# Computational Models of Innovative and Creative Design Processes

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ABSTRACT

Computational support for designing began in the early 1960s, and has had a considerable influence. Only recently has there been the possibility of providing computational support for innovative and creative designing. This paper presents a number of computational models of creative designing; including combination, transformation, analogy, emergence, and first principles as a representative set. It describes them within a uniform framework and indicates the potential of having such models on technological change in a society where designers are the change agents of the physical world. © 2000 Elsevier Science Inc.

## Introduction

Designing is one of the foundations for change in our society. Its genesis is the notion that the world around us either is unsuited to our needs or can be improved. The need for designing is driven by a society's view that it can improve or add value to human existence beyond simple subsistence. When simple subsistence is not met, then the need for it drives the need for designing also. As a consequence of designing, the world that we inhabit is increasingly a designed rather than a naturally occurring one. In that sense it is an "artificial" world. While much of what we use and consume is designed for mass production, there is an increasing demand for individual products. Some of these we are familiar with, such as purpose-designed buildings; however, there is the potential today to directly design individualized artifacts based on direct marketing [1]. Thus, instead of buying a product that has already been designed and manufactured, it may increasingly become possible to specify individual requirements that result in individualized artifacts. This brings with it the need to be able to design such products. While the current demand is for variations of existing designs, there is expected to be a demand for innovative or creative designs. As a consequence, there will be an increasing need to produce such designs on demand.

Designs, particularly technologically based designs, produce social change both by their existence and by the values they change in a society. It is always easier o see this in retrospect. We are all familiar with the effect of the motor car (as a class of designs) in modifying the interaction of people and how it is one of the bases of our means of carrying out commercial activities. It has changed the way we live, where we live, and

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how we live by changing our value systems related to distance. They also introduced a new set of values associated with the design of the car itself unrelated to its original transportation purpose [2]. Thus, a car can also be a symbol of prestige, affluence, status, masculinity, and so on. Many individual creative designs have had noticeable effects. The design of the Sony Walkman® changed the behavior of an entire generation of youth, and its effects can still be seen today in its use in public. It is not entirely clear, for example, how the invention of the Internet and its subsequent design is going to change society, but it appears that the changes it will produce are likely to also be profound. Thus, one way to change any society is to expose it to creative designs.

This then raises the question of how such designs can be produced. Can the production of creative designs be assisted with the use of computers? To explore this and to indicate that it can, we describe a framework upon which to hang computational processes that have the capacity to support creative designing. We will return to the issue of the impact of being able to produce creative designs on societal change.

Humans have a clear and unequivocal capacity to design. They appear to have the capacity to design at various levels, partly depending on need and depending on the designer. We can readily distinguish at least two classes of designing: the first produces designs that are some minor variation of existing designs, called *routine designing*, and the second produces designs that are noticeably different to existing designs, called *nonroutine designing.* We will articulate further differences between innovative and creative designing in this latter class, as this will play a role in describing processes of designing.

Much of the research in design science over the last decades has been concerned with developing an understanding of designing so that design aids may be produced that assist with the first class of designing rather than the second. If there are significant differences in the processes employed in these two classes it is important to be able to distinguish them at least at some semiformal level. Further, we need a framework that allows us to understand where the focus of such design processes may lie in the range of all design processes. Today, the impetus for the development of support tools comes from computational models.

The remainder of this paper commences with a description of a framework that allows us to see the focus of design processes that can be used to support designing. It then distinguishes between different classes of designing before introducing a number of computational models of designing that can be used to support innovative or creative designing. The paper concludes with a discussion on the implications of the potential availability of such support tools on societal change.

## The Function–Behavior–Structure Framework [3]

To appreciate the role of designing, we first need to have a better understanding of designing. Designing appears to be carried out differently to the way we are taught to understand the world. The latter is largely derived from the Greek view of the world. Science has been developed as a means of attempting to explain and understand the world around us. It commences with a description of the world (which in itself is not a trivial act to produce) and some behaviors and attempts to produce causal dependencies between them. Science then may be used to attempt to produce a purpose for the world. Designing exists because the world around us does not suit us, and the goal of designers is to change the world through the creation of artifacts. They do this by positing functions to be achieved and producing descriptions of artifacts capable of generating those functions. In this sense, designing is the opposite of the traditional scientific explanation.

