

Computers and Creative Design¹

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Abstract. This paper introduces notions of creativity and creative design as a form of computational exploration. Exploration is used as a means of defining spaces which are then searched. It is shown that schemas provide an opportunity to describe exploration. Emergence as a process which modifies schemas is described, as a 'creative process'. Visual emergence is elaborated and other forms of emergence are described. The role of emergence in creative design is presented.

Keywords. creative design, design theory, emergence

1. INTRODUCTION

The concepts of creativity lie within both social and cognitive views of the world. The social view holds that creativity is only embodied in an artifact or an act and is a characteristic bestowed on that artifact or act by society. This view has a degree of attractiveness as it divorces the creator from the 'created' and only assesses the 'created'. The cognitive view holds that there are some things about the cognitive acts of the creator which play a significant role in the creativeness of the resulting artifact or act. These two views are complementary rather than contradictory. In this paper we shall be concerned more with the cognitive view played out with a cognisance of the social view.

Gardner (1993) has suggested that there are seven intelligences in order to provide a more adequate view of cognition. These are:

- (i) language intelligence
- (ii) logic and mathematics intelligence
- (iii) spatial thinking intelligence
- (iv) musical intelligence
- (v) bodily-kinesthetic intelligence
- (vi) interpersonal intelligence
- (vii) intrapersonal intelligence.

As a consequence of multiple intelligences we can postulate that an individual who is creative in one intelligence need not necessarily be creative in any other. Further, that the cognitive processes of creativity in one intelligence need not necessarily apply in others. Psychologists studying creativity have suggested that:

- "...creativity is necessarily an interaction, a dynamic, among three discrete constituents:
- The individual with his or her distinctive abilities, style needs, desires and programme;

¹CAAD Futures '95 (to appear)

- The particular domain or discipline of knowledge within which that person is trained and within which that person now works;
- The field – that collection of individuals and institutions which offer training, positions, and awards, and which eventually make decisions about the merits (or lack of merit) of particular products fashioned by the individual." [Gardner, 1995]

Further, Gardner [1995] states that:

"... the individuals whom we consider the most creative ... actually change the nature of the domain. As a consequence, the next generation of individuals will actually study a domain that has been somewhat differently configured."

In this paper I put forward the thesis that the first two of the three of Gardner's constituents can be explored and better understood through the use of computational models. Whilst many people equate design with creativity, here a distinction will be drawn between the two.

Design, in one sense, can be conceived of as a purposeful, constrained, decision making, exploration and learning activity. Decision making implies a set of variables, the values of which have to be decided. Search is the common process used in decision making. Exploration here is akin to changing the problem spaces within which decision making occurs. Learning implies a restructuring of knowledge. The designer operates within a context which partially depends on the designer's perceptions of purposes, constraints and related contexts. These perceptions change as the designer explores the emerging relationships between putative designs and the context and as the designer learns more about possible designs. Whilst much more can be said about design this provides a sufficient context for what follows.

2. MODEL OF CREATIVE DESIGN

Creativity, it has been suggested, is not simply concerned with the introduction of something new into a design, although that appears to be a necessary condition for any process that claims to be labelled creative. Rather, the introduction of 'something new' should lead to a result that is unexpected (as well as being valuable). More formally we can describe routine designing as following a defined schema where the expectations of what follows is defined by the schema. Creative designing, which is part of non-routine designing, can be described as perturbing the schema to produce unexpected and incongruous results. These new results are still understandable either in the current or shifted context.

Although the boundary between routine and creative designing is difficult to define there is less difficulty in articulating differences between processes used in the production of routine and creative designs.

One useful way to provide a framework for design is through the conceptual schema design prototypes [Gero, 1990] which articulates a function-behaviour-structure + knowledge framework. Thus, the state space representation of designs has three subspaces or abstractions: the structure space, *S* (often called the decision space); the behaviour space, *B* (often called the performance space); and the function space, *F* (which defines the artefact's teleology). Figure 1 shows these three subspaces which constitute the state space of designs.

Whilst there are transformations which map function to behaviour and vice-versa and structure to behaviour and vice-versa, there are no transformations which map function to structure. This is a version of the *no-function-in-structure* principle [de Kleer and Brown,

1984; Gero, 1990] where the teleology of an artefact is not found in its structure but is a contextual interpretation of its behaviour. The corollary: no-structure-in-function also holds. This may, at first glance, be counter-intuitive. The reason is that in human experience once a phenomenological connection between function and structure is made it is hard to unmake it.

Often only the structure and behaviour spaces are considered in computational models although function provides an important articulation of ideas about design. Typical computational models of design can be grouped under such processes as simulation, optimization, generation, decomposition, constraint satisfaction, and more generally search and exploration. All of these share one concept in common, namely that structures are produced in a design process and their resultant behaviours are evaluated.

