

Conceptual Design: Creative Patterns and Stimulation

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Abstract

Conceptual design is a creative process. Designers create functions to satisfy customer needs and behaviors and forms to fulfill their functions. Although cognitive processes are at the center of creating new ideas, they are rarely considered in design support methods and systems. In our research, we address the question: “are there creative patterns in design processes? If yes, how can we manage the patterns to promote creativity?” A cognitive model of conceptual design is developed that captures the relationships among the design entities, design operations, and cognitive processes. Our initial experiment studies indicated that designers exhibit observable patterns of creative design behaviors and stimulation has the potential of instilling the patterns into design processes to promote creativity.

1 Introduction

Conceptual design is essentially a creation process. It is the creation of functions to fulfill customer needs, and the creation of forms and behaviors to realize those functions. Early-stage design ideas have a large impact on the cost and quality of a product. Designers have the freedom to generate and explore ideas without being constrained by parameters that exist at the later design stages. However, generating new and useful ideas in conceptual design is not easy. It depends on the designer, the design task, and the ways of doing design.

Both design practice and design research has addressed the issue of how to generate more ideas. One may allocate more time for brainstorming to increase the number of ideas (Osborn 1979), and there have also been intuitive techniques, such as Method 635 (Rhorbach 1969), Syntectics (Gordon 1961), and C-Sketch (Shah 2000), that attempt to stimulate human creativity through exchanging sketches. Artificial intelligence researchers developed programs that automatically generate ideas, e.g., *am* (Lenat 1977) and *bacon* (Langley 1979)). Although various methods and tools are being developed, at the present time, relying on humans’ creativity appears to be the most pragmatic approach for creative conceptual design.

Following Finke et al (1992), we take a *creative cognition* approach for the investigation. The premise here is that creativity is not a mysterious act by itself; rather it is based on the same kinds of cognitive processes that we all use in ordinary, everyday thought such as retrieving memories, transform thoughts from one form to another, and analyzing and using various concepts; creative people are creative because they execute these processes *creatively*. We particularly focus on the question: *Are there creative patterns in design processes? if yes, how can we manage the patterns to promote creativity?*

Our inquiry into creative patterns and stimulation in conceptual design starts with identifying what concepts and processes, both *cognitive* and *operational*, are involved in designers’ thinking process. We developed a cognitive model of creative conceptual design in which two dozens of specific concepts and processes were identified in three categories, namely, *design entities*, *design operations*, and *cognitive processes*. Based on this cognitive model, we conducted two experimental studies to identify creative patterns and to investigate what kind of external information will likely to stimulate creative ideas, respectively.

2 A Cognitive Model of Creative Conceptual Design

Previous investigations of design process have recognized that there are design entities that represent the contents of our thoughts (Gero and McNeill 1998), cognitive processes that produce creative ideas (Finke et al 1992); and design movements, or operations, that forward a design (Gero and McNeill 1998). In our proposed cognitive model, we hypothesize that design entities (i.e., contents or ideas) are generated by certain design operations. These contents then stimulate designer's cognitive processes, e.g., memory retrieval and idea transformation. The activation of the cognitive processes will then lead to the production of both internal (non-observable) and external (observable) operations, which will further generate new ideas. This *generate-stimulate-produce* circle links design contents, operations, and cognitive processes together. It continues as many initial ideas being generated evolve into meaningful design ideas. Figure 1 illustrates this conceptualization. In Figure 1, *design entities* are the content being designed. They include initial raw ideas as well as more mature concepts of a design artifact. *Cognitive processes* are the thinking elements that produce *design operations*. Design operations are actions that bring design entities into a design context. They include observable ones such as writing, sketching, and internal ones such as questioning and suggesting. Once created, design entities stimulate further cognitive processes that lead to production of further design operations, as shown in Figure 1. An important feature of this framework is that design entities are both the object of creation and the catalysts for further creation.

