CREATIVE PROBLEM SOLVING IN ENGINEERING DESIGN

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by

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Extended Summary

This thesis deals with creativity in engineering design. Its main findings are the introduction of a set of objectively stated sufficient conditions that characterize creative engineering solutions and their empirical and psychological validation; the development and empirical validation of SIT (Structured Inventive Thinking), a structured teachable multi-stage method that guides the search towards creative, engineering solutions; and the identification of the fundamental cognitive qualities underpinning the successful use of the method.

Chapter 1 introduces the topics to be investigated in this work. It starts with a short overview of some historical landmarks in the general study of creativity. The factors that impeded the study of creativity at the beginning of the century as well as those that eventually accelerated it towards mid-century are discussed. Next, the accepted approaches for the study and definition of creativity, namely the study of the creative *person*, the creative *process*, and the creative *product* are described. The chapter ends with a discussion of the importance of creativity to engineering design and with a general outline of our approach for the study of creativity in engineering design.

Chapter 2 surveys the main theories of creativity and methods for enhancing creative thinking that have been put forward since the beginning of the 20th century. The chapter is divided into two sections, one dealing with theories and methods, and the second focusing on theories related to engineering design. Later in the work, references are made to these theories in order to compare them to the ideas developed in this thesis.

Chapter 3 presents the theory of sufficient conditions for creative engineering solutions. The chapter begins with an illustrative example of an engineering problem and its creative solution. The theory of the conditions is then unfolded through an informal discussion that helps the reader get the feel of the theory. This is followed by a formal presentation of the conditions. Several case studies elucidating the application of the conditions to real engineering problems are presented next. Then,

the results of an empirical study aimed at demonstrating the validity of the conditions is presented. The chapter ends with a discussion of the rationale behind the conditions and the way they are related to other theories of creativity.

Chapter 4 describes the SIT method. The chapter opens with a description at a conceptual level followed by a detailed description of the method using a special description language. Then, several illustrative examples demonstrate the SIT procedure. An empirical study that proves the effectiveness of SIT is presented next. The chapter ends with a comparative analysis of SIT versus other methods.

Chapter 5 is dedicated to cognitive aspects of the sufficient conditions and the SIT method. The chapter opens with a description of the main research tool, the Kreitler and Kreitler meaning system. Then an experimental study is described, followed by an analysis of the results and their implication to the results of Chapter 3 and 4, to the general understanding of creativity, and their practical relevance for engineering creativity training.

Chapter 6 concludes the work and suggests topics for further research: extending the SIT method to group thinking; computerization of the SIT procedure; adapting the SIT framework to engineering tasks involving design from scratch; adapting SIT to other domains such as software design, management, marketing, advertising; and the development of practical training programs aimed at enhancing an individual's cognitive creative competence.

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INTRODUCTION

Chapter one

This work deals with creative problem solving in engineering . We limit our focus to relatively small scale problems that crop up in the daily work of an engineer. Although largely associated with the term *invention,* we do not deal with large scale problems such as those that led to the discovery of the laser, electricity, or microwave oven. Our focus is even further constrained by the type of inventive *solutions* we focus on. These are characterized by Altshuller [Altshuller, 88] as type three, namely, *Inventions inside a paradigm* (see below a complete account of Altshuller's classification of solutions to engineering problems). In these solutions it is not an application of knowledge or expertise coming from outside the problem domain that renders the solution *inventive*. Rather its is the overcoming of *mental sets* or what Altshuller calls *'psychological inertia'* that underlie their identification as inventive solutions. Although this work deals almost entirely with creativity in engineering design, the study both draws on, and contributes to the general understanding of creativity. We will now specify the three main goals of this work.

The first goal is to supply an objective *test* for the inventiveness of engineering solutions (applicable only to the aforementioned type of engineering problems and solutions.) To better explain this goal we should address a few important issues concerning the definition of inventiveness; limitations of our test (i.e. its incompleteness); and a justification for developing a go-no-go *test* rather than a quantitative *measure.*

A test of inventiveness must be based on a definition of inventiveness. Several approaches can be found in the literature and Section 1.1 is dedicated to this issue. For the development of the test we adopt the following definition: *an inventive solution is one that is deemed inventive by relevant experts*. Based on this definition our goal can be restated as *the development of a test that can predict experts' decision on the* *inventiveness of engineering solutions* (and we have to remind the reader again that we focus only on a limited type of problems and solutions.)

A complete test for inventiveness requires that any solution passing the test is deemed inventive by experts and vice versa (i.e. that any solution that is deemed inventive by experts is ensured to pass the test). Such a test should be based on the identification of a set of *necessary and sufficient* conditions for inventiveness. Finding necessary and sufficient conditions for inventiveness seems a too ambitious goal to us. Therefore we limit our goal to developing an incomplete one-way test. A solution passing this test would be deemed inventive by experts (and this should be verified empirically), but not necessarily vice versa. In other words we are looking for a set of *sufficient conditions* for an engineering solution to be deemed inventive by experts.

Stating our goal as developing a test for the inventiveness of engineering solutions (albeit to a limited types of problems) assumes that inventiveness is a go-no-go property, which is not necessarily the case (e.g. see Arciszewski et al. who suggest a continuos measure of design creativity). This assumption is justified however by the following arguments: 1. We are interested in predicting experts' evaluation of the inventiveness, and being human classifiers, experts tend to form crisp categories such as *inventive* and *non-inventive* 2. Since we are interested only in a one-way test we can limit ourselves only to those solutions that reside in the higher end of the inventiveness scale (which is probably continuos) 3. We conjecture that truly inventive solutions (those residing in the higher end of the inventiveness scale) are in some way qualitatively different from their non-inventive counterparts, and we would like our test to capture this difference.

The ultimate goal of the test is not limited to descriptive aspects: the test should eventually *play a part in a method for inventive design*. As such it must posses some important qualities: 1. The test procedure must be teachable, therefore it should not rely on knowledge not accessible to the problem solver 2. The test should be objective: different people who were taught the test procedure should independently arrive at the same decision about a specific solution. 3. The test should be applicable (at least in part) even before the solution is attained, namely it should help to prune unpromising branches of the search tree . and finally 4. Such a test should potentially lead to development of a mathematical model and implementing it in a computer design support tool.

This brings us to the second goal of this work which is to develop a structured teachable method that guides the (human) problem-solver's search towards solutions that pass the inventiveness test (and therefore are expected to be deemed inventive by their colleagues). We will now explain the terms *method*, *structured*, and *teachable* in our context. One way to look at a problem solving *method* is as a series of prompts. (a prompt is a sign for the problem-solver to supply a defined piece of information, for example, "make a list of objects appearing in the problem".) Each prompt presents the problem solver with a subtask. Methods differ in the philosophy behind the prompts, in their number, in the interrelation among prompts, and in the way the prompts are presented (e.g. textually, diagrammatically, or graphically). A method is *structured* if the prompts can be arranged at the nodes of a directed graph in such a way that each node represent a single prompt. For a method to be teachable it is necessary that any subtask defined by a prompt be simpler than the overall task of solving the problem.

Since our method is to be used by humans it is almost obvious that variations will exist in people's ability to use the method and consequently arrive at solutions that pass our suggested test. It is therefore our third goal to identify the fundamental cognitive qualities underpinning the successful use of the method. Again the ultimate goal is not limited to the descriptive utility of the findings. The findings of this part of the research are expected to form the basis for the development of a *cognitive training program* that would mentally prepare a problem-solver for using our suggested inventive thinking method. Having defined the three main goal of this thesis we will now turn to review the creativity research in historic perspective.

The scientific study of creativity did not start before the beginning of the 20th century. Several factors were responsible for the rejection of creativity as a legitimate scientific domain before that time. One of the main obstacles was what Perkins calls the *ex-nihilo* problem [Perkins,1988, p. 362]. Ex-nihilo means the evolving of something out of nothing - which was supposedly the case with creative ideas. While science has developed tools for dealing with the transformation of one thing into another, difficulties have always been encountered in dealing with something that comes about ex-nihilo. Moreover, the creative process was commonly associated with the breaking of rules, whereas science is about capturing a domain by a set of rules. Great scientists and artists contributed to the view that creativity is not an appropriate scientific domain by describing themselves as being subject to divine intervention. The composer Mahler, for example, said “I do not compose - I am composed”. Others, such as Kekulé, the scientist who discovered the ring structure of the Benzene molecule and the poet Samuel Taylor Coleridge (Kubla Khan) reported that their ideas popped up while dreaming [Weisberg, 1993].

Another factor that impeded the study of creativity was that creative products, being man-made, suffered from the general trend to neglect what Simon calls ‘the science of the artificial’ [Simon, 1981]. Simon says: “*In view of the key role of design in professional activity, it is ironic that in this century the natural sciences have almost driven the sciences of the artificial from professional school curricula*” (Simon page 130). Simon suggests an explanation for moving away from the sciences of the artificial: in the past design had been taught in an intuitive, informal, and cookbooky manner that does not match academic respectability.

The attitude towards creativity began to change when some of the most prominent scientists started reflecting on their own creative processes and published their discoveries. Most notable was the mathematician Henry Poincaré [Poincaré, 1913] who offered a four-stage model characterizing his own discoveries. Based on Pioncaré’s and other reports the psychologist Wallas, in his classic *The Art of Thinking* [Wallas, 1926], offered a model of the creative process as a series of four definable phases: *preparation,* in which the problem solver collects and organizes problem relevant knowledge, *incubation* in which the problem is set aside and no intentional work on it is being done, *illumination* in which the solution appears as a flash of insight and finally *verification* of the solution.