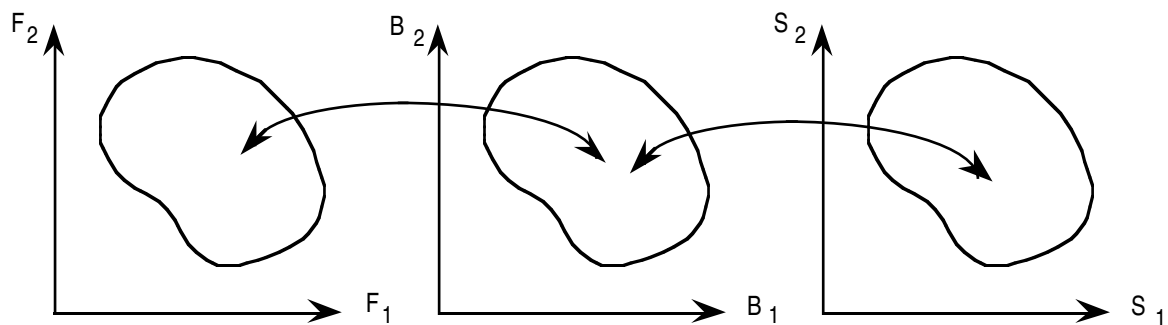


Fig. 1. The three subspaces of function (F), behaviour (B) and structure (S) which constitute the state space of designs, plus the locus of the transformations between them.

2.1 Creativity and Humour

One view of creativity is that it is involved with the production of an unexpected result through the confluence of two schemas. The first schema provides a set of routine expectations, the second schema is needed to understand the unexpected result. The unexpected result can be produced in a number of different ways described later in this paper.

A model for creative design can be found by analogy to models of humour. Humour

“... arises from the view of two or more inconsistent, unsuitable, or incongruous parts or circumstances, considered as united in [a] complex object or assemblage, or as acquiring a sort of mutual relation from the peculiar manner in which the mind takes notice of them” [Beattie, 1776].

Here is an example of the two schema paradigm of humour: An unskilled man, desperate for work, turns up at a construction site and asks the foreman if there are any jobs available. The foreman thinks he looks unintelligent, and doesn't believe he has the qualifications or knowledge for a job but, being a compassionate person, decides to give him a chance. He says, “I'll give you a job if you can tell me the difference between girder and joist.” The man scratches his head and says, “Easy! Can't be caught out by that one. *Everyone* knows the difference ... Goethe wrote *Faust* and Joyce wrote *Ulysses*.” Here the response introduces new variables which require a new schema to understand them.

A model of creative design based on an analogy with humour is presented in Figure 2. This model inheres no particular process but provides a framework for computational processes capable of producing unexpected designs and of finding schemas which support them.

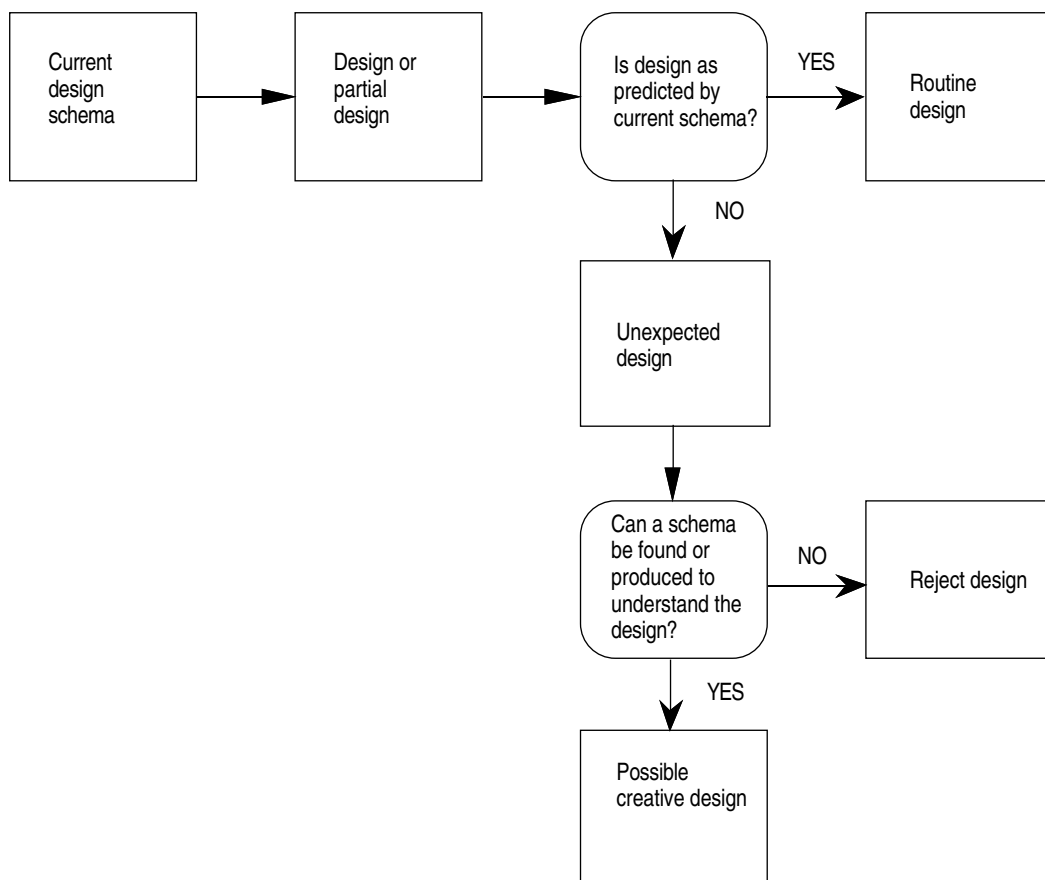


Fig. 2. A model of creative design based on an analogy with humour (after [Suls, 1972]).

