Computational Models of Creative Designing Based on Situated Cognition

John S Gero
Key Centre of Design Computing and Cognition
University of Sydney
NSW 2006 Australia
john@arch.usyd.edu.au

ABSTRACT
This paper presents computational models of creative designing. It commences with describing notions of creative designing within individuals, groups and then societies. In doing so it moves from absolute to situated cognition approaches. The paper then describes various computational approaches that simulate individual create designing processes with exemplars. It then moves on to describe situated cognition as the basis for group creative designing, which is described through a multi-agent example. Finally, the notion of creativity as a social behaviour is explored through simulations.

Categories & Subject Descriptors: I.2 Artificial Intelligence, J.6 Computer-aided engineering

General Terms: Cognitive simulation, Intelligent agents, Multiagent systems, Computer-aided design

Keywords
Design, creativity, artificial intelligence, cognitive simulation

INTRODUCTION

To many people creativity is a mystery and as a consequence is not open to computational exploration. However, it has been studied by psychologists for many years. Wallas's work in the 1920s [32] laid the foundation for much of the psychological and later cognitive studies that were to follow, such as the work of Patrick [23], [24]. Whilst creativity continued to attract the attention of psychologists and others [21] as a special form of human activity, it also was present in the early statements about artificial intelligence [31].

However, it was not until the latter part of the twentieth century that research into computational approaches to creativity began [8], [3], [18], [19]. These early approaches uniformly took the view that creativity was inherent in the computational process as much as in the product and treated creativity as solely an individual activity.

Much later, notions from cognitive science, which themselves were founded on much earlier ideas, about situatedness provided the basis for a new approach to developing computational models of individual creative accounted for the interaction of the process with its environment [4]. This produced the opportunity to develop novel approaches to way individual creative agents interact with each other in terms of creativity.

More recently, this situated cognition approach has been used to study creativity as an emergent social behaviour through the use of interaction situated agents

This paper presents approaches based on all three of these paradigms with examples.

INDIVIDUAL CREATIVE DESIGNING

It is convenient to characterise designing as routine or non-routine. *Routine designing*, in computational terms, can be defined as that designing activity which occurs when all the necessary knowledge is available. It may be more formally expressed as being that designing activity which occurs when all the knowledge about the variables, objectives expressed in terms of those variables, constraints expressed in terms of those variables and the processes needed to find values for those variables, are all known *a priori*. In addition, routine designing operates within a context that constrains the available ranges of the values for the variables through good design practice. Figure 1 show graphically the notion of the state space of routine designs being bounded by a set of a priori decisions and constraints. None of this is to imply that routine designing is not complex or is even easy.

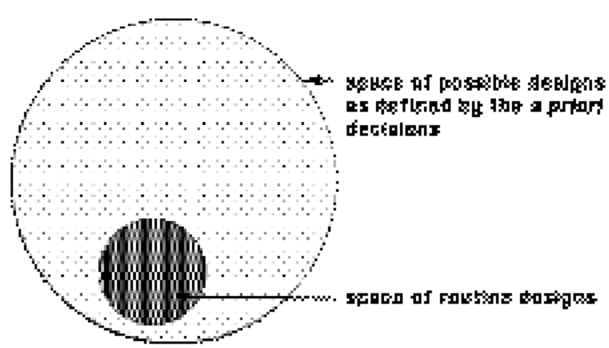

Figure 1. The space of possible designs is defined by the set of *a priori* decisions. The space of routine designs is a subset of those possible designs.

Non-routine designing can be subdivided into two further groups: innovative designing and creative designing. *Innovative designing*, in computational terms, can be defined as that designing activity that occurs when the context that constrains the available ranges of the values for the variables is jettisoned so that unexpected values become possible, Figure 2. This produces two effects, one for the design process and the other for the product or artifact. In terms of the design process, variable values outside the usual ranges have the potential to introduce unexpected as well as unintended behaviours that can only be brought into formal existence if additional knowledge capable of describing them can be introduced. For example, in designing a structural beam to carry a load across a gap there are standard depth-to-span ratios for different materials. If the depth of the beam is made much larger than these then there is the likelihood that the beam will buckle. However, if no buckling knowledge is applied to its design (and buckling is not normally considered in the design of such beams) then no buckling behavior will be found. In terms of the artifact, innovative designing processes produce designs that recognizably belong to the same class as their routine progenitors but are also ‘new’.