Several additional factors contributed to the academic respectability of the study of creativity. The concept of sub-conscious thought helped view the phenomenon of sudden creative insight, as described, for example, by Kekulé and Coleridge, as a transfer of information from subliminal to conscious thought. It became an accepted view that creative ideas do not come into being out of nothing, but rather involve the restructuring of known elements [Perkins, 1988], rendering the ex-nihilo problem irrelevant. The general acceptance of Darwin’s theory of evolution - a theory involving the relatively simple and blind mechanisms of *random mutation* and *natural selection* - made scientists recognize that complex, highly esthetic and efficient creations can result from relatively simple rule-governed mechanisms. This helped freeing researchers from the need to resort to God as a necessary condition for the act of creation. Sciences of the artificial in general have also gained academic respectability and popularity in recent years. Design science is now considered a legitimate academic domain - journals exist, symposiums are held, and some universities have even established special departments for the study of design. In the early days creativity was studied exclusively by psychologists, but in recent time investigators from other domains such as engineering (e.g. [Kolodner and Wills 1993], [Ulrich, 1988], [Williams, 1988]) and Artificial Intelligence (e.g. [Lenat, 1978], [Simon, 1995]) have started their own research projects on creativity.

It would not do justice to the field of problem solving methods not to mention the pioneering work on structured problem solving of Polia [Polia, 1957] who offered a four-stage process for solving mathematical problems and puzzles: understanding the problem; devising a plan; carrying out the plan; and finally looking back. According to Polia "Heuristic reasoning is reasoning not regarded as final and strict but as provisional and plausible only, whose purpose is to discover the solution of the present problem". The main contribution of Polia was to demonstrate the possibility of method in areas that previously seems not amenable to methodic treatment.

The fact that creativity is now a respected scientific domain does not mean that there is general agreement about what it is and how it should be studied. Section 1.1 brings an overview of the different definitions of creativity and the varied approaches to its study. In view of the latter, Section 1.2 describes the approaches that guided this research, the questions asked, and its main modules. Section 1.3 deals with the importance of the study of creativity for engineering and Section 1.4 describes the structure of the work.

1.1. Approaches to the definition of creativity and its study

The first concern of scientific investigation is the determination and delineation of the phenomena to be investigated. Few domains have given rise to such a diverse set of conceptions about their own nature as has creativity. Concerning the definition of creativity Sternberg writes: “some have even wondered if it exists as a single entity or a class of entities aside from its name” [Sternberg, 1988, p. VII]. It is thus not surprising that almost every investigator of creativity uses his or her own definition for the purpose of research. Taylor [Taylor, 1988, page 118] counted 60 different definitions in the literature up to 1988 and it is likely that this number has since increased significantly.

The definitions offered for creativity fall into three main categories: the creative *person* - qualities, personality, way of life etc. (e.g. defining a creative person as one who can tolerate ambiguity); creative *products* - their unique features (e.g. defining a creative product as one that is qualitatively different from other products of the same type [Williams, 1990]); creative *processes* - their basic cognitive elements (e.g. the Gestalt school’s definition of the creative process as destruction of one Gestalt in favor of another [Mayer, 1995]).

In view of this great diversity, it is interesting to note that most of the definitions that are based on creative products, describe creativity in terms of two distinctive sets of features. The first set involves features that highlight the novelty of the creative product using terms such as: *novel, innovative, original, unique, surprising, interesting, unusual, and different*. The second set of features is related to the usefulness of the product and includes terms such as *efficient, true, esthetic, simple, tangible* and the like. Although novelty is an agreed upon necessary condition for products being creative, the question remains: ‘new to whom ?’. Margaret Boden [Boden, 1990] makes an important distinction between two types of novel ideas: The first, H-creative (H for historical) ideas, are new to mankind, the second P-creative (P for psychological) ideas, are new to the person in whose mind they arose, and could not have arisen before. Boden’s distinction between Historical and Psychological creativity can be likened to Kuhn’s distinction in the context of the development of science between paradigm shifts that revolutionize existing scientific theories, and normal science - the more common day-to-day evolution of science [Kuhn, 1962].

Although an agreed upon definition of creativity is lacking, any empirical study requires a working definition. An accepted method is to define a creative idea as one that is *considered creative by domain experts* [Hennessey and Amabile, 1988; Finke, 1995]. This definition is based on the assumption that people, and especially expert judges, can identify a creative idea when they see one, even when unable to supply an *a-priori* list of properties which characterize a creative idea in their domain.

The approaches to the study of creativity fall into three main categories matching those that divide the approaches for its definition. The study of the *creative person* focuses on the intellectual, motivational, personality and other determinants of the creative person. One of the goals of this approach is to develop predictive methods for a person's manifestation of creative outputs in real life. The tools used for the study of the creative person are mainly psychometric tests and biographical studies (such as Gruber study of Darwin [Gruber, 1974]). The study of *creative products* focuses on ideas, things, artifacts, or outputs of any kind, detached from their creator and the process that lead to their creation. The main goal of this approach is to develop subjective criteria, conditions and characteristics of creative products. A characteristic example of this approach is Altshuller's study of patent data [Altshuller, 1985]. The study of *creative processes* focuses on the cognitive processes that bring about creative products. The investigation of creative processes often incorporates *protocol analysis*, a method in which the investigator observes subjects occupied in a creative task, as well as *introspection* in which the investigator delves into his or her own thinking. In recent times, with the advent of Artificial Intelligence, researchers have begun to study creative processes computationally by modeling creative processes through computer programs. Some of these programs achieved considerable success: Lenat's program, Eurisco, 'invented' a new silicon gate and Simon's program Bacon rediscovered Kepler's third law of planetary motion [Boden, 1990].

Each of the three main approaches to the study of creativity can be further divided into sub-categories according to the following additional factors: *single domain*/*across domains*- the research can focus on a single domain (such as creativity in science, engineering, mathematics, arts etc.) or spread across domains; *H/P creativity* - following Boden's classification of H (historical) and P (psychological) creativity one can study great achievements of mankind such as Edison's invention of the light bulb or Einstein's relativity theory , or everyday manifestations of creativity such as the process of solving a puzzle; *descriptive/ normative* - The approach to the study of creativity can be descriptive - how people actually generate creative products, or normative - how creative products should be generated.

1.2. Our approach

This research is divided into three main parts: the first studies creative engineering *products* and suggests a set of features that characterize an important sub-set of them; in the second part a structured *process* that guides the search towards creative products is developed and evaluated; and the third, psychological, part investigates the basic cognitive processes that creative *people* draw on to solve engineering problems, and strengthens the validity of the theories presented in the former parts of the research by relating them to accepted theories of creativity.

A creative engineering product is often called an invention. Although most people associate with the term *invention* H-creative products such as the steam engine, the laser beam and the like, we focus on smaller scale P-creative inventions. Borrowing Kuhn’s terminology and applying it to the engineering domain, it can be said that this work deals with creativity within ‘normal engineering’. The reason for focusing on smaller scale P-creative inventions lies in the ultimate goal of this research - the development of methods and training procedures that enhance the creative competence of an individual or a team working on an engineering problem. We conjecture that H-creative thinking processes draw to a large extent on extra-cognitive factors such as good timing (e.g. working on a problem when the relevant basic technology had ripened); chance (e.g. working on the right problem at the right time and the right place); spirit and determination; and finally large scale social trends. When studying H-creative revolutionary inventions it is harder to make a clear distinction between these extra-cognitive factors and the thought processes that lead to the invention.

Altshuller [Altshuller, 85] proposed a classification of engineering solutions to five categories with an increasing level of novelty and inventiveness. The categories are the following: 1. *Apparent solutions* are simply selected from a class of known solutions in a given engineering domain 2. *Improved solutions* are modified solutions from a given engineering domain or are obtained as a combination of known solutions from this domain 3. *Inventions inside a paradigm* are solutions produced as combinations of known solutions from different but related domains (for example, structural and mechanical engineering) 4. *Inventions outside a paradigm* are solutions produced using knowledge from at least two much different domains (for example structural engineering and electrical engineering) 5. Discoveries are solutions based on new scientific principles (for example an x-ray machine based on the recently discovered principles of radiation). As mentioned above this work deals mainly with Altshuller's third category that deals with those type of inventions that do not revolutionize an engineering domain and yet contribute a lot to its development.

The first part of the research draws to a large extent on the pioneering work of Geinrich Altshuller[Altshuller, 1985] who was one of the first investigators of creativity to recognize the importance of P-creative engineering products as a domain for observation and research. Altshuller examined thousands of creative engineering products, mainly from the patent library, trying to extract their common underlying patterns. A careful analysis of Altshuller's findings, formulated in terms of conditions for creative engineering solutions, lead us to the conclusion that they suffer from several flaws. Following this conclusion we conducted our own survey of a large number of engineering problems and their corresponding plausible creative and routine solutions with the descriptive goal to find a concise and subjective characterization of the creative ones. This survey lead us to the formulation of clearer, more precise and more teachable conditions for creative engineering solutions. We labeled these conditions 'sufficient conditions for creative solutions', rather than the stronger 'necessary and sufficient conditions', since it turned out that these conditions are satisfied by a large and important set of creative engineering solutions but not by all of them. The hypothesis that these conditions are indeed *sufficient* is validated through an extensive empirical study and defended by relating the conditions to other theories of creativity and good design.

The second part of the research was carried out with the normative goal to develop a structured method (see above what we mean by *structured*) leading the problem solver step by step from the problem formulation to a creative solution that satisfies the sufficient conditions. It is empirically shown that the suggested procedure called SIT (for Structured Inventive Thinking) is indeed effective in assisting problem solvers to find creative (conditions-satisfying) solutions to engineering problems, but no claim is made that inventors naturally use the suggested procedure in the course of invention. The development of SIT was influenced in part by the work of Finke [Finke, 1992] who suggested an important distinction between cognitive processes in which meaning precedes structure (form follows function), and those in which meaning is extracted from an existing structure (function follows form).

In the third and last part of this research the focus shifted to the cognitive determinants of engineering creativity. Using the *meaning system,* an empirical method developed by Kreitler and Kreitler [Kreitler, 1976], and drawing on an individual's meaning assignment process to extract his or her preferred cognitive processes, the fundamental cognitive processes underpinning a successful use of the SIT method have been identified. The significance of this part of the research is twofold: Firstly, the results, showing a psychologically significant difference between successful and unsuccessful users of the SIT method, contribute to its validation as a creativity enhancement method; and secondly identifying the cognitive constituents that support the use of the SIT method can serve as the basis for the development of training procedures that will improve, by reinforcing the relevant cognitive processes, performance in using the SIT method, and creative problem solving in general.