2.2 Creativity and Schemas

Schemas are knowledge structures which when cued provide a framework with expectations of what is to come. The particular approach to computers and creative design suggested here is based on the use of schemas to comprehend and explain some of the processes involved. There are two classes of processes which affect schemas in creative design. The first class of processes involves a change which adds to an existing schema. This can occur when a new variable is added to a design description. This addition extends the schema in a homogeneous manner such that the previous schema is wholly contained within the new schema, Figure 3. The effect of this is that the previous schema can now only partially explain the current situation.

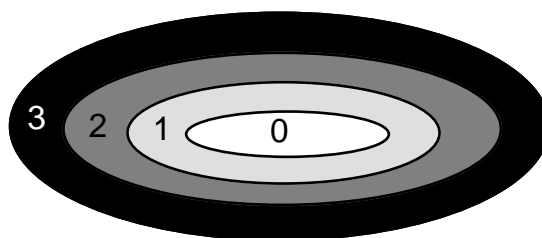


Fig. 3. Additive schemas where each successive schema entirely contains the previous schema.

The second class of processes involves a change which substitutes a new schema for the previously existing schema. This can occur in a number of ways but perhaps the most creative is not when new variables are introduced which cannot be explained by the existing schema but rather when a new 'view' of the existing situation allows new ideas to emerge – ideas which can only be understood through the use of a totally different schema to the current one, Figure 4. This matches the concept of emergence of which more will be said later.

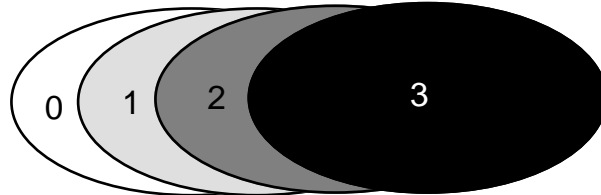


Fig. 4. Substitutive schemas where only a part, or none, of the previous schema is contained within the current schema.

3. CREATIVITY AND EMERGENCE

Whilst there are many processes capable of being called 'creative' in the sense that they introduce either new variables or new schemas into the design [Gero, 1994a, 1994b], perhaps the most intriguing and interesting are those associated with *emergence*.

3.1 Emergence

A property that is only implicit, ie. not represented explicitly, is said to be an emergent property if it can be made explicit. Emergence is considered to play an important role in the introduction of new schemas and consequently new variables. Emergence is a recognised phenomenon in visual representations of structure. It maps directly onto the concept of changing schemas since a new schema is generally needed to describe the emergent property. Consider the case of the three equilateral triangles shown in Figure 5(a).

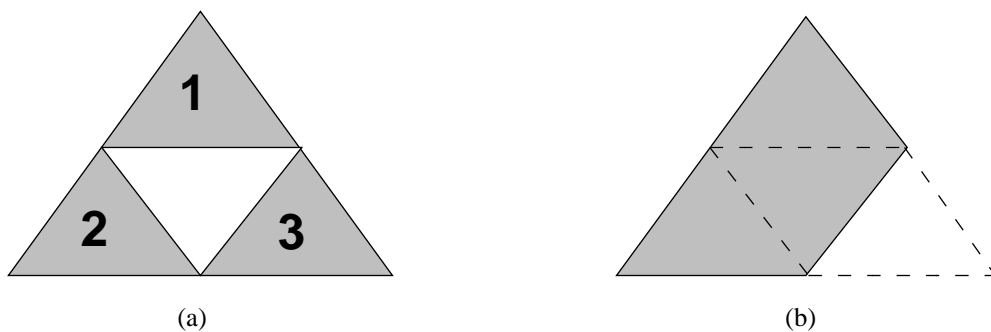


Fig. 5. (a) Three equilateral triangles, which are the only shapes explicitly represented. (b) One emergent form in the shape of a trapezoid moving that shape from being implicit to being explicit.

If the schema is concerned with triangles then only triangles will be found. However, another schema for the structure will find the trapezoid in Figure 5(b) which was not explicitly represented in Figure 5(a). A more striking example of visual emergence can be

found in Figure 6. Consider the object in Figure 6(a). It is copied into three different locations as shown in Figure 6(b). Human observers can readily see the ‘phantom’ forms of the star-of-David and various triangles. In order to see these, new schemas are needed and a computational model of emergence must be able to utilise this concept [Gero, Damski and Jun, 1995]. It is suggested that emergence is an important creative design process.

3.2 Graphical and Visual Emergence

Visual emergence is one of paradigms observed in creative designing [Schön and Wiggins, 1992]. It has the capacity to allow designers to look at unexpected or emergent visual structures from what is in front of them. As a consequence, other alternatives for developing the design become possible.