Thus, designing is purposeful, and the activity of designing is goal oriented. The meta-goal of design is to transform requirements, more generally termed *functions*, that embody the expectations of the purposes of the resulting artifact, into design descriptions. The purposes of a future engineering system in terms of its requirements become functions to be achieved by any resulting design.

The result of the activity of designing is a design description. This design description generally is represented graphically, numerically, and/or textually. The purpose of such a description is to transfer sufficient information about the designed artifact so that it can be manufactured, fabricated, or constructed.

One prevalent and pervasive view of designing is that it can be modeled using variables and decisions taken about what values should be ascribed to those variables. The activity of designing is carried out with the expectation that the designed artifact will operate in the natural world and, generally, in the social world. These assumptions impose constraints on the variables and their values. So, the act of designing could be described as a goal-oriented, constrained decision-making activity. However, design distinguishes itself from other similarly described activities not only by its domain but equally importantly by additional necessary features. Designing involves exploration: exploring what variables may be appropriate. The process of exploration involves both goal variables and decision variables. In addition, designing involves learning: part of the exploration activity is learning; learning about emerging features as a design proceeds [4]. Finally, design activity occurs within two contexts: the context within which the designer operates and the context produced by the developing design itself, both of which create the "situation." The designer's perception of what is the situation affects the implication of the situation on the design. The situation shifts as the designer's perceptions change.

Designing can be now characterized as: *a goal-oriented, constrained, decision-making, exploration and learning activity that operates within a situation that depends on the designer's perception of the situation and results in the description of a future engineering system.*

As a consequence of designing, knowledge is produced. The knowledge acquired during the process of designing is a byproduct of the process, and is available for future designing. In addition to this knowledge, when the design is deployed it affects the society in which it is used. The knowledge of its use and the resulting values it introduces and changes constitute a second form of knowledge.

## Models of Designing

Here we will construct a semiformal framework onto which we can hang our design processes. The purpose of designing is to transform *function*, $F$ (where $F$ is a set), into a *design description*, $D$, in such a way that the artifact being described is capable of producing those functions. For example, when designing windows, some of the functions include the provision of daylight, control of ventilation, and the provision of access to a view. The design description would take the form of drawings and notes. Thus, a naive model of designing is

$$F \rightarrow D$$

where $\rightarrow$ is some transformation. There is, however, no direct transformation capable of achieving this result.

A design description represents the artifact's elements and their relationships; this is labeled *structure*, *S*. Computer-aided drafting systems have become the means by which structure is transformed into a design description, i.e.,

$$S \rightarrow D$$

Another model of designing is

$$F \rightarrow S$$

Here, a transformation occasionally does exist in the form of a direct mapping between function and structure, often termed *catalog lookup*. This occurs at the element level of an artifact and, in general, is not considered designing. More generally, no direct transformation between function and structure exists. This leaves a requirement for an indirect transformation between function and structure.

Function has been defined in another context as "the relation between the goal of a human user and the behavior of a system" [5]. In designing, behavior may be viewed in two ways. There is the behavior of the structure, $B_s$ (where $B_s$ is a set), which is directly derivable from structure

$$S \rightarrow B_s$$

This process is that of *analysis*, and presupposes the delineation of which behaviors to determine in the analysis process.

Transforming function to expected behaviors, $B_e$ (where $B_e$ is a set), provides the second view of behavior. The expected behaviors for the window design example include light transmission, ventilation rates, solar collection, etc. The expected behavior provides the syntax by which the semantics represented by function can be achieved

$$F \rightarrow B_e$$

This process is that of *formulation* or *specification* in design.