So far we have not supplied our own definition of a creative product. Since, as mentioned above, there is an inflation of definitions, we saw no need to suggest yet another one. We follow in that matter Johnson-Laird's view that for some research projects the definition is the outcome of a research rather than its starting point: "*on the whole, a priori definitions do not advance science, but impede it. The advance of science however, enables us to frame superior a posteriori definitions*" [Johnson-Laird, 1988, p. 202]. The formulation of the sufficient conditions can indeed be viewed as at least a partial (since these are not necessary conditions) *a posteriori* definition of a creative product. But since we develop in this work a set of conditions that characterize design inventions, an accepted validation procedure is needed to convince the reader of their usefulness. For empirical validation we use the accepted working definition of a creative idea as an idea that is deemed creative by field experts, in this case engineers. To analyze the rationale underlying these conditions we show that a solution to an engineering problem satisfying these conditions can be expected to be both original and useful.

Apart from specific theories of thinking, creativity, and design this research is largely influenced by Simon's vision of the *science of design* as "*a body of intellectually tough, analytic, partly formalized, partly empirical teachable doctrine*" [Simon, 1981, p. 132]. In line with Simon's requirements our treatment of the subject of engineering creativity is *partly formalized* - the rules are stated in logical formulas, but their meaning still relies on human interpretation; *partly empirical* - in the first two parts of the research an empirical study is used to justify the results, while in the third part the relevant cognitive processes are empirically identified. Both the sufficient conditions for creative engineering solutions developed in the first part of the research, and the SIT method developed in the second part, are teachable as will become apparent in chapters 3 and 4.

1.3. The importance of the study of creativity to engineering

Engineering products are part of a rapidly changing environment: customers' needs change, the physical environment changes, and the technological knowledge accumulates rapidly. These changes bring with them both opportunities and problems arising as technological systems fail to adapt to changes. Creativity is needed to identify opportunities and solve problems in a rapidly changing environment. The arsenal of tools at the disposal of an engineer today includes mainly methods of parametric optimization and concept selection, but lacks tools that support the creation of ideas taking advantage of the unique (and sometimes new) situation at hand.

Engineers are expected to be creative, but most of them seldom are. The fact that innovative engineering products appear almost on a daily basis is due to the fact that companies employ very few highly creative engineers and inventors that 'do the thinking' while the others are occupied in routine engineering. The development of structured tools for creative engineering design will make it possible to widen the circle of those involved in the development of ideas. The development of theories and tools for creative design will also contribute to the curriculum of engineering faculties that currently draw mainly on analysis, while synthesis in general, and creative design in particular are regarded as a subject to be learnt on the job.

1.4. The organization of the dissertation

Chapter 2 presents a survey of the main theories of creativity and methods for enhancing creative thinking that have been put forward since the beginning of the 20^{th} century. The chapter is divided into two sections, one dealing with theories and methods, and the second focusing on theories related to engineering design.

Chapter 3 is dedicated to the presentation of the theory of sufficient conditions for creative engineering solutions. The chapter begins with an illustrative example of an engineering problem and its creative solution. The theory of the conditions is then unfolded through an informal discussion that helps the reader get the feel of the theory, followed by a formal presentation of the conditions. Several case studies elucidating the application of the conditions to real life engineering problems are presented next. Then, the results of an empirical study aimed at demonstrating the validity of the conditions is presented. The chapter ends with a discussion of the rationale behind the conditions and the way they are related to other theories of creativity.

Chapter 4 describes our proposed inventive design method (called SIT for Structured Inventive Thinking) method. The chapter opens with a description at a conceptual level followed by a detailed description of the method using a special description language. Then, several illustrative examples demonstrate the SIT procedure. An empirical study that proves the effectiveness of SIT is presented next. The chapter ends with a comparative analysis of SIT versus other methods.

Chapter 5 is dedicated to psychological aspects of the sufficient conditions and the SIT method. The chapter opens with a description of the main research tool, the Kreitler and Kreitler meaning system. Then the experimental study is described followed by an analysis of the results and their implication to the previous results and to the general understanding of creativity.

This works ends in Chapter 6 with conclusions and suggestions for further research. The main topics suggested for further research are related to extending the SIT method to group thinking; computerization of the SIT procedure; design from scratch, adapting SIT to other domains such as software design, management, marketing, advertising.

LITERATURE REVIEW

Chapter two

This section reviews various theories of creativity and creativity enhancement methods suggested by different investigators from fields such as Cognitive Psychology, Artificial Intelligence and Engineering Design. These theories reflect the points of view of the investigators and the domains of content they have selected: AI researchers emphasize computational aspects of creativity; psychologists describe it in more general terms, sometimes invoking such 'black boxes' as unconscious thought; and engineers focus on technological innovation. The goal of this section is twofold:

- To provide a comprehensive review of what the scientific community thinks of creativity and related cognitive processes, its testing, its possible mechanization, and how it can be enhanced.
- To lay the groundwork for a later discussion about the differences and similarities between current theories of creativity and the theory presented in this work.

This section only presents theories and methods of creativity which are critically discussed later in the thesis when relevant.

The chapter begins with Section 2.1 that describes 15 theories of creativity suggested from 1926 until today; Section 2.2 focuses on engineering design theories of creativity; Section 2.3 describes the four major creativity enhancement methods; and finally Section 1.5 summarizes this chapter.

2.1. Theories of Creative Processes and Products

2.1.1. Creativity as Analogical Thinking

Many investigators claim that analogies play an important role in the cognitive mechanisms involved in creative thinking [Holyoak and Thagard, 1995; Kreitler, 1990]. Analogies are characterized by two disparate domains - the source domain (often a well-explored domain) and the target domain (about which we use the analogy to learn something new). For example, in the analogy between the solar system and the atom's structure the solar system served as the source domain while the atom's structure as the target domain. Analogies connect the target and source domains by creating an awareness of similar aspects. Analogies can be based on the similarity between objects at the lowest level; the similarity between relations; and, on a higher order, the similarity of relations between relations. According to Holyoak and Thagard "The most creative use of analogies depends on both noticing higher-order similarities and being able to map isomorphic systems of relations" [Holyoak and Thagard, 1995, p. 34].

The use of analogies typically involves four steps: selecting a source analog by retrieving information about it from memory; mapping the source analog to the target and generating inferences about the target; evaluating and adopting these inferences to account for the differences between the target and source domains; and finally, learning something more general from the success or failure of the analogy.

2.1.2. de Bono's Theory: Creativity as Lateral Thinking

The term 'lateral thinking' was coined by de Bono [de Bono, 1969] to describe a thinking process that progresses outside habitual channels of thinking. These channels are shaped, according to de Bono, by incoming information, similar to the way water shapes land. As water shapes land, in a like manner incoming information tends to deepen the mind-channels. Like the shape of the water-land system organized only by the internal forces of that system, the mind is also a *self organizing system*. The mind-channels direct the flow of incoming information so as to associate different contents. Thinking about one thing naturally invokes thinking about another. Routine thinking occurs when one's thoughts are allowed to drift in existing channels. Creative thinking, on the other hand, occurs when thoughts are directed or when they accidentally drift laterally across channels. When this occurs, it results in what we frequently call surprising ideas. One of the tools suggested by de Bono for enhancing creative thinking is *provocation.* The role of provocation is to deflect thinking from current channel to other channels. As example for provocation de Bono suggests thinking about square 'wheels' for cars. When trying to think about possible benefits for such as design no known ‘mind-channel’ is useful, and the thinker has to explore unfamiliar grounds.

de Bono’s model of creative thinking - crossing between well-established channels - does not necessarily involve the creation of new channels, but rather finding new paths linking existing channels. Creative ideas are thus formed by connecting two or more previously known, but unconnected, pieces of content. de Bono explains this by the fact that every idea must be logical in hindsight, and therefore must be connected to the existing, well-established system of channels. de Bono uses what he calls K-lines, a simple model of mind-channels to demonstrate how a new idea or insight can emerge from an existing system of channels. Figure 2-1 shows a simple system of such K-lines. The “depth” and “strength” of a mind channel are signified by the number of parallel lines. In an intersection of lines, thoughts always flow to the direction of the stronger line. Now, consider the lines in Figure 2-1 a. Assuming that a thought entered the system at segment 1, it would then move to segment 2, from there to 3, 4, 5, 6, and finally back to 1. It will never get to the solution represented by S. If, however, due to accidental or other circumstances, a thought entered the system at point 1 in Figure 2-1 b, it would flow to segment 2, 3, and finally arrive at solution S. One strategy for creative thinking arising from this model is “try changing entry point”. de Bono suggests mechanisms of random stimulation and provocation to assist creative problem solvers in changing entry points.

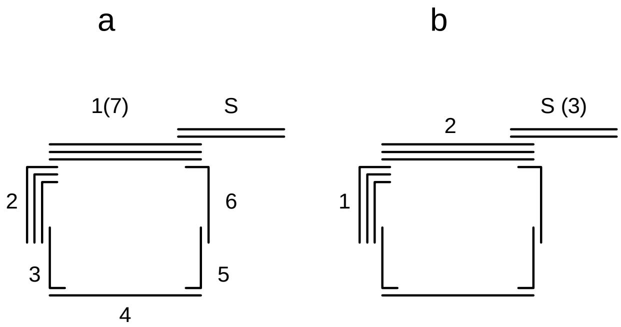

Figure 2-1. de Bono's K-lines model describing his suggestion for the mechanism of insight. In K-lines Models, the number of parallel lines represent the strength of a thought channel. The left K-lines model (a) represents a situation in which a thought entering the system at segment 1, moves to segment 2, from there to 3, 4, 5, 6, and finally back to 1, never to arrive at the solution represented by S. In the right K-lines model a thought is entering the system at a different segment (now marked 1), from there moving to Segment 2 (a stronger channel) and from there to 3 which is the solution.

2.1.3. Guilford's Theory: Creativity as Divergent Thinking

Divergent thinking is defined as the ability to produce a diversity of responses to an open-ended problem [Guilford, 1959]. The importance of the concept of divergent thinking lies in the fact that divergent thinking tests have been used in the past 30 years to asses the creative potential of individuals. The responses for these tests are evaluated in terms of four measures: *fluency* - the raw number of responses; *flexibility* - the number of different categories of responses; *originality* - the uniqueness or statistical infrequency of the responses; and *elaboration* - the richness of the content describing each item.