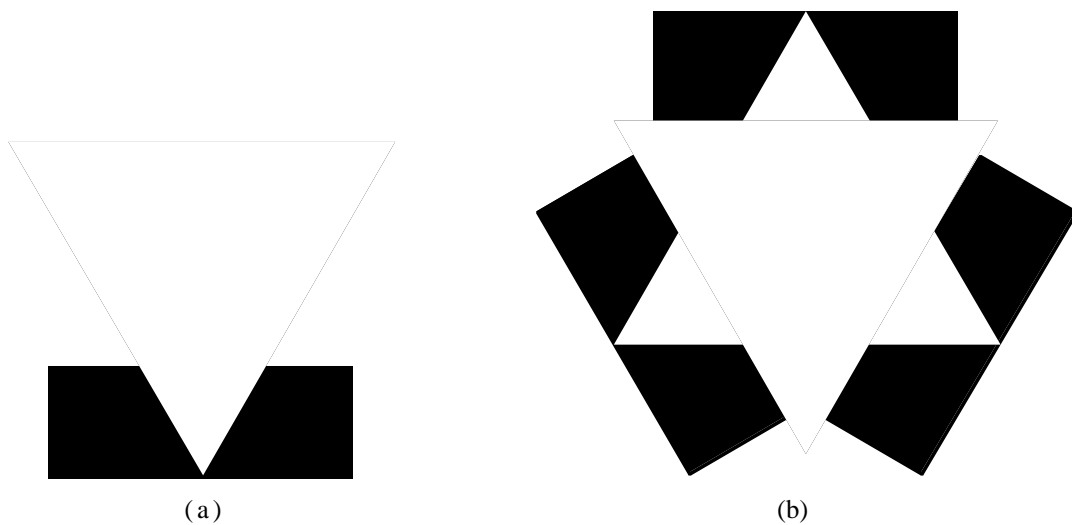


Fig. 6. (a) Single object. (b) Configuration of three copies of the object resulting in a number of emergent forms, the most prominent of which is the 'Star of David'.

Graphical or shape emergence is the process of making explicit graphical shapes which were not explicitly represented previously. This is becoming a widely studied phenomena in cognitive science and is being modelled in computational terms [Gero and Yan, 1994]. It forms the basis of one form of creative interaction amongst designers as well within an individual designer.

Visual semantic emergence [Gero and Jun, 1995a] is the process of making explicit visual patterns, which were not previously indicated, by grouping explicit or implicit structures of objects in defined ways. It is a phenomenon experienced by all humans. In particular, this phenomenon has been studied by Gestalt psychologists, who formulated various laws governing figure perception [Palmer, 1983]. Some principles contained in these laws of perception can be applied to architectural and graphic art design [Meiss, 1986]. Various types of emergent visual semantics can be explained using these laws of perception. There is a vast collection of possible visual semantics which could be emerged. Four classes of shape semantics of architectural design are of interest through interpretations of the visual patterns from plans, facades and perspectives: visual symmetry, visual rhythm, visual movement and visual balance.

There are now formal definitions of each of these concepts [Gero and Jun, 1995a]. Figure 7 shows an architectural plan from which many of these visual semantics can be readily emerged.

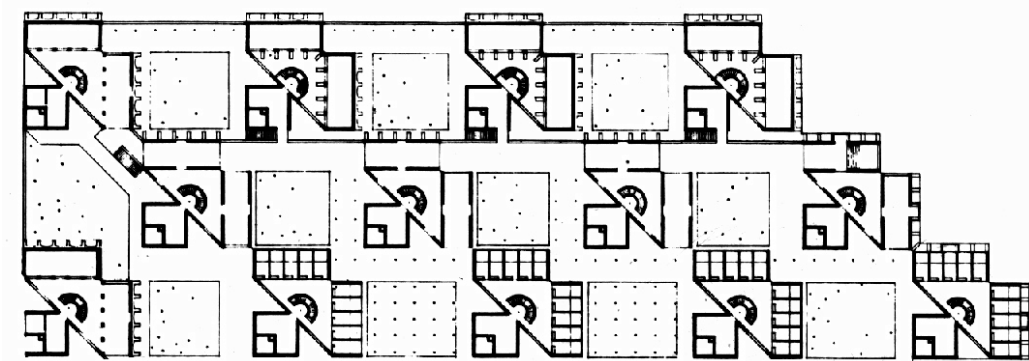


Fig. 7. The plan of the Indian Institute of Management of Ahmedabad in India, designed by Louis I. Kahn, from which many emergent visual semantics can be discovered (after [Gero and Jun, 1995b])

Such concepts can be seen to apply in three dimensions also. Figure 8 shows emergent visual movement in the Temple of Thebes in three dimensions. It can be seen not only in the plan in the upper left corner but also in the isometric section.

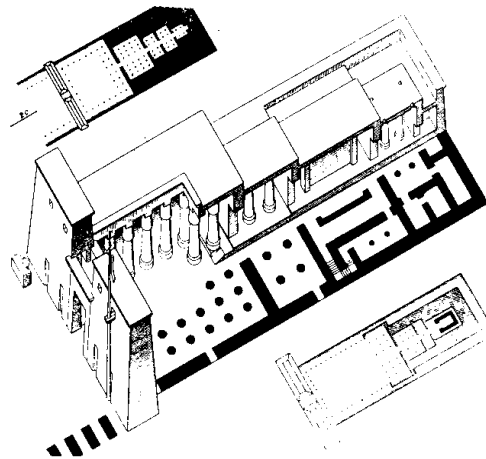


Fig. 8. Visual movement in the southern temple of Thebes (after [Gero and Jun, 1995a])

3.3 Using Visual Emergence

Figure 9(a) shows the primary shape as drawn by the designer. This shape has potentially a number of emergent semantics, one of which is visual rhythm. The designer may now choose to make use of this new interpretation of what was drawn in a number of different ways. A new visual rhythm which has equivalent topological constraints is generated by reshaping the unit of group as shown in Figure 9b). Therefore, the representation of this new visual rhythm is changed based on reshaping the unit.

Figure 9(c) shows a new visual rhythm obtained by changing the topological constraints on groups in the existing rhythm in Figure 9(a). Figure 9(d) shows a new visual rhythm produced by changing the topological constraints on relationship between adjacent groups [Gero and Jun, 1995a].