The predicted behavior of the structure can be compared with the expected behavior required to determine if the structure synthesized is capable of producing the functions.

$$B_e \leftrightarrow B_s$$

where $\leftrightarrow$ is a comparison. This comparison process is termed *evaluation* in design.

Another model of designing is

$$F \rightarrow B_e$$

$$B_e \rightarrow \mathrm{S}(B_s)$$

Here, the function is transformed to expected behavior. This expected behavior is used in the selection and combination of structure based on a knowledge of the behaviors produced by that structure. This process is that of *synthesis*.

When structures are synthesized, they produce their own behaviors that may be a useful superset of the expected behaviors. This may change the expected behaviors, and through them the function being designed for, leading to a *reformulation*. Reformulation can also occur when the evaluation of the comparison between the behavior of the structure and the expected behavior is unsatisfactory and cannot be made satisfactory by manipulating structure. This leads to a change in expected behavior.

Figure 1 shows how these transformations appear in design. We have not included the knowledge acquisition phase in this model, as we shall not be discussing it further in terms of this model.

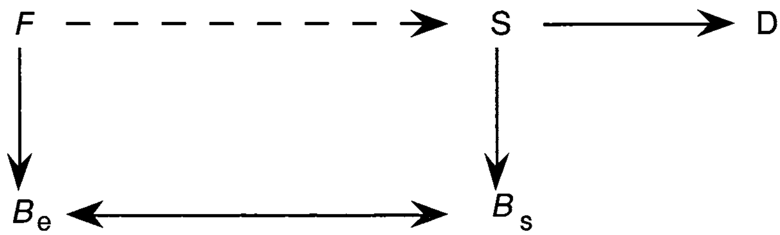


**Fig. 1. Model of designing as process.**

A general model of designing as a process involves the following activities (Figure 2): formulation, synthesis, analysis, evaluation, reformulation, and production of design description.

The relationship between function, behavior, and structure can be seen in Figure 3, where the mapping between the three classes of concepts is presented. We will be using a two-dimensional graphical representation of subspaces to illustrate many of our ideas, even though we really mean that each of these subspaces is multidimensional.

## Routine and Nonnroutine Designing

It is convenient to characterize designing as routine or nonroutine, although there are other ways of categorizing designing processes. *Routine designing*, in computational terms, can be defined as that designing activity that occurs when all the necessary knowledge is available. It may be more formally expressed as being that designing activity that 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 4 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.

Nonroutine 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 5). 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 behaviors 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."

*Creative designing*, in computational terms, can be defined as the designing activity that occurs when one or more new variables is introduced into the design. Processes