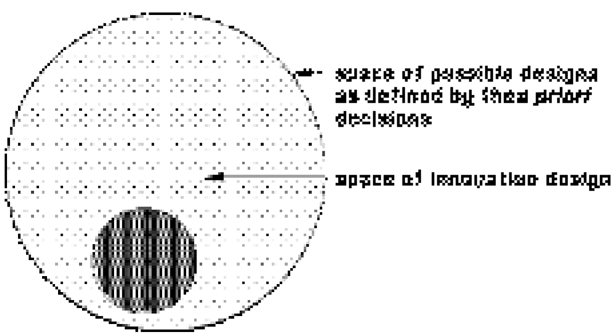

Figure 2. The space of innovative designs is a subset of the possible designs.

Creative designing, in computational terms, can be defined as the designing activity that occurs when one or more new variables are introduced into the design. Processes that carry out this introduction are called “creative designing processes”. Such processes do not guarantee that the artifact is judged to be creative, rather these processes have the potential to aid in the design of creative artifacts. Thus, creative designing, by introducing new variables, has the capacity to produce novel designs and as a result extends or moves the state space of potential designs, Figure 3. In the extreme case a new and disjoint state space is produced that results in a new type of design. Creative designing has the capacity to produce a paradigm shift.

One of the important aspects of creative designing is the distinction that can be drawn between different kinds of creativity. Boden [3] has elucidated two kinds of creativity called H-creativity and P-creativity. In designing, *H-creativity* (historical creativity) occurs when the design falls outside the range of designs previously produced by any designer in a society. Whereas, *P-creativity* (personal or psychological creativity) occurs when the design falls outside the range of designs produced by that designer. A third kind of creativity has been enunciated called S-creativity [29]. *S-creativity* (situated creativity) occurs in designing when the design contains ideas which were not expected to be in the design when the design was commenced. Thus, the design contains ideas that are not necessarily novel in any absolute sense or novel to the designer but that are novel in that particular design situation.

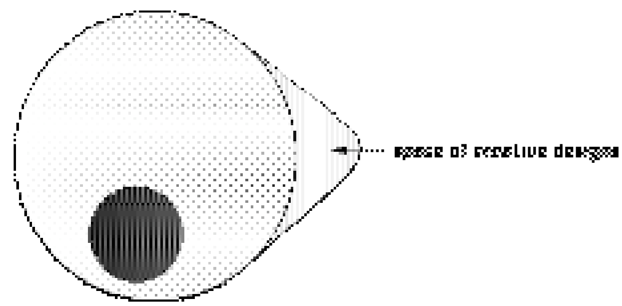

Figure 3. The space of creative designs is a superset of the possible designs, as defined by the set of *a priori* decisions.

Figure 4 shows the same idea in another way. The space of possible designs changes over time as the designer moves away from the then current design state space.

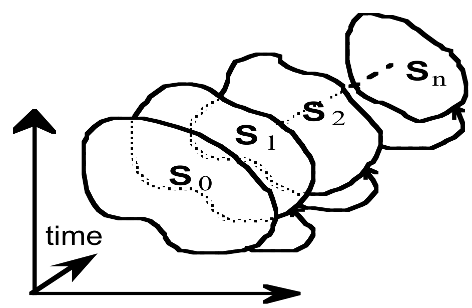

Figure 4. Creative designing involves new and/or changing state spaces of possible designs.

CREATIVE DESIGNING PROCESSES

Computational processes that match this notion of an individual extending the state space of possible designs include:

- combination
- transformation
- analogy
- emergence
- first principles

Combination

One place where computational combination is well developed is in genetic algorithms, in the crossover operation. Here the genes of each parent are combined to produce offspring that combine some of the genetic characteristics of each parent [Goldberg 1989]. However, such combination processes only move the designer around a fixed state space, they do not expand the design space and therefore cannot be considered as creative designing processes. However, it is possible to conceive of genetic crossover as a special case of o more general form of interpolation, Figure 5 [14], [16]. This allows for designs to be produced that are "between" the designs that can be produced by crossover alone.

