a decades long design processes. The information we receive from one interview is a very small part of the final whole. We need to have a very clear idea about the dynamics of the thought processes so that we are able to direct our reconstruction process. Many hypotheses live for seconds but some may live for years and eventually become discarded or restructured. This means that we need an overall schema of human design thinking, which can be used to organize the collection of knowledge, the collected knowledge, select essential parts of the data and to separate non-process aspects of thought contents from the process itself.

References

Akin, O: 1980, *The Psychology of Architectural Design*, Pion, London.

Altshuller, G: 1999, *The Innovation Algorithm. TRIZ, systematic innovation and technical creativity,* Transl. Lev Shulyak, Technical Innovation Center, Inc., Worcester, Ma.

Anderson, JR, Farrell, R and Sauers, R: 1984, Learning to program lisp, *Cognitive Science*, **8**: 87-129.

Cross, N, Christiaans, H and Dorst, K: 1996, *Analyzing Design Activity*. John Wiley and Sons, New York.

Dewey, J: 1910, *How We Think?* McMillan, New York.

Dey, I: 1993, *Qualitative Data Analysis: A User-Friendly Guide for Social Scientists*, Routledge, London.

Denzin, NK and Lincoln, YS: 1994, Introduction: Entering the field of qualitative research, *in* K Denzin and Y S Lincoln (eds.), *Strategies of qualitative inquiry*, Sage London.

Duncker, K: 1945, *On Problem Solving,* Psychological Monographs, vol. 270, APA Washington.

Dym, CL: 1994, *Engineering Design. A Synthesis of Views*, Cambridge University Press, Cambridge.

Ehrlenspiel, K: 2003, On the importance of the unconscious and the cognitive economy in design, *in* U Lindemann (ed.), *Human Behavior in Design. Individuals, Teams, Tools*, Springer, Berlin, pp. 25 – 41.

Ericsson, KA and Simon, HA: 1980, Verbal reports as data. *Psychological Review*, **87**: 215-251.

Ericsson, K and Simon, H: 1984, *Protocol Analysis*, MIT-Press, Cambridge, MA.

Fodor, J. A. 1990. *The Theory of Content,* MIT Press, Cambridge, MA.

de Groot, AD: 1965, *Thought and Choice in Chess*, Mouton, The Hague.

Gullichsen J and Paulapuro H (eds.): 1998 - 2000, *Papermaking Science and Technology*, Books 1- 8, Fapet, Helsinki.

Helfenstein, S and Saariluoma, P: in press, Mental contents in transfer, *Psychological Research.*

Hodder, I: 1994, The interpretation of documents and material culture, *in* NK Denzin and YS Lincoln (eds.), *Handbook of Qualitative Research*, Sage, London.

Johnson-Laird, PN: 1980, Mental models in cognitive science*, Cognitive Science* **4**: 71 – 115.

Johnson-Laird, PN: 1983, *Mental Models. Towards Cognitive Science of Language, Inference, and Consciousness,* Cambridge University Press, Cambridge.

Justus, EJ and Cronin, DC: 1982, Development of extended nip press, TAPPI 1982 Papermakers Conference, Atlanta, GA, *Proceedings*, pp. 39 – 44.

Kant, I: 1781, *Kritik der Reinen Vernunft*. [The Critique of Pure Reason] Philip Reclam, Stuttgart.

Kavakli, M and Gero, JS: 2003, Strategic knowledge differences between an expert and a novice designer, *in* U. Lindemann (Ed.), *Human Behavior in Design. Individuals, Teams, Tools*, Springer, Berlin, pp. 42 - 52.

Köhler, W: 1930, *Gestalt psychology*, London.

Köhler, W: 1956*, The mentality of apes*, Penguin Books, Harmonsdworth.

Leibniz, GW: 1704, *New Essays on human understanding*, Cambridge University Press, Cambridge.

Lindemann, U: 2005, *Methodische Entwicklung technischer Produkte*. Berlin, Springer.

Miller, GA: 1956 The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information*. Psychology Review*, 63: 81 – 97.

Norman, E, Cubbitt, J, Urry, S and Whitaker, M: 2000, *Advanced Design and Technology*, Pearson, Edinburgh.