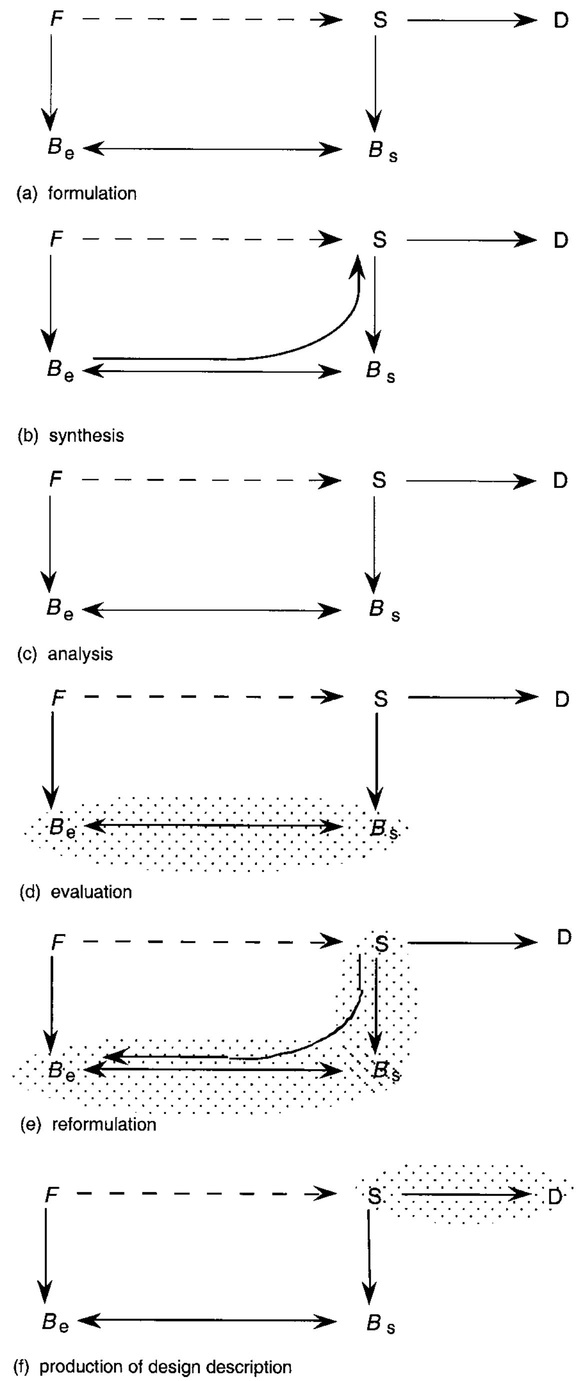


**Fig. 2. Activities in designing: (a) formulation, (b) synthesis, (c) analysis, (d) evaluation, (e) reformulation, and (f) production of design description.**

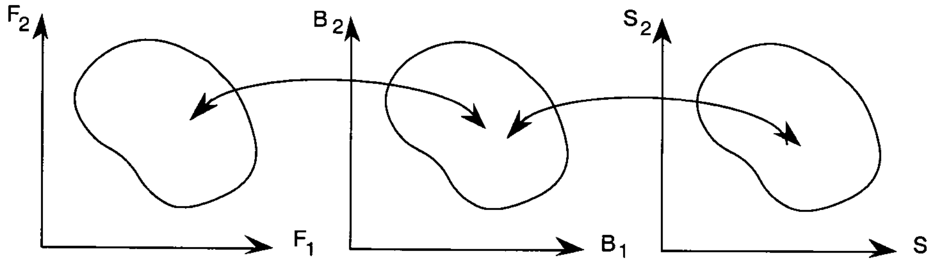


**Fig. 3. The three subspaces of function (*F*),** behavior (*B*), and structure (*S*) that constitute the state space of designs, plus the locus of the transformations between them.

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 6). 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 [6] 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 [7]. *S-creativity* (situated creativity) occurs in designing when the design contains ideas that were not expected to be in the design when the design was commenced. Thus, the design contains ideas

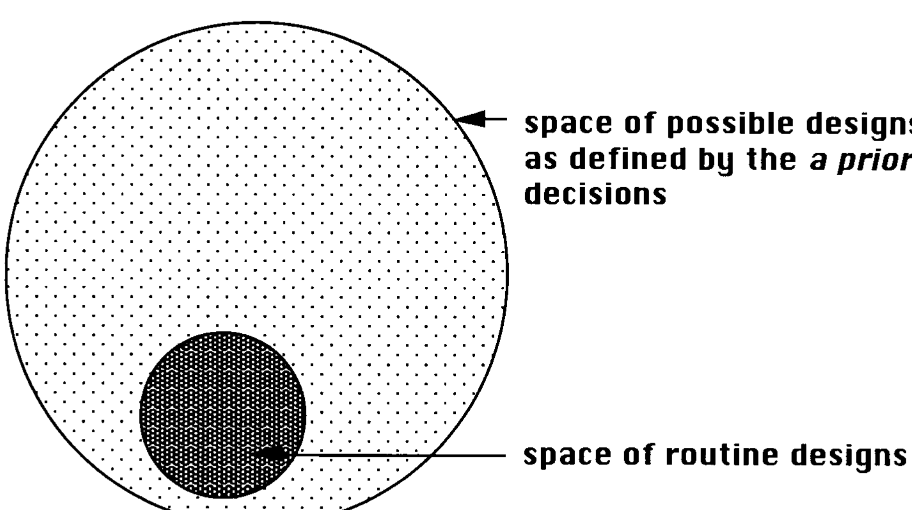


**Fig. 4. The space of possible designs is defined by the set of a priori decisions. The space of routine designs is a subset of those possible designs.**