In Figure 6 the gridded surface shows the state space of possible designs produced by genetic crossover alone. The trajectory of genetic crossover is shown as a solid line but with interpolation between any two designs produced by the crossover operation between the designs P_1 and P_2 is another set of designs that lies on that surface but is otherwise not accessible. Further, there are other interpolations possible that commence with P_1 and P_2 but which do not lie on the original surface. These are quite different to those which lie on the original surface. In addition, it is possible to extrapolate beyond P_1 and P_2 something that has no meaning within genetic crossover [15].

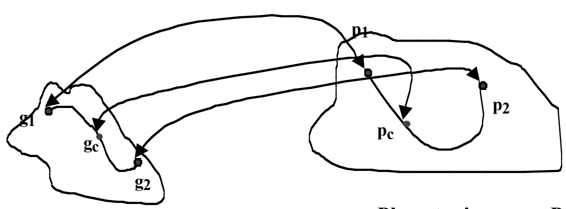

Figure 5. Interpolation as a generalisation of genetic crossover.

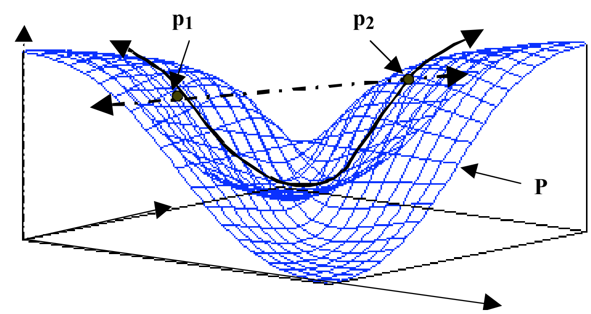

Figure 6. Interpolation as combination takes trajectories outside the original state space of possible design.

Figure 7 shows two "parent" designs of Mondrian-style paintings used as the two starting points for a non-linear interpolation that moves the interpolated designs off the trajectory produced by genetic interpolation.

Figure 8 shows one of the innumerable resulting designs. Of particular interest here is that the shapes produced are not direct linear interpolations of the shapes of the parents. The parents only contain rectangular shapes but here we have triangular and polygonal shapes. The specific designs created are dependent on the interpolation functions utilized. It is also possible to interpolate and extrapolate colours as well as shapes.

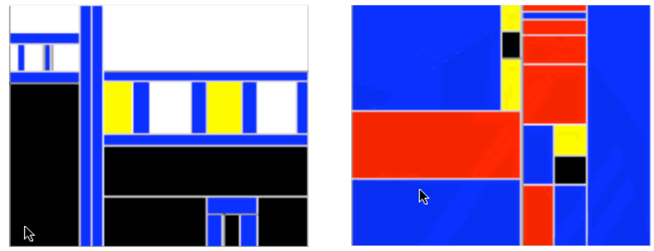

Figure 7. Two Mondrian-style "parent" designs used in the interpolation.

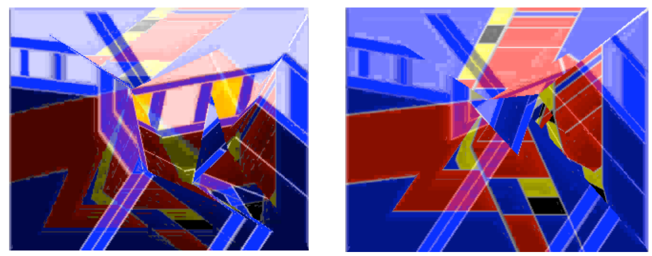

Figure 8. Two of the interpolated designs from the parents shown in Figure 7

SITUATEDNESS

Designing is an activity during which the designers perform actions in order to change the environment. By observing and interpreting the results of their actions, they then decide on new actions to be executed on the environment. This means that the designer's concepts may change according to what they are "seeing", which itself is a function of what they have done. We may speak of a recursive process, an "interaction of making and seeing" [27]. This interaction between the designer and the environment strongly determines the course of designing. This idea is called *situatedness*, whose foundational concepts go back to the work of Dewey [7] and Bartlett [2]. In paraphrasing Clancey [4] we can summarize it as "where you are when you do what you do matters" [10], [11].