Pahl, G, Beitz, W, Feldhusen, J, Grote, KH: 2003, *Konstruktionslehre. Grundlagen erfolgreicher Produktentwicklung. Methoden und Anwendung,* Springer, Berlin.

Petroski, H: 1999, *Remaking the World: Adventures in Engineering*, Vintage Books, New York.

Saariluoma, P: 1990, Apperception and restructuring in chess players' problem solving, *in* KJ Gilhooly, MTG Keane, RH Logie and G Erdos (eds.), *Lines of thought: Reflections on the Psychology of Thinking*, Wiley, London, pp. 41-57.

Saariluoma, P: 1992, Error in chess: Apperception restructuring view, *Psychological Research* **54**: 17-26.

Saariluoma, P: 1995, *Chess Players' Thinking*, Routledge, London.

Saariluoma, P: 1997, *Foundational Analysis: Presuppositions in Experimental Psychology*, Routledge, London.

Saariluoma, P: 1998, Adversary problem solving and working memory, *in* R Logie and K Gilhooly (eds), *Working Memory and Thinking*, Erlbaum, Hove, pp. 115-138.

Saariluoma, P: 2001, Chess and content-oriented psychology of thinking, *Psicologica* **22**: 143-164.

Saariluoma, P: 2002, *Ajattelu Työelämässä* [Thinking in Work Life], *WSOY*, Helsinki.

Saariluoma, P: 2003, Apperception, content-based psychology and design, *in* U Lindemann (ed.), *Human Behavior in Design. Individuals, Teams, Tools*, Springer, Berlin, pp.72-78

Saariluoma, P and Hohlfelt, M: 1994, Apperception in chess players' long-range planning. *European Journal of Cognitive Psychology* 6, 1 – 22.

Saariluoma, P and Maarttola I: 2001, Spatial mental content and visual design, *in* JS Gero, B Tversky, and T Purcell (eds) *Visual and Spatial Reasoning in Design II.* Key Centre of Design Computing and Cognition, University of Sydney, Australia.

Saariluoma, P and Maarttola, I: 2003, Errors and functional reasons in architectural design. Journal of Architectural and Planning Research, *Journal of Architectural and Planning Research* **20**: 344-354.

Shigley, JE and Mitchell LD: 1990*, Mechanical Engineering Design*, McGraw, New York.

Simon, HA: 1969, *The Sciences of the Artificial*, MIT Press, Cambridge, MA.

Simon, HA: 1974, How big is a chunk?, *Science* **183**: 482-488.

Smith, LM: 1994, Biographical method, *in* NK Denzin and YS Lincoln (eds), *Handbook of Qualitative Research,* Sage, London.

Stout, GF: 1896, *Analytic Psychology*, Macmillan, New York.

Suh NP: 1990, *The Principles of Design*, Oxford University Press, New York.

Turing, A: 1936, On computable numbers, with an application to the Entscheidungs problem, *Proceedings of the London Mathematical Society* ***42***: 230-265.

Turing, A: 1950, Computing machinery and intelligence, *in* AR Anderson (ed.), *Minds and Machines,* Prentice-Hall, Englewood Cliffs, NJ.

Tversky, B: 2003, Sketches for design and design of sketches, *in* U Lindemann (ed.), *Human Behavior in Design. Individuals, Teams, Tools*, Springer, Berlin, pp. 25 – 41.

Wallas, G: 1926, *The Art of Thought*, Hartcourt, New York.

Wertheimer, M: 1945*, Productive Thinking*, Harper and Brothers Publishers, London.

Vincenti, WG: 1990, *What Engineers Know and How They Know It. Analytical Studies from Aeronautical History*, The Johns Hopkins University Press, Baltimore.

Visser, W: 2003, Dynamic aspects of individual design activities. A cognitive ergonomics viewpoint, *in* U. Lindemann (ed.), *Human Behavior in Design. Individuals, Teams, Tools*, Springer, Berlin, pp. 87 – 96.

Wundt, W: 1880*, Logik, I* [Logic I], Ferdinand Enke, Stuttgart.

Patent publications:

Canada 1948, Process of an Apparatus for Extracting Liquid From Pervious Sheet Material, Patent No. 452,200, October 26, 1948.

Canada 1975, Hydrodynamically Loaded Web Press, Patent No. 969398, June 17, 1975.