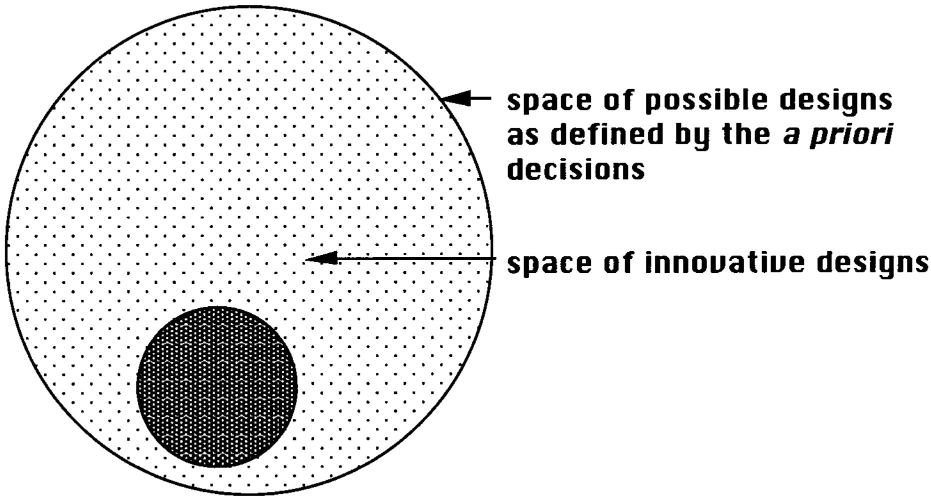


**Fig. 5. The space of innovative designs is a subset of the possible designs.**

that are not necessarily novel in any absolute sense or novel to the designer, but that are novel in that particular design situation.

## Creative Designing Processes

There are a number of processes that can be viewed as creative designing processes because they have the capacity to introduce new variables into the design, and as a consequence, they can change the state space of possible designs. Here we will introduce some of the most promising of such processes, promising in the sense that computational aids can be built using them. The processes we will introduce are: combination, transformation, analogy, emergence, and first principles. There are other processes, but they are often can be decomposed into combinations of these.

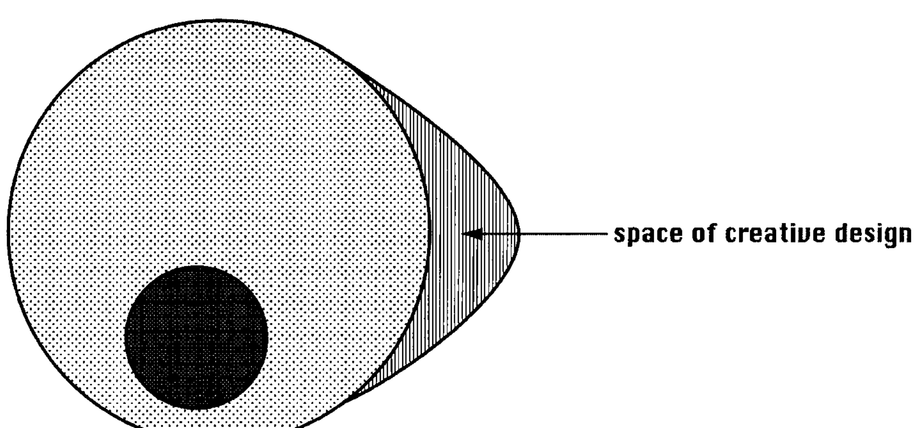


**Fig. 6. The space of creative designs is a superset of the possible designs, as defined by the set of a priori decisions.**