An important idea, which fits into the notion of situatedness, has been proposed by Dewey in 1896 [4] and is today called *constructive memory*. The main idea of constructive memory is that memory, instead of being laid down and fixed at the time of the original experience, must be newly constructed every time there needs to be a memory. Certainly, the original experience, which is to be recalled, is used to construct the memory of it. But this process is also governed by the situation pertaining at the time of the demand for this memory. Therefore, everything that has happened since the original experience determines the result of memory construction. Each memory, after being constructed, is added to the experience and thus becomes part of the situation, which affects the kinds of further memories that can be constructed.

Memory, as an overall term, must be seen as a process rather than a fixed state. This idea has been exemplified by a quote from Dewey via Clancey: "Sequences of acts are composed such that subsequent experiences categorize and hence give meaning to what was experienced before". The significance of the idea of constructive memory in designing has been shown by Gero [12]. Situatedness and constructive memory thus provide the conceptual basis for grounding the knowledge of an agent in the situation being constructed by its interactions with the environment.

Situatedness in designing can be modeled as the interaction of three worlds, Figure 9. The *external world* is the world that is composed of representations outside the designer or design agent. The *interpreted world* is the world that is built up inside the designer or design agent in terms of sensory experiences, percepts and concepts. It is the internal representation of that part of the external world that the designer interacts with. The *expected world* is the world imagined actions will produce. It is the environment in which the effects of actions are predicted according to current goals and interpretations of the current state of the world.

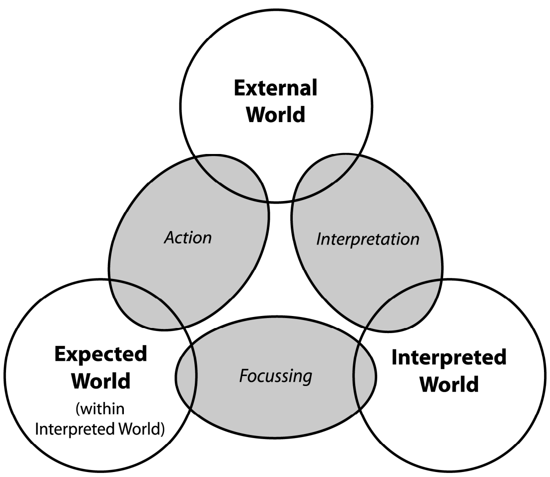

Figure 9. Situatedness can be modeled as the interaction of three worlds.

Constructive Memory

Constructive memory is fundamental to the notion of situatedness. It can be described as being governed both by what was initially there (the original experience) and by what the current situation (made up by previous experiences and memories and the currently focused concepts) makes with it. At this level of abstraction, constructive memory can be viewed in a similar way as the process of interpretation, which Gero and Fujii [13] have described as consisting of two parallel processes interacting with each other: A push process (or data-driven process), where the production of an internal representation is driven ("pushed") by the sensed data, and a pull process (or expectation-driven process), where the interpretation is driven ("pulled") by some of the designer's current concepts, which has the effect that the original data is biased to match the current expectations (about what the interpretation should be).

We can use the idea of a push-pull process for generally representing the interaction of a designer with both its external environment (by interpretation) and its internal environment (by constructive memory). Figure 10 depicts how an original experience (E_0) is produced by interpreting something in the external world at a certain point of time. A push-pull process represents this transition from the external world to the interpreted world. The construction of a memory (M_1) of the original experience, at a later point of time, is also done by a push-pull process, but within the interpreted world. The pull process here is controlled by the current situation.

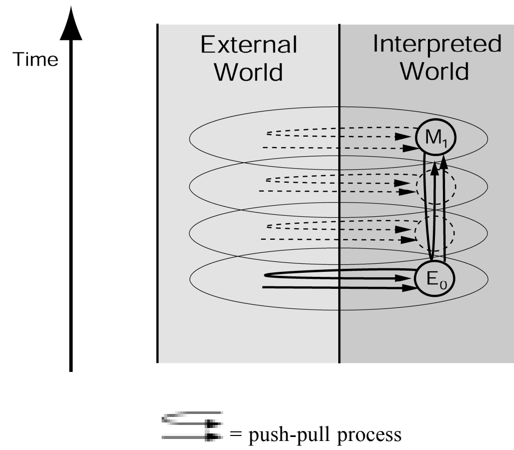

Figure 10. Interpretation and constructive memory.