Finland 1995, Laakeripesien välinen kytkentärakenne pitkänippipuristimella [Coupling Construction between Bearing Housings in an Extended Nip Press], Finnish Patent Application No.963702, August 3, 1995.

Finland 2000, Press shoe for a long-nip press, Finnish Patent Application No. 20002412, November 2, 2000.

Germany 1972, Nasspresse zum Entwässern einer Faserstoffbahn, Offenlegungsschrift 2108423, 7. September 1972. (Anmelder: VEB Papiermachinenwerke Freiberg; X 9200 Freiberg, DDR.)

Germany 1985, Presswaltze, Offenlegungsschrift 3338487, 2. Mai1985.

PCT 1991, Press Roll, International Application Number: PCT/SE91/00325.

PCT 1993a, A Shoe Type Press, International Application Number: PCT/SE93/00390.

PCT 1993b, Press Shoe, International Application Number: PCT/SE92/00874.

USA 1966, Machine for Making Extensible Paper, Patent No. 3,269,893, August 30, 1966.

USA 1974, Anti-rewet Membrane for an Extended Press Nip, Patent No. 3,840,429, October 8, 1974.

JS Gero and ML Maher (eds) (2005).
Computational and Cognitive Models of Creative Design VI,
Key Centre of Design Computing and Cognition, University of Sydney, Australia pp 365-374

METHODOLOGIES FOR UNDERSTANDING SOCIAL CREATIVITY DURING COLLABORATIVE DESIGN ACTIVITIES

A Proposal

ELISABETH SYLVAN
Massachusetts Institute of Technology, USA

Abstract. Complex design tasks often require that people work in groups on creative solutions. This paper proposes a methodology for understanding when social creativity occurs during design activities. The methodology put forth in this paper considers how individuals working on a common task adopt each other's ideas and then reincorporate them into their own creations. It combines diverse sampling techniques and related analytical methodologies, including experience sampling, social network analysis, and the use of computational handhelds. Through the combinations of research methods, this paper proposes new ways of understanding how people influence each other's work and how they co-create.

1. Introduction

Complex design tasks often require that people work in groups on creative solutions. How do we know when people are being creative together? What are the characteristics of social interactions that support creative design?

In order to foster the environments that support creative collaboration, one must understand the features of the interactions that support creative collaboration. How people cocreate can be understood from two basic perspectives at the intersection of creative work and social interaction: 1.) the nature of group creativity and 2.) the social dimension of individual creativity. In this first case, one looks at a group as a whole, considering their processes, goals and progress. To understand how individuals are influenced by a group, one might study individuals' social influence, the culture in which individuals' work, their adoption of others' ideas and their incorporating of the ideas into their own work.

The methodology suggested in this paper considers both perspectives, but focuses more upon how individuals are influence by a group. It first considers how the ideas move through a workgroup, which develops some understanding of the nature of group creativity. It then focuses on how individuals adopt ideas and then reincorporate them into their own creations. The methodology combines diverse sampling techniques and related analytical methodologies that previously have not been considered together. Through these combinations, researchers can create new ways of understanding how people influence each other's work and how they co-create.

The first section of this paper describes some key conceptions of creativity, with a particular focus on creativity as a social system. It then describes work on the flow of innovations and its relevance to the understanding of social creativity during design activities. Ultimately, it outlines a methodology for understanding social creativity through experience sampling, social network analysis, and computational technologies.

2. Relevant Literatures

2.1 CREATIVITY

Creativity can be considered in terms of being historical (H-creativity), psychological (P-creativity), or situated (S-creativity) (Boden 1990). In his seminal conception of creativity and flow, Csikszentmihalyi creates a systemic model of how these different aspects interact, Figure 1. "For creativity to occur, a set of rules and practices must be transmitted from the domain to the individual. The individual must produce a novel variation to the content of the domain (1999). The variation must then be selected by the field for inclusion in the domain." His system approach considers the personal, but focuses more upon how the creativity act is shaped by society and contributes to a domain (1998). Here an individual contributes only when her product is adopted by the broader social system.

Certain features of a social system and the way it functions may be particularly important. "Although creative individuals are often thought of as working in isolation, the role of interaction, and collaboration with other individuals is critical... Social creativity emphasizes that the heart of intelligent human performance is not the individual human mind but groups of minds in interaction with each other and in interaction with tools and artifacts" (Fischer et al 2003). People are not only being acculturated into a community and learning a set of practices. They mutually create and further each other's ideas by working in heterogeneous groups with particular tasks.