Guilford hypothesized that in the course of problem solving a creative individual is likely to use first *divergent thinking*, that draws on fluency, flexibility, and originality in order to "diverge" from what is known to original ideas. The individual then uses c*onvergent thinking,* the logical mode of thought, to converge on a single solution, or idea. Divergent thinking tests, although frequently used, fail to correlate with real-life creative performance [Baer, 1993]. Baer supplied the following explanation for the limited predicative power of divergent thinking tests: "It is possible that divergent thinking skill can be present but not employed at appropriate times - and there is no *a* *priori* reason that this could not be the case - than it is possible that, because students (or, for that matter adults) have not been trained to use divergent thinking in creativity-relevant situations, this skill may have little affect on their performance" (p. 17). In regard to the above idea, Baer suggests that divergent thinking may reflect *competence* rather than *performance*.

2.1.4. Mednick's Theory: Creativity as Remote Associations

The most famous associative theory of creativity is Mednick's theory outlined in his "Associative Basis of the Creative Process" [Mednick, 1962] and operationalized in the "Remote Association Test" known as the RAT. The basic elements of Mednick's theory are ideas, or other meaningful cognitive elements (in contrast to connectionist mind theories, in which basic elements typically called neurons do not carry any meaning). Association means activation of one element as a result of an activation of another.

Mednick suggests three mechanisms for associating previously unconnected elements: *serendipity* - a chance event stimulates two, previously unrelated, elements; *similarity* - the two associative elements, or the stimuli that evoked these elements, are similar; and *meditation* of common elements, typically through the use of symbols. The most important concept of Mednick's theory is *associative hierarchy*: the way an individual's associations are organized. Creative individuals will have a flat hierarchy, meaning that each element is connected to many others; less creative ones will have steep hierarchies in which each element evokes very few other elements. A flat hierarchy system better supports the invocation of more remote, original, and surprising associations. Another type of creative, associative hierarchy, according to Mednick, is a steep, but unusual, hierarchy, in which a stimulus leads to few, though highly original, responses.

Mednick developed the Remote Association Test to assess an individual's hierarchy structure. Each item in the test consists of three words such as "cookies"; "sixteen"; "heart". The task is to find another word that is related to all three (in this case the word is "sweet").

2.1.5. Koestler's Theory: Creativity as Bisociations

Bisociation, a term coined by Koestler [Koestler, 1966], is a thinking process in which one combines two habitually unrelated and incompatible matrices of thought. The term matrix refers to any skill, ability, or any pattern of activity governed by a set of rules - its code. Koestler notes that routine thinking processes operate on a single 'plane', such as when following a single set of rules or playing a single game. The bisociative, creative process, which *always* operates on more than one plane, is double minded, or involves playing simultaneously more than one game.

Koestler perceives humor as representing many of the properties of the creative act. He uses the following anecdote to elucidate his theory: The Marquis of the court of Louis XIV who, on entering his wife's boudoir and finding her in the arms of a Bishop, walked calmly to the window and went through the motions of blessing people in the street. 'What are you doing ?' cried the anguished wife. 'Monsignor is performing my functions,' replied the Marquis, 'so I'm performing his'. That this anecdote makes people laugh is due to the story's unexpected ending.

But the unexpected alone is not enough to produce a comic effect. The unexpected must be perfectly logical, within a framework of logic or set of game rules that are usually applied to a different situation, in other words, 'bisociated' logic. In this case, the two unrelated matrices of thoughts were: a. 'a husband finds his wife in bed with another man' and b. the logic of cooperative work - 'division of labor'. If the anecdote ended in the husband singing a happy song, the story would not be as amusing since a true relation between the two cases would not have been formed. .

Koestler cites a number of case studies of bisociation in science: Gutenberg who invented the printing process combined the techniques of the wine press and the seal; Kepler in discovering the form of planetary movement around the sun married physics to astronomy; Darwin connected biological evolution with the struggle to survive. Koestler claims that unconscious thinking plays an important role in the process of Bisociation. In the incubation phase (see Section 1.1.12) of a problem-solving process, combinations of thought matrices are formed on various levels of consciousness (from completely conscious to completely unconscious). This activity creates a state of receptivity, the readiness of the 'prepared mind' to pounce on a favorable chance constellation, and to profit from any casual hint. The function of the unconscious seems to be mainly to keep the problem constantly on the agenda, even while conscious attention is occupied elsewhere.

2.1.6. Newell and Simon's Theory: Creativity as Search

Newel and Simon [Newel and Simon, 72] view the cognitive system as a goal seeking system connected to the outside environment through two kinds of channels: a sensory channel through which it receives information and the and the motor channel through which it acts on the environment. The system has memory for storing both kinds of information: information on the current and past states of the environment and information of possible acts. Goals are attained by the cognitive system's ability to build associations between particular changes in in the state of the world and particular actions that that will bring these changes about.

The above assumptions about the mechanism of the cognitive systems lead Newell and Simon to develop the Means-Ends Analysis model of cognition and to the construction of the GPS computer program that simulates human problem solving based on the Means-Ends analysis model. GPS is a system that searches selectively through a possibly very large environment in order to discover and assemble sequences of actions that will lead it from a given situation to a desired situation. At any given moment GPS is always faced with a single question: "What action will I try next". When faced with a difference between the current state and the desired (End) state GPS searches for an action (Means) that removes the difference. If no such action is found, GPS searches for an action that will at decrease the difference (according to some domain-specific metrics) either from the current state to an intermediate state or from the goal state back to an intermediate state. This results in a new difference to be removed and the process continuos recursively.

2.1.7. Lenat's Theory: Creativity as Heuristic Search with criteria for interestingness

According to Lenat, heuristic search can account for many cognitive activities including creative problem-solving: "It turns out that we can model a surprising variety of cognitive activities (recognizing, problem solving, inventing) as search in which the performer is guided by a large collection of informal 'rules of thumb' which we shall call heuristics or heuristic rules".[Lenat, 1978, P. 262]. Although, according to Lenat, each heuristic has its own domain of applicability outside of which it is meaningless or useless, he claims that many heuristics are identical, or, at least similar across domains.

Lenat lists examples of possible heuristics in various domains. For the domain of *everyday invention,* for example, Lenat suggests, among others, the following rules of thumb: "Try to do something more general than what is strictly requested" (e.g. if you want to invent a new cheese cutting device, think of *cutting* in general instead of *cutting cheese*); "Consider what variables affect the success/failure of the current (inadequate) technique and look for motivation at the extreme cases of the various known relationships involving those variables" (e.g. there is relationship between the thickness of the knife and the thickness of the slice of cheese, so one may consider using an extremely thin knife which could be a thin wire); "Look carefully at what is truly wanted, maybe the problem can be bypassed or perhaps it is over-specified (e.g. maybe it is not necessary to cut cheese; one can think, instead, of a 'cheese press' that takes the crumbs and squeezes them into shapes that resemble cheese slices)".

Several computer programs use heuristic search to arrive at innovative solutions or concepts. Lenat describes, DENDRAL, a heuristics-based computer program aimed at enumerating atom-bond graphs of organic molecules developed by Feigenbaum and Buchanan [Feigenbaum, 1977]. DENDRAL produced results in its very specific field that were interesting even for experienced chemists. DENDRAL's success, Lenat argues, lies in the fact that its few dozen heuristics represent a balanced set of both highly domain-specific and more abstract domain-independent heuristics. Lenat's own program AM and its successor, Eurisco, were designed to discover interesting new (at least for the program) mathematical concepts. Both programs were guided by a set of a few hundred heuristic rules of varied generality (Euriscoalso included second-order heuristics whose manipulatory domain was other heuristics). An example of a heuristic used by AM is: 'If F is an interesting operation, then look at its inverse'.

AM began its investigation with a set of one hundred elementary concepts of set theory and discovered natural numbers, primes, and many other number-theory concepts. However, at a certain point, the program stopped producing any new interesting concepts. The explanation Lenat supplies for this behavior is that when the program arrived at more specialized fields, such as number theory, its set of heuristics was too weak to effectively guide it into more interesting concepts.

2.1.8. Perkins's Theory: Creativity as a Search in a "Klondike space"

Perkins [Perkins, 1995, 1995a] views the creative process as search through a space of possibilities to attain end-states called resolutions. Perkins metaphorically likens search in a space of possibilities to searching for gold in the Klondike, where the fundamental principle is: 'Gold is where you find it'. The most obvious heuristic for search in a Klondike space is to start at a certain point, test some points around it, and then move in the direction of the highest payoff. Such strategies are called *hill-climbing* by Artificial Intelligence researchers. Two fundamental problems are associated with hill-climbing strategies: first, they do not necessarily lead to the best solution; and second, and even more important, in searching for gold (or for a creative solution) hill-climbing leads to where everyone else is going.

Perkins identified four distinct regions of a problem space, each posing a unique difficulty to hill-climbing. It is in these regions, he argues, that creative ideas are likely to be found. The four problems are: the *rarity problem,* arising in a part of the search space in which resolutions are very rare among the possibilities in question; the *isolation problem* arises if resolutions lie in another part of the possibilities space, not accessible to the search mechanism except by changing its rules in some sense (e.g. temporarily switching to 'hill-descending' strategy); the *oasis problem* is linked to a region of the problem space where search lingers in areas close to success but not quite there (i.e. the problem of local maxima in the idioms of heuristic search); finally the *plateau problem* which arises in large regions of a search space where there is no indication of promising directions of search.

Perkins describes the different strategies inventors use to tackle the four problems. The *rarity problem* is solved through automated search, teamwork, the use of heuristics to prune large segments of the search-space and the use of heuristics to direct the problem-solver towards promising lands (e.g., combining something with its "inverse"). Another strategy for dealing with the rarity problem is to search in a (supposedly smaller) space of abstract concepts. The *isolation problem* can be solved by searching through nonviable, yet interesting, forms. But truly isolated areas of the search-space can be reached only by sheer chance, or cultivated chance (i.e., the researcher deliberately opens himself or herself to new, varied, information). The *oasis problem* can be solved by becoming aware of it, by changing the point of entry (an idea that is reminiscent of de Bono's theory of insight - Section 1.2). The *plateau problem* can be solved by systematized chance, or by trying to identify the boundaries of the plateau and simply jumping from there to other districts of the search space.