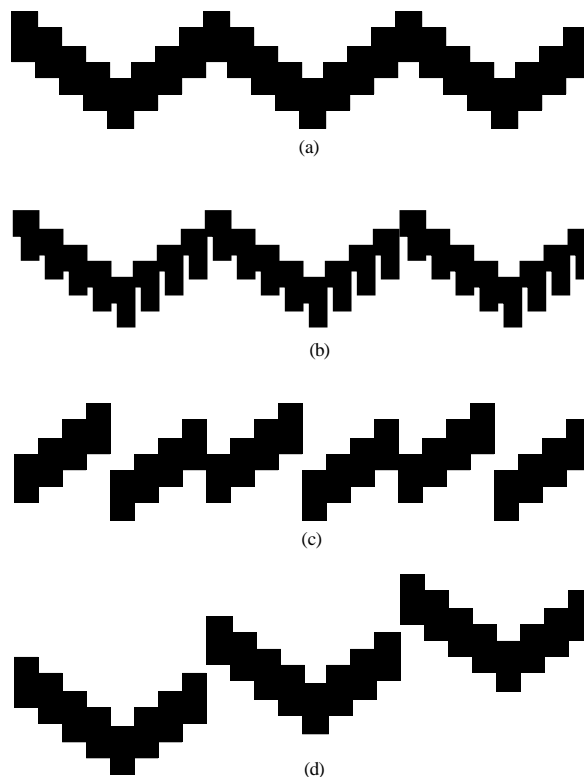


Figure 9: Use of emergent visual rhythm in design: (a) discovered visual rhythm; (b) generating new visual rhythm by reshaping unit of rhythm; (c) generating new visual rhythm by changing topological constraint on group; and (d) generating new visual rhythm by changing topological constraint on relationship between group (after [Gero and Jun, 1995a]).

3.4 Other Forms of Emergence

All of the above has concentrated on both visual emergence and on emergence in the structure or descriptive part of the design. There are examples of function emergence in the literature, Figures 10 and 11, but no computational models for function emergence.

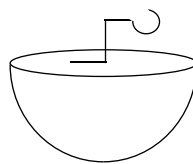


Fig. 10. Fixed structure used in function emergence (after [Finke, 1990]).

Forms of emergence other than in the visual domain are now being explored. Of particular interest is the emergence of schemas themselves. Schemas which are the basis of a representation of a design have been shown to emerge when genetic engineering principles are applied in evolutionary design [Schnier and Gero, 1995].

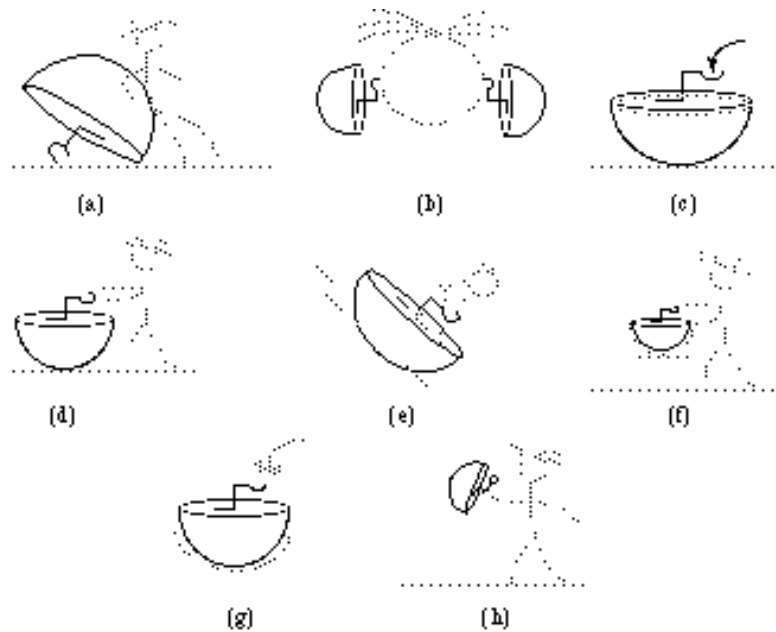


Fig. 11. Various functions the structure in Figure 10 could serve, such as (a) lawn lounge (furniture), (b) global earrings (jewellery), (c) water weigher (scientific instruments), (d) portable agitator (appliance), (e) snow sled (transportation), (f) rotating masher (tools and utensils), (g) top or spinner (toys and games) and (h) slasher basher (weapons) (after [Finke, 1990]).

4. EVOLUTION IN CREATIVE DESIGN

4.1 Evolution and Genetic Engineering

Computational models of evolution are the foundation of the field of ‘genetic algorithms’. Genetic algorithms, originally developed by Holland [1975], model natural selection and the process of evolution. Conceptually, genetic algorithms use the mechanisms of inheritance, genetic crossover and natural selection in evolving individuals that, over time, adapt to their environment. They can also be considered a search process, searching for better individuals in the space of all possible individuals.

The terminology of genetic representations is based on natural genetics. In genetics a set of genes is analogous to a string of symbols in an artificial genetic system. Genes can take values. A gene can be considered as an instruction in a recipe. The position of a gene in the string is identified separately from the gene’s function. A *genotype* consists of a finite set of genes. The information represented in a gene can be seen as a set of instructions or procedures for the production of the *phenotype* which is the realisation of the genotype. The phenotype is the resulting design. The *fitness* of the phenotype in its environment is used to determine the probability of that phenotypes genetic material being propagated into the next generation. The process of moving from one generation to the next involves the crossover of the genetic material in one genotype with that of another, in a manner analogous to natural genetic propagation.