Understanding social creativity may be more successful when studying communities of interest: the heterogeneous communities bond by their common goals, rather than bond by common practice.

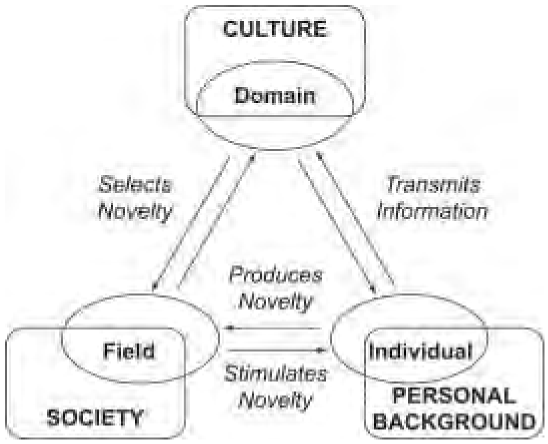


Figure 1. Csikszentmihalyi's System Model of Creativity

In Csikszentmihalyi's words, "ideal conditions for creativity would be a social system that is highly differentiated into specialized fields and roles, yet is held together by what Durkheim called the bonds of organic solidarity" (1999). Based on these conceptions social creativity occurs:

- When individuals make novel contributions
- *and* the contribution is adopted by a society or group
- often when people work in heterogeneous groups with common interests

Once we come to consider creativity as a system in which culture, society, and an individual all play a role, we might ask what is known about these components. It may be constructive to identify *the individual's contribution* and *society's adoption of it*.

Understanding the individuals' contributions is important because it gives us insight into who innovates, under what conditions, and perhaps even where ideas come from. A typical definition of a creative product or act is that is is unobvious, novel, and useful. As the group adopts ideas, the "usefulness" of individuals' creative products is validated. Once the idea has been adopted, it becomes not only a part of a group project, it also becomes part of the group's thinking. Then the ideas may be *adapted* to suit group needs or might spurn additional new ideas. Thus new creative output may be developed communally that are not possible by the individuals separately.

3. Developing General Methodologies

For this type of investigation, it is important to understand the social fabric of a work group: who is involved in the collaboration, the characteristics of their individual roles, and the nature of their interactions. It is also necessary to know how design ideas are created by individuals and adopted by the group, and how the ideas contribute to the progress towards the design goal.

Certain work environments would best support this type of inquiry. Projects that leave logs of the creative process are necessary because they allow researchers to identify who did what and when. It is even better if this process can be mapped to particular sub-goals within the project's specification. Projects that involved the creation of shared artifacts because there are likely to be more design tasks accomplished collaboratively.

The fields of architecture, documentary filmmaking, and Research and Development work in information technology (cf Amabile 1999) might provide these attributes. In these environments, people with diverse backgrounds work together, the tasks are complex, and the work itself produces artifacts to use as data.

The approach taken in this paper is to first identify individuals' design contributions, then identify who adopts these contributions, and, finally, consider how other group members adapt these contributions. By combining new technologies that log design process with different analysis tools, researchers can gain insight into individual's creative process, the shape of a social network, and which creative ideas are adopted.

3.1 TECHNIQUES FOR DATA GATHERING

How would this data be gathered? Several techniques, if used in combination, may provide new insights into creative collaborative design. These include experience sampling, ethnography, social network analysis, and logging of work activity, supplemented with interviews and surveys.

3.1.1 Experience Sampling

Experience sampling, a technique well regarded in creativity research (Larson and Csikszentmihalyi 1983), involves prompting people to self-report while they are engaged in an activity. Computerized tools, including ones for experience sampling on PDAs, exists and would be used (Feldman Barrett and Barrett 2001). These methods provide a journal of each person's life during a period of study.

3.1.2 Social Network Analysis

Social network analysis describes social structure as patterns of relationships between individuals. These patterns can be determined between standardized survey methods or through logging real-world data. For the purposes of this research, survey methods and logging of real-world correspondence will be used to measure closeness (an indicator of tie strength), predictors of strength (such as kinship and neighboring) adapted from Marsden and Campbell (1984) and determine the size of personal networks, (Killworth et al 1990). In addition, the exchange of ideas will be measured via methods developed through the study of the flow of innovations.