2.1.9. Hofstadter's Theory: Creativity as Variations on a Theme

Hofstadter's theory of creativity [Hofstadter, 1985] draws on a "simple but crucial" distinction between an object and a mind's concept of the object. Hofstadter metaphorically views concepts as "a metallic black box with a panel on it, containing a row of plastic knobs with little pointers on them, telling you what each one's setting is" (page 234). To make the metaphor of a 'knobbed machine' more useful for modeling concepts, the concept of 'knob' should be stretched to allow for new knobs to emerge, depending on the setting of other knobs, or even depending on other concepts currently in the active domain of concepts (no real machine has these features). The concepts, according to Hofstadter, don't come with a fixed number of knobs from the outset. An infinite number of them can spring into existence.

Using the knobbed machine metaphor, Hofstadter describes creativity as a mechanism that supports the making of variations on a theme by changing the setting of the knobs or by extending degrees of freedom through recognizing new knobs. Creativity 'enjoys' the fact that concepts have a natural tendency of "slipping" from one into another, following an unpredictable path. An example of a slippage may be someone saying "Tuesday" meaning "February", thus slipping from the concept of a *year* (divided into months) to that of a *week* (divided into days). In this accidental slippage, the unconscious mind confused the concept of year with the concept of week and the outcome cannot be considered creative. Hofstadter argues that the same mechanism of slippage, one that is nonaccidental, yet still comes non-deliberately from the unconscious mind, accounts for truly creative ideas. In his article, Hofstadter refers to Koestler's theory of bisociations saying that "this view emphasizes the coming together of *two* concepts while bypassing discussion of the internal structure of a single concept ... By contrast I have been emphasizing the internal structure of one concept" (page 251).

2.1.10. Gestalt-School's Theory: Creativity as Breaking Sets

Gestalt is defined as an overall quality of a content of consciousness that transcends its parts. In the context of engineering Gestalt can be said to be "An overall utility of a system which is different than that of its individual parts"[1]. The whole is more than the sum of its parts, and that additional quality can be transposed, which means that the same content can support different Gestalts. This feature of Gestalt is commonly exemplified by the shift in perception often occurring when viewing pictures such as the famous rabbit-duck picture or the Necker cube. Gestalt psychologists use the term *Insight* to refer to the moment the Gestalt changes. Kohler [Kohler, 1947], for example, views insight as a process occurring when the problem-solver suddenly re-organizes visual information in a way that satisfies the requirements of the goal. Perception involves building an organized structure (a Gestalt) from visual input while creative thinking involves breaking and reorganizing that structure. Duncker's view of the creative step focuses on the process of reformulating the given information or the problem solving goal so as to arrive at a more productive problem formulation [Duncker, 1945]. As an example of reformulating the given information, Duncker presents the following problem "Why are all six digit numbers of the form XYZXYZ such as 267267 divisible by 13?" To solve the problem the problem-solver must redefine the given information so as to recognize that $XYZXYZ = XYZ \times 1001$ (and 1001 is divisible by 13).

Gestalts psychologists were interested in the factors preventing problem-solvers from arriving at creative solutions. Duncker introduced the concept of *Functional Fixedness* as one of the important mechanisms leading to impasse. Functional fixedness occurs when a problem-solver thinks only of using an object for its most common and habitual use in a problem that requires a novel use of that object.

2.1.11. Boden's Theory: Creativity as Exploring and Transforming a Conceptual Space

Generative rule systems — structures such as English grammar, mathematical equations, and the like — are fundamental to Boden's theory of creativity. Each

[1] This definition is due to Thomas Arciszewski

generative system can (timelessly) describe a set of possible structures. Sometimes we want to know whether a particular structure could have been produced in principle by a certain generative system. For example, one might ask whether a certain logical formula could have been derived by a generative system composed of a set of logical axioms and derivation laws.

Margaret Boden views creative ideas as ones that *could not* have been generated before by the generative rule system. In contrast, a merely novel idea is one that can be described by the same generative system as other, familiar ideas, but for some reason had not been produced before. A truly creative idea is one that cannot be so described. According to Boden, creativity always involves tacit or explicit reference to some specific generative system. The view of creative ideas as ones that cannot be produced by a certain generative system also highlights the importance of constraints in creativity - they make creativity possible.

The creative process as exploring and transforming a *conceptual space* follows from Boden's view of the creative product. A conceptual space is the organizing principle that unifies and structures a domain of thinking, or, in other words, its generative system. Exploration of a conceptual space can tell us something about its nature, show us the limits of the space, or identify points where changes can be made. Changes of a conceptual space can be small (a "tweak") in a relatively superficial dimension of the space, or large (a "transformation") in a fundamental dimension. Boden lists some possible mechanisms for transforming a conceptual space: dropping a constraint (for example, the development of non-Euclidean geometry was made possible by dropping Euclid's fifth axiom) and negating a constraint (which is different from dropping a constraint). She also suggests some tweaking heuristics: look for numerals in the conceptual space and change their value (in such a way an artist may draw a face with three eyes).

2.1.12. Finke's Theory: Creativity as a Process of 'Function Follows Form'

Finke's [Finke et al., 1992] distinction between divergent and convergent insight reflects the classic distinction between divergent and convergent thinking. Finke's theory deals with divergent insight which is described as a process of 'function follows form'. One begins with a structure and seeks to find novel uses or novel implications for that structure. As Finke notes: “In divergent insight one tries to find meaning in the structure rather than to structure that which is meaningful”.

The structure one uses as a starting point for divergent insight is defined by Finke as ‘pre-inventive form’. To determine the factors that affect divergent insight - in particular the role of pre-inventive forms - Finke carried out a set of experiments in which pre-inventive forms were represented by a collection of 15 drawings of mostly three-dimensional geometrical shapes such as a spheres, half-spheres, cubes, cylinders, wires, tubes and wheels. At the start of each trial, three of these figures were selected at random. The subjects were instructed to use all three parts to imagine an interesting-looking object, one that might be useful in some general way, and yet which did not correspond to any specific familiar type of object. (The subjects were not asked at this point to elaborate on what might be the function of the object). The subjects were then given the name of a general object category selected randomly from a set of eight possibilities (e.g. furniture, appliances, scientific instruments). Subjects were to interpret their pre-inventive form as a practical object or device within the given category. All tasks were time constrained (1 minute for both tasks). The resulting inventions were rated by judges on a 5-point scale for their apparent originality and practicality. If the form scored highly both on practicality and originality, it was considered a *creative invention*.

The results of the experiment showed that about 16% of the trials were rated as creative inventions - a high figure indicating that forced divergent exploration enhances creative performance. Allowing subjects to choose the three objects from which the pre-inventive form was constructed or to choose the category reduced the likelihood of producing a creative invention. Even in cases where the category was presented before the three forms (and thus the preventive form was constructed with a goal in mind) reduced creativity. The results indicate, Finke argues, that divergent insight is enhanced by forcing a truly ‘function follows form process’ in which the pre-inventive form is constructed with almost no reference to its function, implication, or meaning.

2.1.13. Wallas' Theory: Creativity as a Process of Preparation, Incubation, Illumination and Elaboration

Wallas, drawing on Poincare's [Poincare, 1913] and other introspective reports formulated a theory of the creative process based on necessary stages. In Wallas's theory, the act of creation begins in the *preparation* stage where the existence of a problem, a deficiency or a need is identified; the elements involved in the situation are explored; and some ideas for solving the problem are evaluated but are found inappropriate. After completing the preparation stage, the problem-solver enters (often unintentionally) the *incubation* stage in which the problem is put aside and no conscious thought is devoted to trying to solve it. The problem solving process continues, however, on the subconscious level of the mind where many combinations are tested until one of them suddenly, in a flash of insight, crosses the boundaries to the conscious level - an event that constitutes the *illumination* stage. Since it is most likely that illumination will not bring with it the solution with all the necessary details or, very possibly, the idea may even be simply wrong, an additional stage, *elaboration*, is needed to work out the details and verify the idea.

Wallas' model of the creative process has been widely accepted in the cognitive science community [Torrance, 1988] and has motivated other researchers to suggest refined models of the events that occur during each of the four stages. Seifert et al [Seifert et al, 1995] used laboratory experiments to study the different stages. Their findings point to the role of failure in the preparation stage: "When an impasse has been reached, it must be deemed such in order that special facilitative memory traces of the impasse get properly stored" (p. 110). Their study of the incubation stage made it possible to identify three substages: *intermediate incubation* in which the problem-solver is engaged in other activities that increase the probability of incidental exposure to various external stimuli; *external exposure to new information* in which the problem-solver incidentally hits upon a piece of information that supplies the necessary cue for solving the problem; *retrieval of failure indices* in which exposure to new information triggers the access of failure indices associated with a prior problem-solving impasse.

Hadamard offered a model of the incubation stage that draws on a three-level model of the mind: the fully conscious, referring to our daily mode of thought in which we are aware of the mental steps we traverse; the unconscious level, referring to thought processes that are not available to introspection; and the fringe level, the gray area between the two extremes in which we are aware of ideas but are not focusing on them [Langley and Jones, 1988]. According to Hadmard's model, during the incubation stage the unconscious takes charge and actively evaluates alternative solutions and combinations, as if working on purpose. When one, very promising idea is found, the unconscious level transfers it to the fringe level. The mind seizes on this new idea and experiences the illumination stage. Hadmard's view is in contrast to many of the more recent theories of incubation that emphasize chance combinations in the subliminal as the mechanism of incubation [Csikszentmihalyi and Sawyer, 1995].

S*elective-forgetting,* Simon's [Simon, 1977] model for incubation effect, assumes that the incubation phase allows problem-solvers to forget inappropriate solution strategies that previously impaired the solution process. Although the four stage model has been widely accepted, doubts are still heard. For example, Perkins argues that "There is little reason to believe that incubation, in the sense of extended unconscious reasoning exists" [Perkins, 1995].