Genetic engineering in design is derived from genetic engineering notions related to human intervention in the genetics of natural organisms. In the genetics of natural organisms we distinguish three classes: the genes which go to make the genotype, the phenotype which is the organic expression of genotype, and the fitness of the phenotype in its environment. When there is a unique identifiable fitness which is performing particularly well or particularly badly amongst all the fitnesses of interest we can hypothesize that there is a unique cause for it and that this unique cause can be directly

related to the organism's genes which appear in a structured form in its genotype. Genetic engineering is concerned with locating those genes which produce the fitness under consideration and in modifying those genes in some appropriate manner. This is normally done in a stochastic process where we concentrate on populations rather than on individuals.

Organisms which perform well (or badly) in the fitness of interest are segregated from these organisms which do not exhibit that fitness or do so only in a minimal sense. This bifurcates the population into two groups. The genotypes of the former organisms are analysed to determine whether they exhibit common characteristics which are not exhibited by the organisms in the latter group, Figure 12. If they are disjunctive, these genes are isolated on the basis that they are responsible for the performance of the fitness of interest. In natural genetic engineering these isolated genes are either the putative cause of positive or negative fitness. If negative then they are substituted for by "good" genes which do not generate the negative fitness. If they are associated with positive fitness they are reused in other organisms. It is this latter purpose which maps on to our area of interest.

The analog in design is that high performance in desirable fitnesses can be traced to particular genes or gene sequences which the system would like to keep in order to increase the probability that highly performing designs would be produced. These genes are 'engineered' to become a single evolved gene and become part of the pool of genes from which a design is produced. As a consequence, the likelihood of producing novel designs is greatly increased.

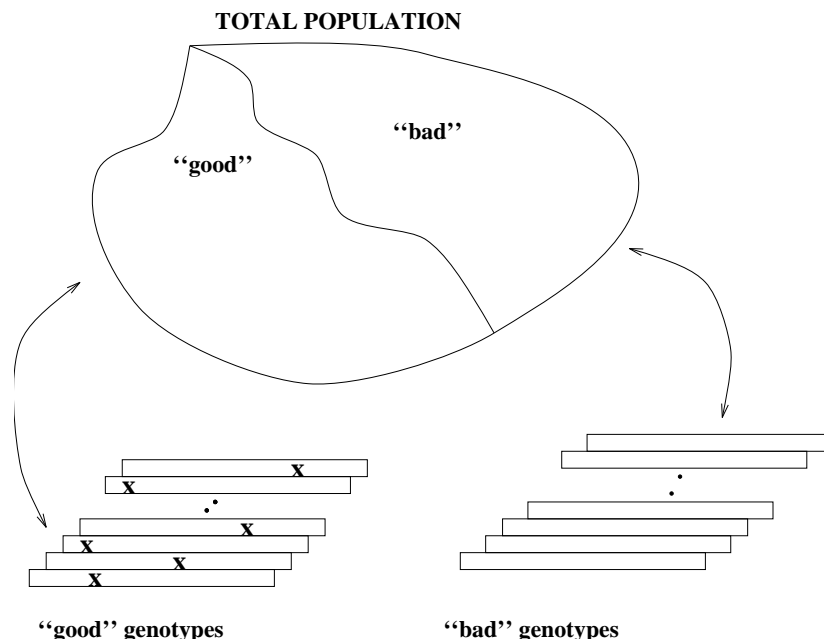


Figure 12. The genotypes of the 'good' members of population all exhibit gene combinations, X, which are not exhibited by the genotypes of the 'bad' members. These gene combinations are the ones of interest in genetic engineering (Gero and Kazakov 1995).

4.2 Computational models

The computational model of genetic engineering used can be easily illustrated as follows. Let us commence with a single phenotypic building block and that a design is assembled from combinations of this building block using the 8 rules shown in Figure 13.

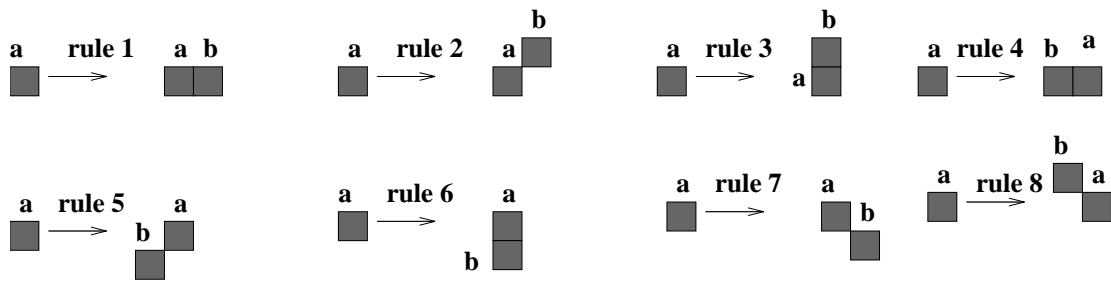


Figure 13. The assembly (transformation) rules used in the example (Gero and Kazakov, 1995).