To illustrate situatedness further, consider the image in Figure 11. Figure 11 shows a set of arrowheads. They can be interpreted as pointing towards the upper left or horizontally to the right or towards the bottom left. Which way they point is a function not of the objects in the image but on the situation within which the interpretation takes place.

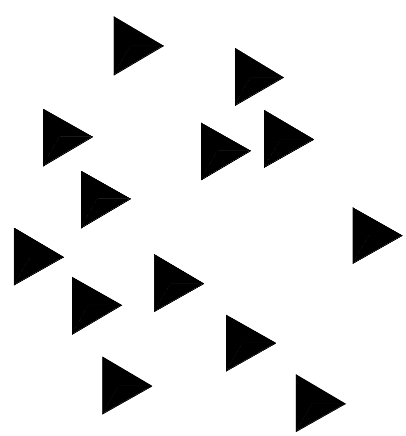

Figure 11. A set of arrowheads, the direction they are pointing is a function of the interpretation by a situated observer, not directly of the objects themselves.

Situated Analogy

Analogy making relies on finding a mapping between two relational structures (that is two representations). Each design is represented as a relational graph that indicates the relational dependencies between three essential states: structure, behaviour and function. Situated analogy constructs a situation within which the analogy itself is constructed. This construction process involves both the target design and the environment within which the target design can be interpreted [17].

Figure 12 shows the architecture of a situated analogy system that commences with the target design and re-represents it according to the situation.

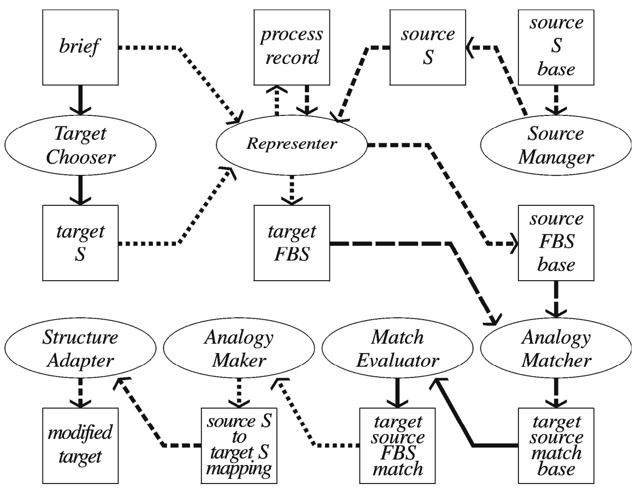

Figure 12. Architecture of a situated analogy design system.

The system then uses features from that re-representation to see if there are other designs that can be re-represented to have those features. It then uses those constructed features as the index to source designs [17]. Thus, the same target design in different situations has different features associated with it. With these different features the system uses the way they were obtained to see if they can be obtained from other potential source designs. As a consequence the same target in different situations will draw different analogies.

Figure 13 shows the output and graphic interpretations of a situated analogy design system given the task of coming up with the conceptual design for having two bottles of men's toiletries within a situation that involves traveling. Figure 14 shows a commercial design based on similar principles to those found by analogy as shown in Figure 13.

Systems such as these, based on situated approaches, are broadly consistent with empirical results derived from experiments with designers [30]. Empirical results show that designers appear to construct their representations "on the fly" to meet their expectations, rather than the other way around as is the case with computational systems. They then refocus their attention based on these newly constructed views of the world [29].

This can be viewed as a more general approach to database search beyond it application in analogy. Here, we should be able to search a database by it situated, emergent features.

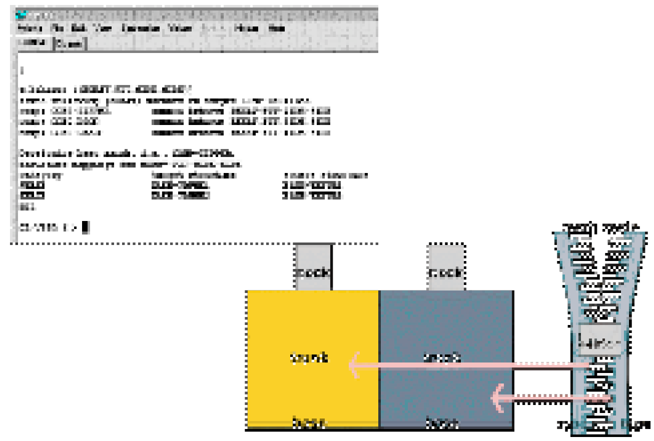

Figure 13. Proposal from a situated analogy design system for the conceptual design of two bottles within a travel situation. The proposal contains the concept derived analogically from a zipper, that the two bottles together should occupy less space than the simple sum of their individual space requirements.