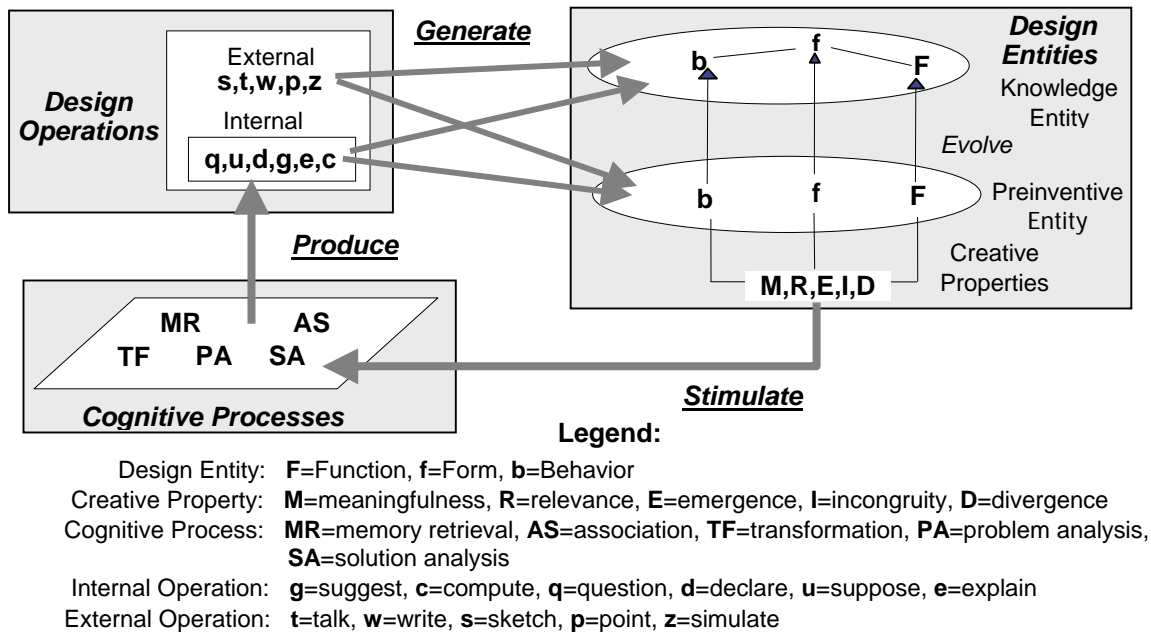


Figure 1: A Cognitive Model of Creative Conceptual Design

As shown in Figure 1, during design designers go through a cyclic process of creative generation and exploration of design entities. In this process, preinventive entities evolve into knowledge through the action cycles. In the *stimulation* phase, designers are stimulated to generate and explore ideas after perceiving existing design entities in catalogues and other documentation. Entities that are meaningful (M), relevant (R), emergent (E), divergent (D), and incongruous (I) stimulate memory retrieval (MR), associations (AS), and transform (T). The second phase is the *production* of internal design operations. Designers ask questions (q), make suppositions (u), suggestions (g), and declarations (d), explain (e) themselves, and make

computations (c). Internal operations lead to *production* of external design operations. Sketches (s) are often the easiest way to record design ideas. They are rapid and spontaneous, but their residual traces are stable and can be subsequently examined by the designer at his or her leisure. They embody abstract and high-level design ideas; they allow a degree of uncertainty about particular physical attributes and they impose constraints (Gross et al 1998).

Designers also express their ideas in writing (w). While images lead to access of more perceptually based knowledge, words lead to access of conceptual knowledge (Peterson 1993). Designers also talk out loud (t) to exchange ideas, point (p) to forms, and simulate (z) behavior.

As more and more design elements are *generated*, design entities evolve from *preinventive* entities into *knowledge* entities. However, the creative process is not complete until stimulation of cognitive processes, production of design operations, and generation of design entities are iterated many times, to produce a set of acceptable ideas. The cognitive model shown in Figure 1 provides a foundation for us to conduct experimental studies of creative conceptual design. It tells us what are the specific information and patterns of behaviors we can, and should, observe and analyze.

3 Creative Patterns

The following description was used as the design problem for the investigation of creative patterns: “*Oars often propel boats that operate manually (human powered). However, oars can be difficult to maneuver. Inexperienced operators tire quickly, and if the oars are not used correctly, they rock the boat, and splash water on the deck where people are sitting. Your task is to develop designs for alternative means (besides oars) to manually propel boats.*” Four mechanical engineering students (two senior students and two master students) participated in the study. Following are the creative patterns revealed from the protocol analysis.