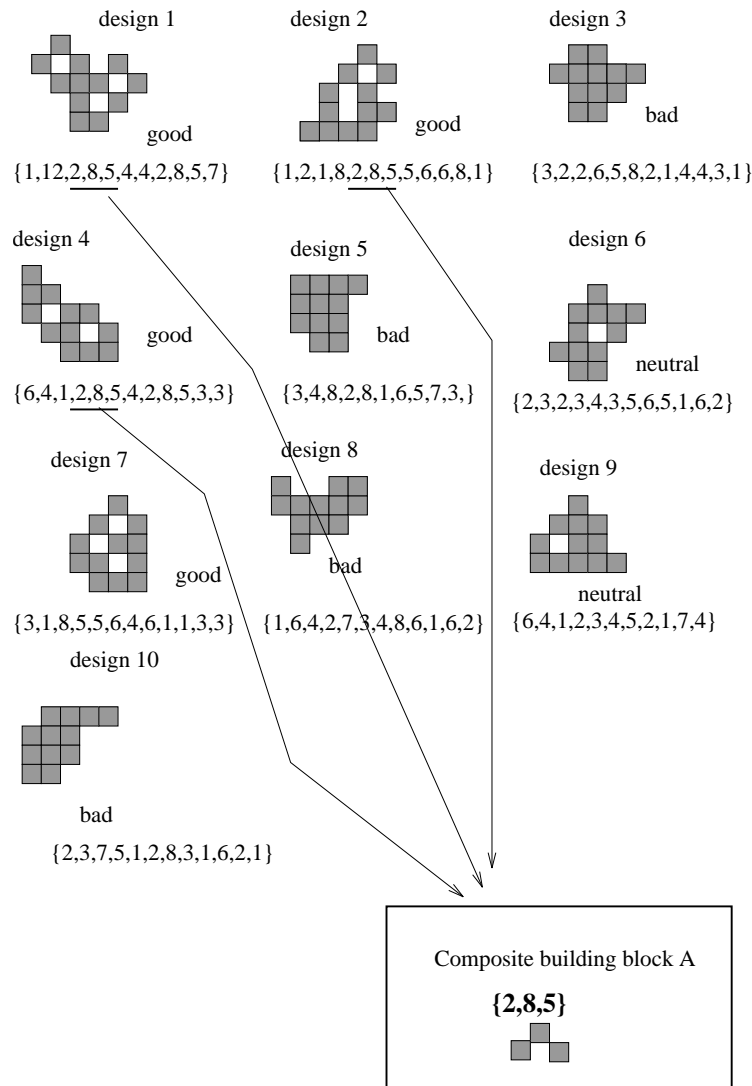


Figure 14. The identification of the pattern {2,8,5} and corresponding composite building block A in the genotypes of “good” designs.

Any design can be coded as a sequence of these rules used to assemble it. Assume we are trying to produce a design which has the maximum number of holes in it and that each design contains not more than 20 blocks. We start the cycle by generating a set of coding sequences and corresponding designs Figure 14. Then we notice that a number (4) of the

designs have the maximal number of holes (designs 1, 2, 4, and 7—the “good” sampling set) contain the composite building block *A* and that for three of them their coding sequences contain the pattern {2,8,5}. We also notice that only a few (none in this case) of the designs without holes (designs 3, 5, 8 and 10—the “bad” sampling set) contain this block and none contain this pattern in their coding sequence. Then we can generate the next population of coding sequences using the identified sequence {2,8,5} as a new rule which uses the composite building block *A* in the design. Assuming that we employ some optimization method to generate this new population we can expect that the “good” sampling set from the new population is better than the previous one (that is, the designs which belong to it have on average more holes than the ones from the previous “good” sampling set). Then we again try to identify the patterns which are more likely to be found in designs from this “good” sampling set than from the “bad” one. This time these patterns may contain the previously identified patterns as a component. Then we generate a new population of designs using these additional pattern sequences of rules as an additional assembly rule and so on.

4.3 Examples from case-based design

Case-based design is a computational process concerned with re-using previously produced designs, called cases, in the development of a new design. A particularly difficult problem in case-based design [Maher et al., 1995] is that of finding a suitable means of adapting a case after it has been selected as having analogous features to the design problem at hand.

“Case adaptation can be simply stated as making changes to a recalled case so that it can be used in the current situation. Recognising what needs to change and how these changes are made are the major considerations. Adapting design cases is more than the surface considerations of making changes to the previous design, it is a design process itself.” [Maher et al., 1995]

We use the engineered genes (there it maps onto the concept of gene evolution) to evolve a representation of the selected cases. This representation is then used to produce new designs which have features which are derived from the cases.

In order to commence we use a basic coding, which will be evolved to produce a representation of the cases, founded on turtle graphics with four different basic genes. This coding is able to represent any two dimensional orthogonal shapes such as floor plans. Figure 15 shows the two rooms plans which are the cases that have been selected. Figure 16 shows the evolution of a engineered gene which is used in the representation of the cases.

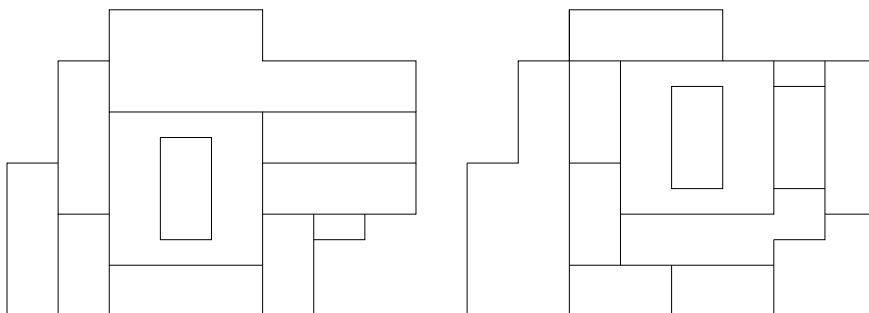


Figure 15. Room plans as cases [Gero and Schnier, 1995].