Figure 14. A commercial design apparently based on similar principles to those proposed in Figure 13.

CREATIVITY THROUGH SOCIAL ACTS

The systems view of creativity was developed by Csikszentmihalyi as a model of the dynamic behaviour of creative systems that include interactions between the major components of a creative society [5], [6]. Csikszentmihalyi identified three important components of a creative system.

- *Individual* – who generates ideas
- *domain* – cultural or symbolic, component
- *field* – social or interactive, component

Figure 15 shows the connection between these three components at a conceptual level.

An individual's role in the systems view is to bring about some transformation of the knowledge held in the domain. The field is a set of social institutions that selects from the variations produced by individuals those that are worth preserving. The domain is a repository of knowledge held by the culture that preserves ideas or forms selected by the field.

In a typical cycle, an individual takes some information provided by the culture and transforms it, if the transformation is deemed valuable by society, it will be included in the domain of knowledge held by the culture, thus providing a new starting point for the next cycle of transformation and evaluation. In Csikszentmihalyi's view, creativity is not to be found in any one of these elements, but in the interactions between them.

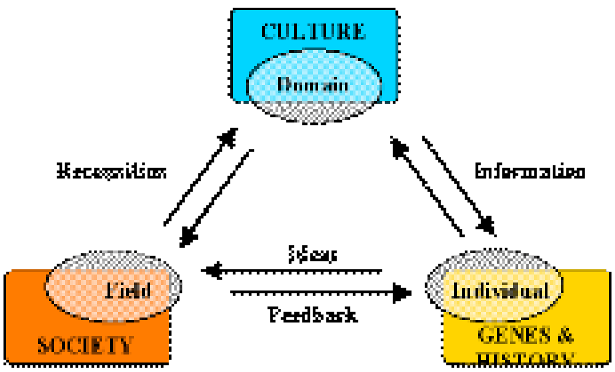

Figure 15. Csikszentmihalyi's model of creative situations.

Saunders and Gero [25] have developed and implemented a computational model of artificial design creativity based on Csikszentmihalyi's model. Figure 16 shows their interpretation of Csikszentmihalyi's model.

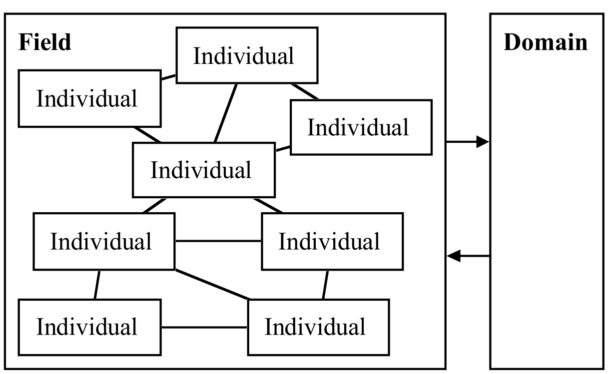

Figure 16. Saunders and Gero's interpretation of Csikszentmihalyi's model of creative situations.

Saunders and Gero have used this approach to study how creativity is generated and assessed within a social context and how creativity emerges from the interactions between design agents that are individually creative but whose creativity is not only assessed by themselves individually. The creativity of an individual is assessed by that individual and also by the other agents operating at the time each individual is operating.