Patterns of Stimulation

The encoding of creative stimulation from all design sessions has been input into a stimulation matrix as shown in Table 1. The matrix identifies the creative properties of form, function, and behavior that stimulate each cognitive process during design sessions (see Figure 1).

Design
Element

Table 1: Stimulation Matrix

| | | Cognitive Process | | | | |
|----------|--|-------------------|----------|----|--------------|----------|
| | | MR | AS | TF | PA | SA |
| Function | | | | | <i>M</i> | |
| Form | | <i>M,R,E</i> | | | <i>R</i> | <i>E</i> |
| Behavior | | <i>M,R,E</i> | <i>M</i> | | <i>M,R,I</i> | |

Meaningfulness and *relevance* of *form* and *behavior* are the most stimulating properties. In fact, *meaningfulness* and *relevance* were found in every creative design episode. If the subject found the information was not *meaningful* and *relevant*, it was not used in a creative process.

Once the designer found that the information was *meaningful* and *relevant*, additional properties were also found. *Emergence* of *form* and *behavior* stimulated *memory retrieval* and *solution analysis*. *Incongruity* of *behavior* stimulated *problem analysis*.

The dominant pattern was *meaningfulness*, *relevance*, and *emergence* of *form* and *behavior* stimulating *memory retrieval*, *problem analysis* and *solution evaluation*.

Patterns in Production

Following the same matrix-based method, we looked into what cognitive processes may produce what design operations. From the encoded creative segments, we cross link how each type of cognitive process leads to specific internal design operations, as shown in Table 2. As indicated by the Production Matrix in Table 2, *memory retrieval* produced *suggestions*, *explanations* and *computations*; *associations* and *transformations* produced *explanations*;

problem analysis produces *questions, declarations, and explanations*; and *solution analysis* produced *suggestions, declarations, and explanations*

The matrix of Table 2 reveals that exploratory processes were externalized in more ways than generative processes; and the dominant cognitive processes are *memory retrieval* and *problem analysis*; and the dominant operations are *explanations, declarations*.

Patterns of Generation

Design entities generated during design are finally externalized and written on a piece of paper. It is interesting to understand how internal and external design operations work together to generate these written design symbols and sketches. Based on the analysis of encoded design protocols, we

compiled the Generation Matrix, shown in Table 3, that identifies relationships between internal design operations, external design operations, and design entities. *Suggestions* were made while *sketching forms, writing* descriptions of *forms, writing* about *behaviors* and *simulating behaviors*. *Declarations* were made while *sketching, writing, and pointing* to *forms; sketching* and *simulating behaviors*. *Explanations* were made while *sketching* and *pointing* to *forms, sketching* and *simulating behaviors*.

Table 3 reveals that *sketching* is the most pervasive external operation performed by a designer. This is in agreement with previous research, which shows that *sketching* plays a central role in creativity (Kokotovich 2000). Other important external operations were *writing, pointing, and simulating*. *Talking* was not an issue because the designer was working alone. The essential internal operations were *suggestions, explanations, and declarations*.

4 Creative Stimulation

Based on our model and these creative patterns, it can be seen that the patterns of stimulation from design entities' creative properties to cognitive processes are the origin of creating new ideas. We conducted an experiment study on creative stimulation to investigate how patterns of creativity can be infused into conceptual design. Twenty engineering students (16 senior students and 4 master students) participated in the experiment. The students were asked to think aloud while being videotaped in their design sessions. The same watercraft design problem as in the creative patterns study, shown in Figure 2, was provided to the subjects.

The students were randomly divided into four equal treatment groups. In addition to the design problem, each group was provided with additional information as shown in Figure 2. The analysis of the results is composed of two parts. First, we analyzed protocol data to investigate each type of stimulation. Second, the numbers of concepts generated by the subjects were counted and compared to investigate the effectiveness of different types of stimulation. The latter is described below.