The study of the diffusion of innovation illuminates how a society or a group adopts new ideas. Diffusion of innovation in this field is defined as the spread of new ideas through a society. “Diffusion is the process by which an innovation is communicated through certain channels over time among members of a social system.” (Rogers 1983 quoting Beal and Bohlen 1955). Different units in a network are willing to adopt at different rates depending on personal characteristics. Some characteristics that appear to be important include centrality, age, and network thresholds (Valente 1996). According to this research, once 10-25% of a community adopts, then adoption rates increase rapidly (the tipping point.) For the purposes of the current research, the analysis will address adoption rates of ideas and influence among the designers.

3.1.3 Data collection with wearables

The question remains how to gather data on when people generate ideas, who they share the ideas with and who adopts them. As handheld proliferate more and more, researchers may look to them as a viable resource for understanding daily behavior. They allow precise descriptions of where a person is, what they are doing, and who they are with. More and more people either have handheld devices, particularly cell phones.

Previous work on people creating and sending their creations on wearables demonstrates that 1.) it is a worthwhile data gathering technique and 2.) engaging creative activities can be built upon these platforms. For instance, the Iballs project allowed children to create and share animations on small physical devices and then see where their creations would go through the school’s community (Borovoy et al 2001.) Children built animations on key-chain sized computers with which they create animations that are sent or could “hitchhike” to other devices. They could then go to a public display at the school to see the paths animations took through the network and which animations were popular and with whom. This work supported 1.) people’s creative designs 2.) sharing of the work 3.) logging of social network and flow of innovation data and 4.) near real-time display of the data. Still their work’s focus was not on collaboration during work and, thus did not develop methodologies to support an understanding of the current area of interest.

Previous work on reality mining techniques with cell phone data (Eagle and Pentland 2005) suggests it is possible to describe a social network on cell phones. The structure of the social network of designers can be described using survey data and social network analysis of cell phone usage, (particularly in the case of a dataset of children programming on cell phones.) One would then identify who each individual calls and how often and create similar models using real-life data.

3.2 MEASURES FROM THE LITERATURE

Through a combination of experience sampling, social network surveys, logging of real-world correspondence and idea-exchange on handhelds, it is possible to understand how individuals contribute to group design tasks and how ideas are adopted in creative group work.

In order understand the scope of the design project, some initial data should be collected. First the goals of the group should be identified. This information could be gathered by through interviews with the participants or by viewing any project documentation, both initial plans and logs of activities. Later the researcher would use this description to interpret when the goals were met through the contributions of the group. Next the individuals' creative output would be described through real-time artifacts, including logging of tasks and experience sampling. Finally, the researcher would describe the social network and how ideas move through it using the social network techniques described above. This would include analyzing the overall social interaction, task-related social interaction, social cohesion of teams, and individual influence. For the generation of ideas, the researcher maps specific individual creative contributions to particular design tasks, observe when others view the contributions, and, more importantly, when others adopt them. The researcher would then create a model of the adoption of ideas and the factors that impact the process.

The following chart outlines the types of data needed to describe a group's creative output.

4 An Example of a Study Design

Our research group develops programming environments for children. With one particular program called Scratch (Maloney et al 2004), children can write programs in a visual environment to create videogames and interactive animations. Currently, we are in the early stages of porting the project to cell phones. This new platform will allow children to work on projects together in ways that couldn't in the environment previously. They can exchange code samples, share games with each other, and incorporate others' project components into their own all on their phone. In addition, they can, of course, use their phones to talk to each other. Their individual programming process, finished programs, sharing of projects, incorporation of each other's ideas and cell-phone communication will be logged.

But how would such a methodology actually be implemented? Who would the participants be, what would their task be, and how would their mutual creation be understood? The next section describes a specific example of how such a methodology will be implemented.

A study using this technology addresses how children exchange ideas as they design interactive animations and games in Scratch. First the research will describe the children's social network and how they fit into it. Second it can describe how ideas move through the network from one child to another.

4.1 METHODS

Participants will be thirty 12 to 13-year olds of approximately equal mix of gender who volunteer to participate in an after-school programming activity. Each child will receive a cell phone with the Scratch program installed. The phone will come with a phone plan.