Figure 17 shows one screenshot of the results of modeling the emergence of creativity as a situated social phenomenon. Agents that assess each other's designs as being creative gradually form cliques of appreciative like-minded designers. Details can be found in [26]

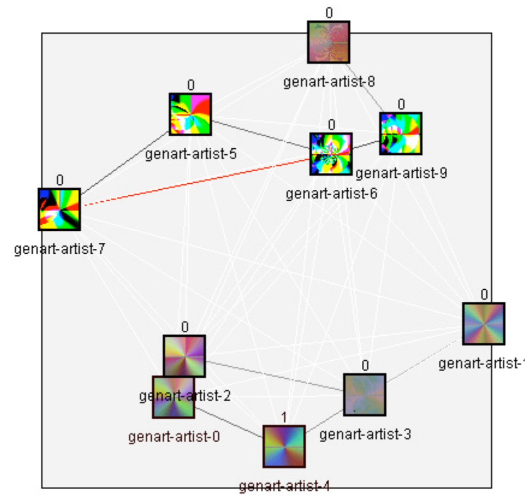

Figure 17. Agents forming cliques based on their like-minded assessments of each other's creativity (after [26]).

CREATIVITY AS SOCIAL INFLUENCE

One model of social influence is based on the cellular automata voter model [22] as applied by Axelrod [1] to address one of the simplest notions of social influence, namely, who we are affects whom we interact with, and whom we interact with shapes who we become. This is considered a mechanism of social interaction and culture formation (where culture is defined as a set of shared values reached by the interaction of individual members of a population) that deals with how individuals become more similar as they interact. This takes into account the fundamental principle of human communication that the transfer of ideas tends to occur most frequently between individuals who are similar in certain attributes such as beliefs, education, social status, and the like. The study of the designing of artefacts and their subsequent impact in society could benefit from findings of such simulation models if these artefacts are considered as a population of agents interacting within a shared environment.

Sosa and Gero [28] have implemented such a system to study creativity as social influence. They used a simple model based on grid of reflexive agents represented through features. Each feature has one or more traits. The individual behaviour follows these rules:

- pick an agent and one of its neighbours at random
- pick a common feature at random, if they share the same trait then

- pick a feature where both agents differ, if any
- copy the trait from the neighbour into the agent.
-

Cultures are defined as sets of agents that share features and traits. Figure 18 shows how a new a culture emerges and then dominates an existing culture of designers. Simulation models such as these provide environments to study the implications of differing views about social behaviour.

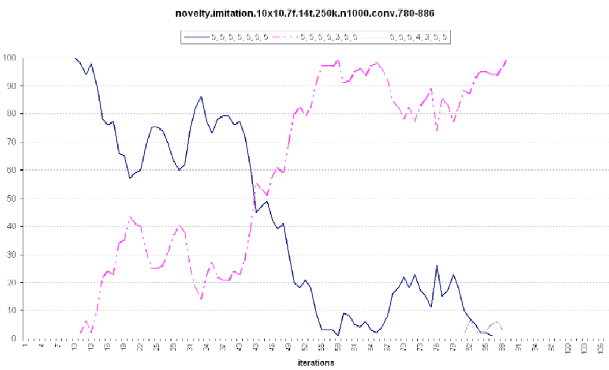

Figure 18. Simulation resulting in the emergence of a culture and its domination of the existing culture over an extended time period (after [28]).

ACKNOWLEDGMENTS

The work reported here has been supported by grants from the Australian Research Council and the University of Sydney Sesqui R & D Grant Scheme as well as by Australian Postgraduate Awards and International Postgraduate Awards. It has been carried out in collaboration with Vladimir Kazakov, Jarek, Kulinski, Terry Purcell, Lena Qian, Rob Saunders, Ricardo Sosa and Masaki Suwa.