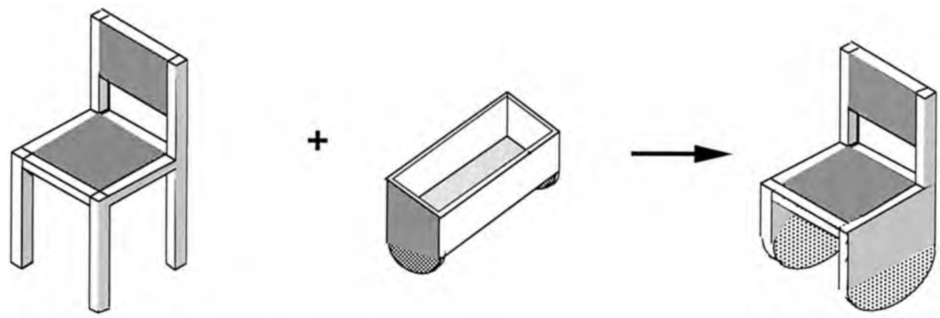

**Fig. 7. A graphical example of designing using combination (after [11]).**

COMBINATION

Combination as a creative design process involves the addition of two sets of design ideas or some subset of them (Figure 7). It can occur at the function, behavior, or structure levels, i.e.,

$$F_{\text{new}} = F_{\text{existing1}} \cup F_{\text{existing2}}$$

$$B_{\text{new}} = B_{\text{existing1}} \cup B_{\text{existing2}}$$

$$S_{\text{new}} = S_{\text{existing1}} \cup S_{\text{existing2}}$$

Most commonly, we only consider combining components at the structure level. There are computational mechanisms to model combination [8–10]. One approach is to draw the structure components from like designs, and thus, incorporate ideas from similar designs. Another is to draw the structure components from unlike designs and thus, incorporate ideas from dissimilar and even unrelated designs.

TRANSFORMATION

Transformation is the alteration of one or more structure variables by an external process (Figure 8). Transformation can be modeled as

$$S_{\text{new}} = \phi_m \, (S_{\text{existing}}),$$

where $\phi_m$ = a transformation operator.

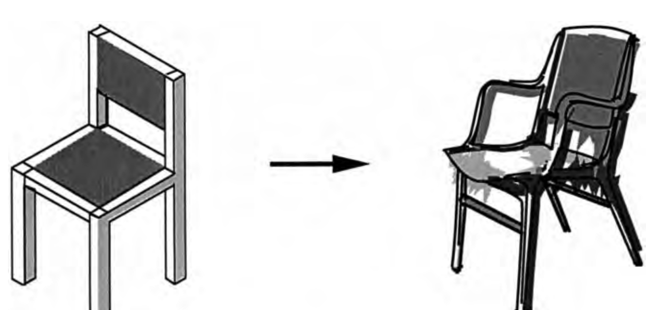

**Fig. 8. A graphical example of designing using transformation (after [11]).**

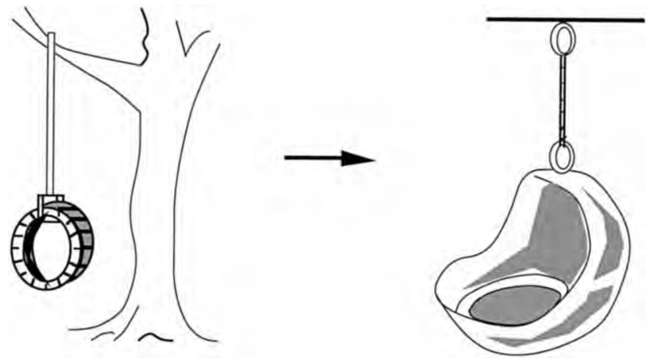

**Fig. 9. A graphical example of designing using analogy (after [11]).**

Of interest in creative designing is the use of transformation to produce new variables. Typical transformation operations include the algebraic and set theoretic operators. Thus, division, for example, divides a single variable into two. Such operations can affect the resultant topology of the artifact. Transformation operators fall into two classes: homogeneous and heterogeneous. Homogeneous operators are those that produce new variables of the same class as the variable being mutated. For example, a length is mutated into two lengths. Heterogeneous operators are those that produce new variables of a different class to the variable being transformed. For example, a length is transformed into a length and an angle. Heterogeneous transformations require additional knowledge to incorporate them into the existing design [11]. Because transformation produces new structure variables, it meets the formal definition of being a creative design process. There are computational mechanisms to model transformation [12, 13].