After gaining permission from their parents, a survey will be sent home asking about previous relevant experiences and the children's social networks. An experience survey will include questions about after-school activities along with previous computer, programming, and video game experience. A social network survey will include measures of closeness, kinship, and neighboring (adapted for children from Marsden and Campbell 1984) and the size of personal networks (adapted from Killworth et al 1990). Then the participants will begin an after-school programming workshop where they will receive their phones. The workshop will occur twice a week for three months and will be taught by the developers of the software. During this time, the children use the phone to make normal phone calls, as well as use the phone as part of a 3-month programming after-school project. In the workshop the children will create programs that can exchange on their phones during the workshop or outside of the workshop setting.

TABLE 1. Data gathering and analysis

AREA	DATA	METHOD	ANALYSIS AND REPORTING
Design Task	Design goal and subtasks	Interviews, logging of transfers of information	Descriptive text and descriptive statistics.
Individual	Individuals' backgrounds	Surveys and interviews	Descriptive text and descriptive stats.
Individual	Individuals' creative output	Experience sampling, ethnography, logging of work tasks/changes to project	Descriptive stats and pattern recognition of logs using reality mining techniques
Group	Group background	Observation, interviews	Descriptive text and descriptive stats

Group	Social network: Group social structure individuals' influence	SNA surveys of closeness and kinship, logging of intragroup communication	SNA: closeness, kinship, models of social network
Group	Transfer of design components	Logging of group activity	Descriptive stats and pattern recognition of logs using reality mining techniques
Group	Adoption of design components	Logging of group activity	Descriptive text, stats and pattern recognition of logs using reality mining techniques

4.2 ANALYSIS

The structure of the social network of children will be described using survey data and social network analysis of cell phone usage. Based on the survey data, an initial model of closeness, along with social network size and shape will be generated for each child and for the group. Then the researcher can identify whom each child calls and how often they call, data that can be used to describe the social network. The analyses will address who sends programs to whom, using techniques reported by Valente (1996). This analysis will identify adoption rates of ideas, a measure of social creativity.

Social networks can be described using cell phone use and program exchange data, along with the social network surveys. The advantage of this potential study is that it will be possible to capture the social network data (including location), individual work data, and group exchange and adoption of ideas all on one device.

The data will describe:

- The characteristics of the children's social networks overall
- The social network in the programming group
- Who is influential in the group
- When children generate new ideas
- Which new ideas are transferred through the network and where they go in the network
- Adoption rates of the ideas
- How other children's new ideas are incorporated into children's work

Through these data sets, Table 2, it will be possible to individuals' design process, when their ideas are adopted by others, the shape of the social network and the exchange of ideas, and, finally, how children adapt each other's design ideas into their own.

TABLE 2. Data sets

DATA COLLECTED	MEASURES
Social network survey	The characteristics of the children's social networks overall
Logging of children's location and cell phone usage	The social network in the programming group. Who is influential in the group
Logging of the children's programming	When children generate new ideas individually
Logging of program exchanges between children	Which new ideas are transferred through the network and where they go in the network. Adoption rates of the ideas
Children's use of other's code	How other children's new ideas are incorporated into children's work

5. Conclusions

These developments represent a new potential direction in understanding how people create together. By working with multiple innovative methodologies, it may be possible to learn about how people collaborate on design projects and how they adopt and adapt each other's ideas. Through these findings, we may discover that it is possible to further define and understand when social creativity occurs and what features of environments and communities support it.

Acknowledgements

The author thanks her advisor, Mitchel Resnick, for his ongoing support.

References

Amabile, TM and Conti R: 1999, Changes in the Work Environment for Creativity during Downsizing, *in Academy of Management Journal* **42**: 630-640.

Boden MA: 1990, *The Creative Mind: Myths and Mechanism,* Cardinal, London.

Borovoy, R, Silverman, B, Gorton, T, Klann, J, Notowidigdo, M, Knep, B, and Resnick, M: 2001, Folk computing: Revisiting oral tradition as a scaffold for co-present communities, *CHI 2001 Conference on Human Factors in Computing Systems*, New York: ACM.

Csikszenmihalyi, M: 1988, Society, culture and person: A systems view of creativity, *in* RJ Sternberg (ed.), *The Nature of Creativity*, Cambridge University Press, Cambridge, pp 325-339.