REFERENCES

1. Axelrod, R. *The Complexity of Cooperation, Agent-based Models of Competition and Collaboration,* Princeton University Press, New York, 1997.
2. Bartlett, F.C. *Remembering: A Study in Experimental and Social Psychology*, Cambridge University Press, Cambridge, 1932 reprinted in 1977.
3. Boden. M.A. The Creative Mind: Myths and Mechanisms, Cardinal, London, 1990.
4. Clancey, W.J. *Situated Cognition: On Human Knowledge and Computer Representations,* Cambridge University Press, Cambridge, England, 1997.
5. Csikszentmihalyi, M. Society, culture, and person: a systems view of creativity, *in* R.J. Sternberg (ed.), *The Nature of Creativity,* Cambridge University Press, Cambridge (1988), 325–339.
6. Csikszentmihalyi, M., *Creativity, Flow and the Psychology of Discovery and Invention*, HarperCollins, New York, 1997.
7. Dewey, J. The reflex arc concept in psychology, *Psychological Review, 3,* (1896 reprinted in 1981), 357-370.
8. Gero, J.S. (ed.) *Preprints Modeling Creativity and Knowledge-Based Creative Design*, Design Computing Unit, Department of Architectural and Design Science, University of Sydney, Australia, 1989.
9. Gero, J.S. Design prototypes: a knowledge representation schema for design, *AI Magazine*, 11, 4, (1990), 26-36.
10. Gero, J.S. Conceptual designing as a sequence of situated acts, *in* I. Smith (ed.), *Artificial Intelligence in Structural Engineering,* Springer, Berlin, (1998), 165-177.
11. Gero, J.S. Towards a model of designing which includes its situatedness, *in* H. Grabowski, S. Rude and G. Grein (eds), *Universal Design Theory,* Shaker Verlag, Aachen (1998), 47-55.
12. Gero, J.S. Constructive memory in design thinking, *in* G Goldschmidt and W Porter (eds), *Design Thinking Research Symposium: Design Representation,* MIT, Cambridge, MA (1999), 29-35.
13. Gero, J.S. and Fujii, H. A computational framework for concept formation for a situated design agent, *Knowledge-Based Systems 13,* 6 (2000), 361-368.
14. Gero, J.S. and Kazakov, V. Adaptive enlargement of state spaces in evolutionary designing, *AIEDAM, 14*, 1 (2000), 31-38.
15. Gero, J.S. and Kazakov, V. Adapting evolutionary computing to model exploration in creative designing, *IJDC, 2* (2000), http://www.arch.usyd.EDU.AU/kcdc/journal/vol2/articles.html
16. Gero, J.S. and Kazakov, V. A genetic engineering extension to genetic algorithms, *Evolutionary Systems,* 9, 1 (2001), 71-92.
17. Gero, J. S. and Kulinski, J. A situated approach to analogy in designing, *in* B-K. Tang, M. Tan and Y-C. Wong (eds), *CAADRIA2000,* CASA, Singapore (2000), 225-234.
18. Gero, J.S. and Maher, M.L. (eds) *Modeling Creativity and Knowledge-Based Creative Design*, Lawrence Erlbaum, Hillsdale, New Jersey, 1993.
19. Gero, J.S., Maher, M.L. and Sudweeks, F. (eds) *Computational Models of Creative Design,* Key Centre of Design Computing, University of Sydney, Australia, 1995.
20. Goldberg, D.E. *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley, Reading, Massachusetts, 1989.
21. Koestler, A. *The Act of Creation,* Macmillan, New York, 1964.
22. Liggett, T.M. *Stochastic Interacting Systems: Contact, Voter, and Exclusion Processes*, Springer-Verlag, Berlin, 1999.

23. Patrick, C. Creative thought in artists. *Journal of Psychology, 4* (1937), 35-73.

24. Patrick, C. Scientific thought. *Journal of* Psychology, *5* (1938), 55-83.

25. Saunders, R. and Gero, J.S. 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 (2001), 113-139.

26. Saunders, R. and Gero, J.S. How to study artificial creativity, *Creativity and Cognition 4* (2002) (this proceedings)

27. Schön, D. and Wiggins, G. Kinds of seeing and their functions in designing, *Design Studies 13*, 2, (1992) 135-156.

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

29. Suwa, M., Gero, J. S. and Purcell, T. Unexpected discoveries and s-inventions of design requirements: Important vehicles for a design process, *Design Studies, 21*, 6 (2000), 539-567.

30. Suwa, M., Tversky, B., Gero, J.S. and Purcell, A.T. Seeing into sketches: Regrouping parts encourages new interpretations, *in* J.S. Gero, B. Tversky and T. Purcell (eds), *Visual and Spatial Reasoning in Design II,* Key Centre of Design Computing and Cognition, University of Sydney, Sydney, (2001), 207-219.

31. Turing, A.M. Computer machinery and intelligence, *Mind*, *LIX,* 236 (1950), 433–460.

32. Wallas, G. *The Art of Thought,* Harcourt, Brace and Company, NY, 1926.

This is a copy of the paper: 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, New York, NY, pp. 3-10.