ANALOGY

Analogy is defined as the product of processes in which specific coherent aspect of the conceptual structure of one problem or domain are matched with and transferred to another problem or domain (Figure 9). Based on the nature of the knowledge transferred to the new problem, analogical reasoning processes can be placed into one of two classes: transformational analogy and derivational analogy [14, 15].

Transformational analogy adapts the structure of a past solution to the new problem. Derivational analogy applies the successful problem-solving process to the process of producing a solution of the new problem.

Analogies can operate on function, behavior, and structure of knowledge. Analogy requires a target (the artifact being designed) and a source (an artifact from which an analogy is to be drawn). Most analogies are drawn between situations in the same domain [16], although interesting analogies can be drawn between situations in different domains [17]. The most common form of analogical transfer is at the structure level, although methods exist for transferring behaviors [18].

Thus,

$$S_{\text{target}} = \tau_a\ (S_{\text{source}})$$

where $\tau_a$ = an analogical operation.

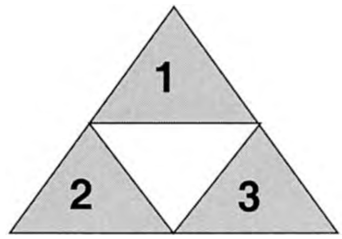


**Fig. 10. The triangles, as drawn.**

The effect of analogy on structure is the introduction of new variables into the original structure. The effect of analogy on function, behavior, and knowledge may be the introduction of a new variable into the original structure. Hence, analogy meets the formal definition of being a creative design process. Computational models of analogy are well developed, particularly for transformational analogy, and these have been used in design [19–21].

EMERGENCE

Emergence can be restated as the process whereby extensional properties of a structure are recognized beyond its intentional ones. If we look at Figure 10 as the set of intentional triangles, and then examine Figure 11, we can see a set of extensional or emergent shapes.

Emergence of structure can be modeled as

$$S_e' = \tau_e\,(S)$$

where $S'$ = intentional structure, $S_e$ = emergent structure, and $\tau_e$ = emergence transformation by substitution.

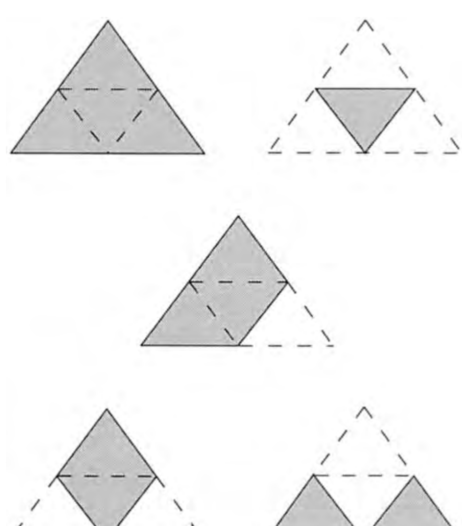

**Fig. 11. Some emergent shapes (extensional shapes) inferred from the original intentional shapes in Figure 10. These emergent shapes include two additional triangles as well as a trapezoid, a rhomboid, and a chevron.**

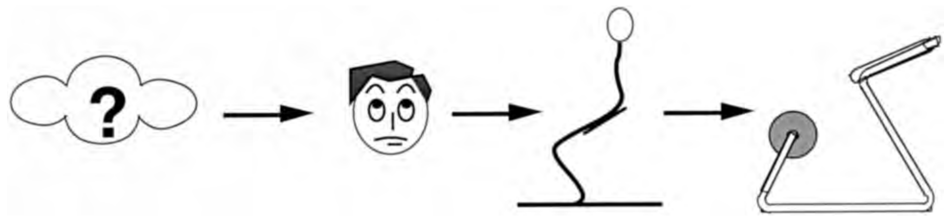


**Fig. 12. A graphical example of design using first principles (after [11]).**

Computational models of visual emergence have been developed and, generally, rely on separating the representation of geometry and topology from a symbolic representation from which geometry can be inferred [22–24]. The effect of this is to break the nexus between intentional shapes and a fixed representation from which only those shapes can be found.