Csikszentmihalyi, M: 1999, Implications of a systems perspective for the study of creativity, *in* Sternberg, RJ (ed.), *Handbook of Creativity,* pp. 313-335.

Eagle, N and Pentland, A: 2005, Reality mining: Sensing complex social systems, personal and ubiquitous computing, (to appear).

Feldman Barrett, L and Barrett, DJ: 2001, An introduction to computerized experience sampling in psychology, *Social Science Computer Review* **19**(2): 175-185.

Fischer, G: 2003, *Designing Social Networks in Support of Social Creativity*, Position Paper for the Workshop "Moving From Analysis to Design: Social Networks in the CSCW Context", ECSCW'03.

Killworth, P et al: 1990, Estimating the size of personal networks, *Social Networks* **12**: 289-312.

Larson, R and Csikszentmihalyi M: 1983, The experience sampling method, *New Directions for Methodology of Social and Behavioral Science* **15**: 41-56.

Lave, J and Wenger E: 1991, *Situated Learning: Legitimate Peripheral Participation*, Cambridge: Cambridge University Press.

Maloney, J, Burd, L, Kafai, Y, Rusk, N, Silverman, B and Resnick, M: 2004, Scratch: A sneak preview. *Second International Conference on Creating, Connecting, and Collaborating through Computing*, Kyoto, Japan, pp. 104-109.

Marsden P and Campbell K: 1984, Measuring tie strength, *Social Forces* **63**: 482-501.

Sternberg and Lubart: 1999*,* The concept of creativity: Prospects and paradigms, *in handbook of dreativity,* Cambridge University Press, Cambridge pp: 3-15.

Valente TW: 1996, Social network thresholds in the diffusion of innovations, *Social Networks* **18**: 69-89.

CONTACT AUTHORS' EMAIL ADDRESSES

Carrara, G	gianfranco.carrara@uniroma1.it
Dorst, K	C.H.Dorst@tue.nl
Edmonds, E	ernest@ernestedmonds.com
Evans, M	m.d.evans@salford.ac.uk
Fioravanti, A	antonio.fioravanti@uniroma1.it
Fischer, G	gerhard@colorado.edu
Gao, S	sgao@arch.hku.hk
Gero, JS	john@arch.usyd.edu.au
Hanna, S	S.Hanna@cs.ucl.ac.uk
Hepting, D	daryl.hepting@uregina.ca
Hoffman, O	oliver@hoffmann.org
Karvinen, M	mikko.karvinen@vtt.fi
Kim, MJ	mkim9133@arch.usyd.edu.au
Knight, T	tknight@MIT.EDU
Kvan, T	tkvan@arch.hku.hk
Lawson, B	b.lawson@sheffield.ac.uk
Liikkanen, L	liikkane@cc.helsinki.fi
Macindoe, O	macindoe@usyd.edu.au
Maher, ML	mary@arch.usyd.edu.au
Merrick, K	Kathryn.Merrick@nicta.com.au
Muller, L	lizzie@lizziemuller.com
Nagai, Y	ynagai@jaist.ac.jp
Nevala, K	Kalevi.Nevala@oulu.fi
Perttula, M	Matti.Perttula@hut.fi
Saariluoma, P	psa@it.jyu.fi
Sosa, R	rdsosam@itesm.mx
Sylvan, E	sylvan@media.mit.edu
Takala, T	tta@cs.hut.fi
Taura, T	taura@mech.kobe-u.ac.jp
Tversky, B	bt@psych.stanford.edu

AUTHOR INDEX

Carrara, G	275
Dorst, K	213
Edmonds, E	303
Evans, M	319
Fiorvanti, A	275
Fischer, G	73
Gao, S	251
Gero, JS	21
Hanna, S	47
Hepting, D	333
Hoffman, O	139
Karvinen, M	349
Kim, MJ	233
Knight, T	157
Kvan, T	251
Lawson, B	213
Liikkanen, L	195
Macindoe, O	113
Maher, ML	113, 233
Merrick, K	113
Muller, L	303
Nagai, Y	179
Nevala, K	249
Perttula, M	195
Saariluoma, P	349
Sosa, R	21
Sylvan, E	365
Takala, T	97
Taura, T	179
Tversky, B	3