2.1.14. Creativity as a Second Order Change

The authors of the book Change [Watzlawick et al ,1979] make an interesting distinction between two types of system changes: *first order* changes in which system components are modified at the logical level of a system's framework; and *second order* changes which operate on the meta level (i.e., another, higher level system for which the current system is either a sub-component or a sub-category). Although not referring directly to creativity, the examples given in the book suggest a close link between solutions incorporating second order changes and creative solutions. A simple example (though our own, not the authors') that clarifies the difference between first order and second order changes is a case in which someone accidentally exits the elevator at the wrong floor, goes to "his office" by following the same path he is accustomed to, and than unsuccessfully tries to open what he thinks is his office (or worse, bursts into someone else's office in the middle of an important meeting). First order changes in this case include such moves as trying harder or trying another key; second order changes require viewing the situation at a meta level (the building) instead of at the current level (the corridor, or the floor). Solutions at the meta system level often seems paradoxical at the system level since conflicting requirements must be satisfied.

2.1.15. Schank's Theory: Creativity as a Mechanical Process

Schank [Schank, 1988, 1995] tries to view creativity as a computational mechanical process. Arguing that behind the creative process an algorithm must exist in principle, he tries to characterize such algorithms using a special construct called *explanation patterns* (or XPs). Schank deals with a particular kind of creativity: the creation of novel explanations. An XP is a standard explanation for an event that has been used many times before. XPs are thus a type of fossilized reasoning, a culturally shared pattern. Creative explanations can be formed by two consecutive sub-processes: a search process for candidate XPs (that are stored in memory) and a modification and adaptation of an XP in such a way as to allow an explanation originally derived from one situation to be relevant to a rather different situation.

Creativity, Schank argues, perhaps means no more than the application of technique or a rule where one would not expect to apply it. It is an *intentional misapplication* of XPs. Constructing an explanation is the essence of creativity, because explanations are predictions about how things will happen. The creative explanation starts with a failure, and ends with an explanation of why the previous explanations have failed. According to Schank, the most important part of the creative process is to notice that something is wrong. To make computers creative, they must be equipped with the ability to detect anomaly (a situation where no standard explanation is known), and then the ability to change the original situation or event, through a standard set of *explanation questions* EQs, that are asked whenever an anomaly is found. The EQs transform the current unexpected event into one that an XP in the storage, attached to a different event, would fit and serve as an explanation (an intentional misapplication) for the current event. In order to achieve this, the machine has to be supplied with a great many XPs and EQs. In addition to EQs, tweaking rules can be used to modify a situation so that a standard XP can be attached to it. Schank specifies the following rules as ones that may be used: "If a rule applies in a given situation, try reversing its actors and objects and see what happens"; or "Rather than the obvious object, change the obvious into another object that also satisfies the rule".

2.1.16. Weisberg Theory: Creativity as 'Nothing Special'

The 14 theories of creativity presented above, though different in their approach to the mechanism of creative thought, have one thing in common: they all view the creative process as one that is qualitatively different from other non-creative problem-solving processes and hence try to expose its unique features. In contrast, Weisberg [Weisberg, 1993] argues that the so-called 'creative process' is nothing but a manifestation of good problem-solving. The fact that most researchers view the creative process as a distinct phenomenon is attributed to what Weisberg calls "the myth of genius".

Creative thinking, according to Weisberg, begins with what we know, but also goes beyond the past, on the basis of new information arising from the situation. Weisberg suggests the following mechanisms as ones that underlie problem-solving processes that may seem (to the problem-solver and possibly to others) as creative processes: *near analogies* in which target analogy selection is based on salient similar cues that exist in both the target and the source domain; *associations-chain* triggered by an environmental event and resulting in an unexpected idea (unlike Mednick's theory Weisberg makes no distinctions concerning the structure of the association hierarchy); *revisions and modifications* - in contrast to some creator's reports describing their creation as conceived whole or brought forth without revision, any large scale work begins with only a glimpsing of the final product and always undergoes revisions and modifications between their initial and final form. All the above mechanisms are types of ordinary thinking used by ordinary people and great achievers alike. Individual differences in creative output, Weisberg argues, arise from domain-specific expertise, environmental support, chance, motivation, and commitment.

2.2. Engineering Design Theories of creativity

Theories of engineering creativity draw on theories of creativity in general. However, limiting the focus to engineering domains enabled researchers in engineering creativity to present their theories in less abstract, more concrete terms. Although many engineering design theorists treat creativity from the viewpoint of its computational automation, in this section we present their basic ideas about engineering creativity without going into computational issues.

2.2.1. Creative Design as Case Based Reasoning and Use of First Principles

The process of engineering design draws to a large extent on the retrieval of past designs or design principles which are then adapted to current requirements. Past designs can be stored in two different granularity levels, both of which can potentially give rise to creative designs: pieces of elaborate design solutions at a low granularity level, and first principles at a high granularity level. Using elaborate design pieces to support new design is *called case-based reasoning*. The science of case-based reasoning deals with how to re-use solutions to old problems for solving new ones, how to build and search case libraries, and how to merge and adapt cases.

According to Kolodner [Kolodner, 1993], creative design in the generative phase involves incorporating familiar design pieces, one into the other, using or modifying a well-known design piece in unusual ways. Since all the design processes mentioned above rely heavily on previous design experiences, cased-based reasoning can be one of the methods to model them.

Design from first principles is opposed to design from libraries of design fragments. According to Wiliams [Wiliams, 1990], creativity is a facility to construct non-obvious solutions which are qualitatively different from those seen before. Libraries of designs, he argues, use but do not produce innovation. They have no ability to use first principles, or to focus their application on constructing innovative devices. A way to accomplish invention is to reason from fundamental principles of physics that characterize technologies. Design from 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 [Cagan and Agogino, 1987].

2.2.2. Creative Design as Increasing Dimensionality

Cagan and Agogino [Cagan and Agogino, 1987] express a concept of creative design that is similar to Boden's view of the creative process in general: "Non-routine Design differ from routine designs in that the latter are derived from a fixed space while the former are characterized by an expanded design space" (page 95). Based on their definition of non-routine design, Cagan and Agogino suggest a computation mechanism that uses optimization information to make decisions on how to manipulate and expand the design space by introducing new variables, thus increasing its dimensionality. For example, in the course of designing an optimal beam, their program can expand the initial design space comprising two variables - dimensions of rectangular cross section - with a third variable - the beam's taper angle.

2.2.3. Altshuller's Theory: Creative Design as Overcoming Contradictions

According to Altshuller, a design is creative when it resolves a conflict but not through tradeoff or compromise [Altshuller, 1985]. Altshuller generalized his theory by observing a large number of engineering inventions and juxtaposing them with ordinary or routine solutions suggested for the same problem. Since Altshuller theory forms the basis for this research, a more detailed description in Chapter 3 describes the theory of the sufficient conditions and how they were developed from Altshuller's principle of conflict resolution.

2.2.4. Ulrich's Theory: Creative Design as Function Sharing

Function sharing in mechanical design, according to Ulrich [Ulrich, 1988], is the simultaneous implementation of several functions in an artifact, by a single structural element. Ulrich states three main reasons for the importance of function sharing in engineering design: first, designs that exhibit function sharing are in most respects better than those that do not (fewer parts, easier assembly, less required maintenance, better performance due to decreased size and weight etc.); second, awareness of the process of function sharing allows the designer to think in a modular, decomposed fashion with the option of subsequently using function sharing to make the design more efficient; third, function sharing is one of the sources of novelty or interest in mechanical design. Ulrich suggests the following procedure for function sharing: 1. a structural element is deleted from the physical description; 2. alternative features that can potentially implement the function of the deleted element are identified; 3. the identified features are modified to accentuate their desirable secondary properties.

2.3. Method for Supporting the Creative Process

This section presents four of the most popular, creativity enhancements methods used currently by corporations. The methods differ in their underlying principles, reflecting the various theoretical approaches for the creative process presented in the former sections.

2.3.1. Altshuller: TRIZ

TRIZ a Russian acronym for Theory of Inventive Problem Solving (or *TIPS* in English) was developed by Altshuller [Altshuller, 1985] and is continually being developed and modified. One of the newest versions of TRIZ is called Ideation-TRIZ and is being by Ideation International in the USA [Ideation, 1998]. TRIZ is composed of a few distinct problem-solving and problem-definition procedures and principles as well as a unifying algorithm called ARIZ. the following list describes some of TRIZ's main elements, some of them developed recently by Ideation company.

Innovation Situation Questioner(*). A list of questions the problem solver should answer about the problem at hand. The following is a sample of these questions: think about the worst possible consequences if the problem is not solved; consider appropriate typical problems; consider bypass ways to solve the problem.

Ideality Principle. One of TRIZ's most important principles. Ideality is defines as the ratio of All useful functions over harmful functions. According to Altshuller the very being of a system cases harmful effects (cost, volume, wear etc.) and therefore "the ideal system is when there is no system". TRIZ provides two main approaches for achieving close-to-ideal solutions: use of resources and use of physical, chemical, geometrical and other effects (see next for more details)

Resources. Resources in TRIZ are entities that can be obtained for free (in the broad sense of the word), and that be harnessed to perform desired functions in the system. Resources generally reside in the system itself or in its environment. Since they are there anyway one can utilize them for free.

Operators: "ready made" solutions learned from past problems. Each operator point to the way a specific problem situation can be solved. There are three type of operators in TRIZ: principles, standards, and effects. They differ in their abstraction level and in the way they are indexed.

Contradictions. TRIZ identifies two types of contradictions: technical contradiction and physical contradictions. Technical contradictions are a situation where an improvement that is made in one feature of a system directly leads to a deterioration of another. Physical contradictions are formed when there is physical attribute that needs to be high and low (at the time and location), or the attribute needs to be present and absent simultaneously. In TRIZ one has to identify first a technical contradiction and then derive from it the physical contradiction.

Contradiction table. A two dimensional look-up matrix that connects pairs of physical attributes representing physical contradictions (e.g. length and weight) to operators that are known from past experience to be capable of resolving the specific contradiction.