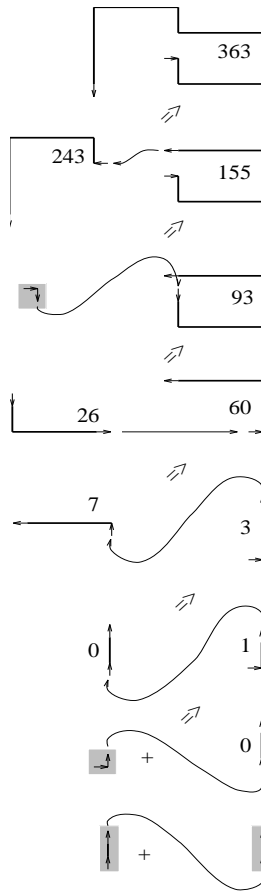


Figure 16. Evolving a representation: part of the evolution of the evolved gene 363 [Gero and Schnier, 1995].

The cases need to be adapted to the following design requirements to produce a floor plan with six rooms, fixed room areas, and minimal overall wall length
 The engineered genes are now used to produce new designs with the characteristics of the cases, Figure 17.

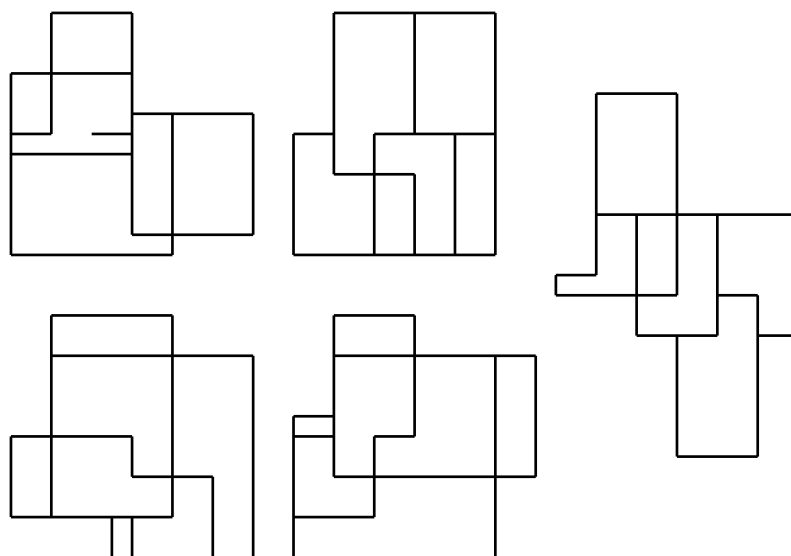


Figure 17. Novel floor plans, using design knowledge from the cases [Gero and Schnier, 1995].

5. DISCUSSION

From a computational viewpoint design can be treated paradigmatically as a process of producing variables, determining relationships between them and finding values for some of those variables such that useful values are determined for some other of those variables. In design the variables can be conveniently categorised into a number of classes, the three most significant of which are those variables which define structure, those variables which define behaviour and those variables which define function. The variables used to describe structure are also often called design or decision variables, whilst those used to describe behaviour are also often called performance, objective or criteria variables.

Most computer-aided design systems use the computational process of search as the primary synthesis mechanism. Search, as a computational process, requires that the state spaces of behaviour and structure be well-defined, ie. that all the states be directly specifiable a priori. In design this implies that the variables which define the structure and the behaviour are known a priori as are the relationships between them. Search then determines feasible, satisficing or, in appropriate circumstances, optimal values for structure variables which produce desired behaviours. Much of current design research is focussed on representations and processes founded on the design-as-search paradigm. There are good reasons for this. Much of design can be readily characterized in this manner and as a consequence swift progress can be achieved in the research needed to underpin the development of design support tools. The entire field of design optimization is founded on the design-as-search paradigm.

However, as stated earlier in this paper, creative design involves not just search within a defined space but also the introduction of either new variables or new schemas – a process called exploration. Exploration in design can be characterised as a process which creates new design state spaces or modifies existing design state spaces. New state spaces are rarely created de novo in design rather existing design state spaces are modified. The result of exploring a design state space is an altered state space. For a given set of variables and processes operating within a bounded context or focus any computational model will construct a bounded (although in some cases countably infinite) state space. Exploration in design can be represented in such a state space by a change in the state space. Emergence is a basic exploration process, however, A number of other computational processes support this concept of exploration. They include:

- adaptation
- analogy
- combination
- evolution
- first principles
- mutation.

Whilst the conjunction of the two concepts of computers and creative design appear to be far apart this paper has shown that they can be directly connected and that the computer can play a useful and even significant role in helping us understand creative design as well as contributing to the production of creative designs.

Acknowledgments. This work has been supported by grants from the Australian Research Council. The ideas in this paper have benefited from discussions with many members of the Key Centre of Design Computing, in particular, Jose Damski, Han Jun, Lena Qian, Thorsten Schnier and Min Yan.

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