FIRST PRINCIPLES

First principles relies on causal, qualitative, or computational knowledge used abductively to relate function to behavior and behavior to structure without the use of compiled knowledge (Figure 12).

Thus, first principles can be modeled as

$$S = \tau_k (B)$$

where $\tau_k$ = abductive knowledge-based transformation.

Designing using first principles is the computational process that is the least developed because of the difficulty in relating behavior to structure without the use of compiled knowledge. However, the division of the problem into basic independent behaviors is the crux of the idea so that the compiled knowledge can be utilized at the level of indivisible behaviors. Because the use of first principles introduces new variables, it meets the formal definition of a creative design process. Computational models of first principles processes generally rely on the use of qualitative physics, and have been used in design [25].

## Implication of the Availability of Creative Designing Processes

There are five standard steps in the process of developing and commercializing an innovative product (International Institute for Management Development, Lausanne):

1. *Imagining.* Having the initial insight about the market opportunity for a particular development.
2. *Incubating.* Nurturing the technology sufficiently to gauge whether it can be commercialized.
3. *Demonstrating.* Building prototypes and getting feedback from potential investors and customers.
4. *Promoting.* Persuading the market to adopt the innovation.
5. *Sustaining.* Ensuring that the product or process has as long a life in the market as possible.

The provision of computational support for creative designing has the capacity to short circuit the process of developing an innovative product.

Each of the models of creative designing processes presented in this paper has been implemented as a computational system. These computational systems do not automate the production of designs that may be evaluated as being creative. Rather, they assist a human designer to work towards the generation of designs that are evaluated by the human designer as being creative. However, they aim to increase the capacity of the human designer to produce innovative and creative designs on demand. The effect of this is likely to be the opposite of the standardization that often results from the automated generation of designs when using computers. The ability to produce innovative and creative designs with an increased frequency will increase the demand for such designs.

We already have the capacity to produce designs that are individualized through parametric variations. In the manufacturing industries, such flexible manufacturing with individualized results already exists in the computer industry, and is in the process of being implemented in the motor car and white goods industries. What is being suggested is an analogy in designing with this form of manufacturing. Individualized designs that can be manufactured as one-off artefacts would be the result of the availability of such creative designing processes (i.e., mass customization). The cost of designing at the individual level would become comparable to parametric designing, just as the cost of flexible manufacturing has become comparable to that for batch manufacturing. Change would occur faster as each new design moved the technological frontier, and individuals would have their needs met in more specific ways. The demand for products that exhibited high-quality designing would increase.

There are additional technological factors that are likely to affect both the designing of creative products and their takeup in a society. The use of high-quality immersive virtual reality visualization and sensing technologies such as CAVEs (a CAVE is a three-dimensional immersive physical and virtual environment in the form of a hollow cube whose walls are computer projection screens; a virtual world is projected onto these screens, and the whole system allows a designer and user some kinaesthetic movement as well as the large-scale virtual visual environment) [26, 27], has the capacity to reintroduce the user into the design process. With the user participating in such a design process we can expect a much higher takeup of novel designs than previously as the user's values change to meet the design as they are exposed to the design while it develops rather than only after it has been designed. Rapid prototyping, where a physical model of an object is made from the virtual representation in the computer and three-dimensional scanning of physical models to produce virtual representations close the loop between the virtual and the physical. These technologies open up not only new ways of designing, but new forms of designs as yet only dreamt of—a blend of physicality and virtuality. These creative designs have the capacity to change our world.

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