Principles. based on the specific type of contradiction, defined by the variables involved, that a case can potentially resolve. For example, if a problem involves a conflict between the *length of a mechanical element* and its *strength* (increasing length deteriorates the strength), the method directs the problem-solver to look at relevant principles.

Standards are more elaborated ideas based on past solutions (70 exist)

Effects. a collection of physical, chemical and geometrical effects indexed according to the functions that each effect can carry out (about 1000 are known).

Substance-Field modeling and analysis: A model of a physical problem comprising three components each can be either a field or a substance.

Engineering System Analysis. In TRIZ system analysis comprises the following steps: analysis of system's structure including system elements, subsystems and the way they are connected, system environment; determining the primary useful function of the system, and a graphical model depicting desired and harmful relations among system elements; analysis of the past, present, and future form of the system, its subsystems and super system

Anticipatory Failure Determination(*). A method for determining the root cause of a problem. The method is based on an interesting reversal of the thinking process: instead of thinking "what could have caused the problem", the problem solver is guided to think "how to create the undesired effect associated with the problem". To solve this "how to" problem (generating the undesired effect) one can use the power of TRIZ itself (e.g. look for resources to generate the [un]desired effect)

Patterns of Evolution of Systems. The identification of distinct patterns of evolution of engineering systems was based on the premise that engineering systems evolve not randomly, but according to objective patterns that can be extracted from patent literature. The following lists the main patterns discovered by Altshuller and his disciples.

1. There are distinct stages in the evolution of a system that can be depicted by an S-curve whose arcs are: childhood, growth, maturity, decline. When dealing with a system one has to determine its current evolution stage and derive from that desired ways of improving it (e.g. if a system is in the decline stage may there is no point in further improving it and its better to move to a new technology)
2. Systems evolve toward increased ideality (See above a TRIZ's definition of ideality)
3. System elements evolve in a non-uniform rate (i.e. each element evolves according to his own S-curve). This results in contradictions that halt the system's development. Their elimination allows the system to continue to improve.
4. Systems evolve toward increased Dynamism and controllability
5. System evolve in pulses of increased complexity followed by simplification
6. System evolve by matching mismatching elements (e.g. by inserting an adapter) or vice versa casing matching elements to mismatch
7. Systems evolve by replacing elements that operate on the macro level (e.g. mechanical grips) with elements the operate on the micro level or by the use of fields (using magnet).
8. Evolution toward decreased human involvement

The technique of "smart little people". Using this technique the problem solver is guided to model the (yet unknown) agent that is to be added to the system and operate there so as to reduce the undesired effects associated with the problem as a collection of smart little people. By determining their exact action, location, timing etc. the problem solver characterizes the physical object that is capable of solving the problem.

ARIZ. A Russian acronym for “Algorithm for Inventive Problem Solving”. ARIZ is a logical structured process that incrementally evolves a complex problem to a point where it is simple to use. ARIZ integrates different pieces of TRIZ by asking questions and by pointing to the relevant tool at a specific problem solving stage. ARIZ’s main steps are the following:

1. Problem analysis (based in part on TRIZ’s system analysis)

2. Describe the problem in such a way that required function is realized, undesired effects are minimized and “everything in the system remains the same”. This description of the problem is referred to in ARIZ as the “mini-problem”

3. Identify the conflict (technical contradiction) in the system in two ways: A. by trying to eliminate the harmful effect the useful function is lessened and B. by trying to improve useful action, the harmful action increases. To clarify the conflict definition intensify the conflict – make positive effects best possible, and negative effects the worse it can be. Select the conflict description with which you wish to continue the problem-solving process.

4. Determine and describe (in text and diagram) the “operation zone” and the “operation time”. The operation zone (and time) is composed of zone (period)1 – the zone of useful action, and zone (period) 2 – the zone of harmful action.

5. List all types of resources that reside in the operation zone and the operation time.

6. Define Ideal Final Result (e.g. The *resources* will eliminate the *negative effect* within *operating zone* during the *operation time*) and derive from it the physical contradiction on the macro level.

7. Try out different resources. The problem may be solved at this point.

8. Define the physical contradiction on the micro level (when resources are seen as particles)

9. Apply S-field analysis and standard solutions (if a solution not found – continue)

10. Apply one of the four general principles for overcoming physical contradictions: Separation in time, Separation in space, Separation between the

system and its components, have both physical states coexist in the same substance

11. Use the technique of “smart little people”

12. “Step Back” from Ideal Final Result (IFR): if the problem has not been solved yet, it may be necessary to compromise IFR either by slightly deteriorating the system or altering it somewhat, or disassembling it.

13. Apply scientific physical effects.

2.3.2. Osborn: Brain Storming

Brain Storming [Osborn, 1959] is perhaps the most popular and most widely used creativity enhancement method. It is a group method that divides the thinking process into two main phases: idea generation, and idea evaluation. The strict rules of brain storming prohibit any sort of evaluation within the idea generation phase. In this stage, ‘crazy’ ideas are most welcome; producing as many ideas as possible is encouraged. Brain storming is based on the premise that the participants will be inspired by their colleagues’ ideas and that quality will arise out of quantity. Although in spirit the emphasis on creative ideas is strong, in practice there is no element in the method that would direct the thinking process towards creative ideas. The scope of the method is general, any problem can be tackled.

2.3.3. Gordon: Synectics

Synectics means the joining together of different and apparently unrelated elements. According to Gordon, who developed Synectics [Gordon, 1961], problem-solvers often fail to discover a creative solution because the problem may be either too familiar or strange. Synectics uses analogies and metaphors as a means to turn the familiar into strange and the strange into familiar. Synectics, like Brain Storming, encourages suspension of judgment, and also ‘play with apparent irrelevancies’ during what is called the *excursion* stage. In the excursion stage, different analogies are used to view the problems from different directions and to direct the thoughts toward a creative solution.

Four types of analogies are used within the framework of Synectics. *Personal analogy* occurs when the individual imagines himself to be the object with which he is working; *Direct analogy* is using facts, knowledge, or technology from one domain or field in another (Gordon states that biology is one of most fruitful areas to look for ideas). The problem-solver is guided to select a close analogy when the problem is new and a remote one when the problem is known and well explored. *Symbolic analogy* uses objective and impersonal images to describe the essential paradox of the problem, as if inventing a title for it. This compressed description is used as a gateway to other problems. *Fantasy analogy* re-states the problem in terms of ideal wishes.

2.3.4. Allen: Morphological Analysis

Morphological analysis [Allen, 1962] is used mainly to invent new products rather than solve problems. Using this method, the inventor first constructs a list of the properties of an existing product and the possible set of discrete values the property can assume. For example, if the product is chocolate, the properties may be color (values: black, brown, white); length (values: 5, 10, 15 , 20 , 25 cm); and so on. In the generative stage, the user systematically searches the space of all combinations, or part of it, if it is too large, to find promising ones.

2.4. Chapter Summary

This chapter presented 15 theories of creativity, 5 theories of creative design and 4 creativity enhancement methods. It is interesting to note that the summaries presented in this chapter do not create the impression that there is much disagreement among the different theories despite the relatively large number of theories and the different terminology used by each researcher. The reason for this somewhat surprising observation is twofold. First, the theories regard creativity from different aspects and abstraction levels. The discoveries of one theorist seem to complement rather than contradict those of another; Second, due to the different, mostly ad hoc, terminology adopted by each investigator, similarities among theories are often hidden. Although not always explicitly stated, the main questions most researchers try to answer are the following:

1. What are the individual differences that are responsible for the variations in the ability to produce a creative solution?
2. What are the unique processes involved in the search for a creative solution ?

3. Why is it difficult to find a creative solution ?

4. What are the properties of a creative solution ?

Guilford and Mednick deal directly with the first question. Guilford suggests that creative individuals excel in a distinct cognitive competence he calls divergent thinking. Mednick's theory goes one step further, suggesting that creative people posses a qualitatively different memory structure, namely a flatter association hierarchy structure. The two theories are similar in many respects: both emphasize quantity (Guilford - fluency of responses; Mednick - number of associations) and cognitive distance from current content (Guilford - flexibility of responses; Mednick - remote associations).

Regarding question two, most researchers surprisingly almost unanimously agree that the novelty of a creative idea arises from a new *combination* of contents rather than *new* contents. The main differences among theories lie in the mechanisms suggested for combining two formerly unrelated pieces of content. *Analogy* combines two content domains through mapping the abstract concepts of one domain into another. Drawing analogies is an a-symmetrical operation as each of the two domains involved has a different role - one as a source analog and another as a target analog. In contrast, *Bissociation* is a symmetrical operation in which some of the content from two previously unrelated domains are part of the solution itself on a concrete, not just abstract level. Hofstadter's concept of *slippage* and Schank's concept of *intentional misapplication of an explanation pattern* are both mechanisms for combining two previously unrelated domains that can be viewed as private cases of bissociation.

Search-space is a metaphor many researchers use as a basis for presenting their ideas. Through the search-space metaphor, question two can be restated as follows: "What are the control mechanisms leading creative individuals to districts not traversed by others?". Boden's answer is that creative people do not just select different paths in the search-space, they also construct new branches of the search space that lead them to districts unexplored by others. Hofstadter's model of concept as a *knobbed machine* can also be viewed as a search space, in which knob settings play the role of the search-space branches. Hofstadter suggests that identifying new knobs, in contrast to just modifying their settings, is one of the main creative mechanisms. This idea is very similar to Boden's concept of expanding the search space. Lenat's answer to the revised question two is that creative individuals use special heuristics - rules of a thumb not used by others.

Some of the theorists try to explain why it is difficult to arrive at a creative idea, the subject of question three. The unique position of a creative idea in the search-space is the answer supplied by Perkins, who specifies four different problems an explorer of a search-space may encounter: the *rarity* problem, the *oasis* problem, the *isolation* problem, and the *plateau* problem. de Bono's answer to this question is that a creative solution lies outside the mind's established patterns. The Gestalt school introduced the concept of a mind-set or *fixedness* to explain the impasse one might encounter on the way to creative solutions. Functional fixedness, for example, can prevent an individual from identifying new unusual uses for an object which may be required for solving a problem.