In the design concept comparison study, a design concept in this analysis is defined as a unique working principle that can be employed to solve the design problem. The reason we used

Table 2: Production Matrix

| | | Internal Operations | | | | | |
|-------------------|----|---------------------|---|---|---|---|---|
| | | q | u | d | g | e | c |
| Cognitive Process | MR | | + | + | + | + | |
| | AS | | | | | + | |
| | TF | | | | | + | |
| | PA | + | | + | | + | |
| | SA | | + | + | + | + | |

Table 3: Generation Matrix

| | | External Design Operation | | | | |
|---------------------------|----------|---------------------------|-------|-------|----------|-------|
| | | sketch | write | point | simulate | talk |
| Internal Design operation | Question | | | | | N / A |
| | Suggest | f | f,b | | b | |
| | Suppose | | | | | |
| | Declare | f,b | f | f | b | |
| | Explain | f,b | | f | b | |
| | Compute | | | | | |

the number of design concepts, instead of that of design entities is that we wanted to have a measure of design performance. Comparing with design entities, the number of design concepts is a more reliable measure of design performance. Table 4 shows the numbers of design concepts generated by the subjects in different treatment groups.

One-way analysis of variance (ANOVA) was performed to test whether the type of stimulation significantly affect the number of generated ideas. The analysis indicates that the type of stimulation has significant effect on the number of generated ideas ($p = 0.000$). To reveal which stimulation types differ from which others, a multiple comparison test needs to be carried out.

The results indicate that form and behavior, which are less mature entities, stimulated more ideas than knowledge and function. Further, behavior tends to stimulate more ideas than form.

Functions and knowledge entities are fixating, while form and behavior entities are more ambiguous and stimulate ideas that are more original. Entities that are more mature tend to be more fixating, while entities that are more ambiguous tend to be less fixating. Therefore, in an ideal situation, designers should encounter many abstract preinventive entities to stimulate a wide variety of new ideas.

Based on the patterns of stimulation identified through modeling and protocol analysis and evaluated in the experiment, we see that the most preferable stimuli are behaviors. The least preferable stimuli are knowledge entities. The stimuli should be meaningful, relevant, and ambiguous to attract attention. The stimuli should be novel so that the designer does not immediately assume a specific meaning of the information. There should be some incongruity in the information so that the designer will make an effort to explore. Finally, there should be divergent properties, so that in the exploration process, the designer will generate a variety of ideas.

5 Concluding Remarks

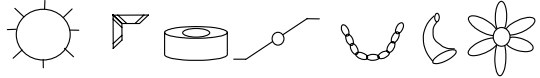
In this paper, a descriptive model of the thinking process in conceptual design was developed. The model consists of three major components: 1) design entities, 2) cognitive processes, and 3) design operations. The design process is modeled as action cycles of

Try to use these functions to stimulate your thinking:

- A fish swims under water
- A duck paddles on the water
- An otter dives under water
- An elephant blows water out of its trunk
- A bird flaps its wings
- A monkey swings on branches
- An owl hunts at night

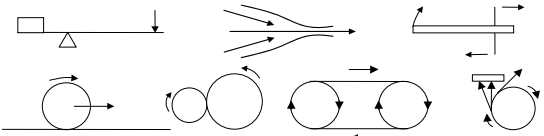
(a) Information Provided to Group A

Try to use these forms to stimulate your thinking:




(b) Information Provided to Group B

Try to use these behaviors to stimulate your thinking. The arrows can designate force or movement:



(c) Information Provided to Group C

Try to use the bicycle to stimulate your thinking:



(d) Information Provided to Group D

Figure 2: Stimulation Information

Table 4: Generation Matrix

| Subj | Group A Function Stimulation | Group B Form Stimulation | Group C Behavior Stimulation | Group D Knowledge Stimulation |
|------|------------------------------------|--------------------------------|------------------------------------|-------------------------------------|
| 1 | 3 | 6 | 6 | 2 |
| 2 | 4 | 3 | 4 | 2 |
| 3 | 1 | 3 | 5 | 2 |
| 4 | 3 | 4 | 6 | 2 |
| 5 | 3 | 5 | 7 | 3 |

generate(design-entities)-*stimulate*(cognitive processes)-*produce*(design operations). Experiment studies were carried out to develop and validate the proposed model. The main results of our investigation can be summarized as follows:

- Our proposed cognitive model of creative conceptual design provides a useful framework for studying creative design processes in conceptual design. The two experimental studies demonstrated its usefulness.
- There exist patterns in designers' creative thinking process by which certain intermediate design concepts stimulate cognitive processes, cognitive processes produce design operations, and design operations generate new design concepts.
- Different design concepts have different effects in stimulating design concept generation. More behavioral and less mature concepts tend to be more effective, and more product-oriented and mature concepts lead to less effective stimulation.

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