Three theories deal directly with the properties of the creative solution itself (question four). Altshuller claims that a creative solution resolves a *contradiction,* in the problem situation. Watzlawick et al., introduce the concept of second order change as a characteristic feature of creative ideas. Hofstadter's theory of *variations on a theme* is the only theory to emphasize not only changes, but also constraints characterizing a creative product - the creative solution to a problem should lie within the framework of the current theme or concept.

A few theories emphasize the role of failure as a starter for the creative process. Seifert et al. used laboratory experiments to study the different stages. Their findings point to the role of failure in the preparation stage: "When an impasse has been reached, it must be deemed such in order that special facilitative memory traces of the impasse get properly stored". According to Schank, creative explanation starts with a failure and ends with an explanation why the previous explanations have failed.

In the course of presenting their theories, some researchers present a few interesting *rules of a thumb* that can be used to accelerate the search for creative solutions. Three investigators recommend mechanisms of *reversal.* Lenat suggested the following rule: "If F is an interesting operation, then look at its *inverse*". Schank states that "If a rule applies in a given situation, try reversing its actors and objects and see what happens", Perkins writes: "Try to combine something with its inverse". Boden uses the term "negating a constraint" to actually mean reversing it. Lenat and Boden refer to dropping constraint. “Look carefully at what is truly wanted, maybe the problem can be bypassed or perhaps it’s over-specified” (Lenat). “Try dropping a constraint” (Boden). Boden suggests a strategy for tweaking heuristics: “Look for numerals in the conceptual space and change their value”.

The following is a very selective set of recommendations for an individual seeking a creative solution drawn from the different theories presented in this section. These recommendations were selected on the basis of maximum resemblance to this work’s theory of creativity and will set the stage for presenting it.

> Set the problem solving goal as *overcoming a contradiction* or *second order change*, but confine your search-space to *variations on a current theme* (rather than abandoning current theme and moving to another one). This may lead you to a temporary state of *failure* which is a good starting point for the creative process. Draw on your *divergent thinking* ability and skill, mainly *fluency* and *flexibility,* to *expand the search-space.* Be aware of the possibility that the solution lies in an *isolated* area of the search space due to functional and structural *fixedness.* Use heuristics such as *reversal*, *dropping constraints*, *function-sharing*, and *changing the value of a numeral*.

SUFFICIENT CONDITIONS FOR INVENTIVE DESIGNS

Chapter three

This chapter describes the results of a research aimed at characterizing creative engineering solutions (design inventions) in terms of a set of objective, testable, and teachable features. The goal of such a characterization is twofold: theoretically it will serve as a (possibly partial) answer to the question "what is there in an engineering solution (in terms of its observable internal structure) that make relevant experts judge it as a creative one"; practically, a discovery of the common features of a possibly large (and yet only a partial) set of creative engineering solutions can develop into a computerized problem solving aid that will direct the engineer to those districts of the search space where creative solutions are likely to reside. The identification and formulation of these features were based on an extensive empirical study and on theoretical considerations drawn mainly from Altshuller theory of creative problem solving [Altshuller, 1985].

It is important to note that despite the efforts (described in the previous chapters) to define and categorize creativity, it is still an elusive and highly disputed term. Therefore it is very important, before we begin the presentation of this research, to characterize the (limited) type of problems (and the corresponding limited type of solutions) we investigate here, and also to explicate our interpretation of the term "creative" as it is used in the context of this dissertation.

Problems arise at different stages of a product's life cycle. It is generally accepted that creativity is mostly required in the initial stages [Ulrich, 88, Wiliams, 90, Gero, 89] where the number of constraints is still relatively low and many alternative design concepts can be explored. But creativity is also needed to solve problems that crop up in more advanced stages such as detailed design, process planning, production or service where an engineering system already exists. In these stages conceptual changes, though sometimes unavoidable, are generally not desirable. This research deals with such problems. Altshuller classifies the solutions to these problems as "inventions within a paradigm" [Altshuller, 1985], while Arciszewski calls them 'improved solutions' [Arciszewski, 1995]. ARIZ (TRIZ's problem solving algorithm) makes a distinction between the "mini-problem" in which one tries to solve a problem while keeping to a minimum the modifications made to the existing system, and the "maxi-problem" in which large (often conceptual) modifications are sought. The focus of this dissertation is thus the mini-problem.

In Chapter 1 we have supplied a formal definition of the term 'creative' as it applies to engineering solutions that fall into the category of 'improved solutions'. We have also justified our division of the set of possible solutions into creative and non-creative rather than viewing them as residing on a continuos creativity scale. We would like now to illustrate informally our use of the term "creative" by examining a common real-life situation. An engineer is facing a problem manifested in the presence of undesired effects associated with an exiting (or relatively detailed designed) system. The engineer would probably first retrieve from memory some straightforward solutions (e.g. "brute force" solutions such as: if a load-carrying component collapses – add material). If these solutions turn out non-satisfactory, more mental effort would probably be invested either individually by the engineer, or by a team (often in the format of brainstorming sessions). These efforts would add more solutions to the pull (commonly involving more drastic changes to the existing system). Often these efforts would lead to the conception of a satisfactory solution. In some occasions though, they would turn out futile, and an acceptable solution would still be missing. Then, commonly after some time of leaving the problem aside (what is known in cognitive psychology as 'incubation' time), someone may come up with an idea that evokes in the others the question of "how didn't I think of that before". This idea may simple, not requiring drastic changes to the existing system and also not involving pieces of expertise knowledge from outside the current domain. Also, if the same problem is presented to other engineers, only a small percentage of them (say less than 5%) would produce this idea, while when it is revealed to them, the majority would deem it creative. Ideas of this type are the focus of this dissertation.

Initially the goal was to identify a set of features that would form the basis for a classification of solutions to engineering problems (of the type described above) into creative solutions (design inventions) and non creative ones. Such a classification is equivalent to a formulation of *necessary and sufficient* conditions for creative solutions. Eventually, a complete classification scheme was not identified. Instead, it has been possible to characterize only a large portion (but not all) of creative solutions in terms of two simultaneous conditions. These conditions were thus labeled *sufficient* (and not necessary) conditions for design inventions. This means that solutions that satisfy these conditions are *assured* to be deemed creative by relevant experts (and also that only a small fraction of engineers would come up with such solutions), but not exclusively: solutions that do not satisfy them may also be deemed creative.

The chapter begins in Section 3.1 with a description of the process of the development of the conditions and their informal presentation; Section 3.2 presents a case study of an engineering problem and demonstrates how the sufficient conditions (in their yet informal form) are applied to its solution; Section 3.3 presents a formal definition of the conditions; Section 3.4 brings more examples of inventive solutions to further illustrate the previously developed principles; Section 3.5 elaborates on the rationale underlying the sufficient conditions and their relationship with other theories of creativity; Section 3.6 presents an extensive empirical study, aimed at demonstrating the relation between the sufficient conditions and creativity evaluation, the results of which indicate close correspondence between a solution being classified as satisfying the conditions and its independently being deemed creative by domain experts.

3.1. The development of the sufficient conditions for design inventions

The following process lead to the development of the sufficient conditions: first, an existing theory, Altshuller's criterion for design invention [Altshuller, 1985; Fey 1994], was selected as a starting point for the research. Then the theory was empirically investigated against observations of real world design inventions, and some discrepancies were found. An attempt to improve Altshuller's theory lead to the development of our theory of sufficient conditions for design inventions. Finally, the new theory was verified empirically. In this section we describe the process in detail.

3.1.1. Altshuller's Theory

One of the few attempts to characterize design inventions in terms of objective necessary and/or sufficient conditions was carried out by Altshuller [Altshuller, 1985]. Altshuller conducted a comprehensive study of a large body of data stored in patent collections. His main finding was that a necessary condition for design inventions is that they incorporate an 'elimination of a conflict'. Conflicts in engineering systems arise between a system parameter that should be improved to meet the requirements, and another system parameter which inadmissibly deteriorates as a result of the improvements. Consider for example the conflict in the design of an incandescent light bulb: on the one hand a requirement for efficient energy consumption dictates high filament temperatures, while on the other hand filament temperature should be kept low to ensure the bulb's long life.

Routine engineering deals with a state of conflict through trade-off - a search for the best compromise between the conflicting requirements. Designers of filaments, for example, try to identify the filament temperature that would best reflect customers' requirements. Elimination of a conflict means resolving the conflict under the condition that a compromise is unacceptable. For the filament conflict, this would mean improving both energy consumption and durability. Because Altshuller's criterion of conflict elimination is one of very few attempts for objectively characterizing inventions[2] in terms of their internal features (patent offices, for example, use an 'external' criterion based on the relation between the examined solution and other known solutions), and because it paved the way for the development of the successful TRIZ method [Fey, 1994; Sushkov 1995; Lirov, 1990] for supporting creative design, we used the idea of 'elimination of conflict' as a starting point for our research.

3.1.2. Empirical Analysis of Altshuller's Theory

To investigate Altshuller's notion of an 'elimination of conflict' as a necessary condition for design invention we prepared a list of about 200 creative and non

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[2] Another criterion based on the concept of logical distance was suggested by Arciszewski et Al

creative (at first according to our subjective standards) engineering solutions for 50 problems (See Appendix B for a sample of 20 problems and their corresponding solutions taken from the 50 we used) . Each solution was then tested against Altshuller's criterion. Our findings were that Altshuller's criterion suffers from two major drawbacks: it is not *well defined*, and it is not *sufficient* for design invention. In the following paragraphs we elaborate on these findings.

3.1.2.1. Altshuller's Criterion is not Well Defined

Elimination of a conflict means finding a way to separately satisfy two conflicting requirements. The problem is that Altshuller does not supply a definite criterion for the satisfaction of a single requirement, and therefore it is not clear when a conflict has been truly eliminated. Let us suppose, for example, that a new filament material is developed, that can operate over the same (or even longer) time period, at substantially higher temperature. How much should the temperature increase for this solution to qualify as a true elimination of the conflict? There is no definite answer to this question within Altshuller's criterion.

3.1.2.2. Altshuller's Criterion is not Sufficient

Even among those cases, where it seemed (at least intuitively) that a true elimination of a conflict did take place, some apparently non creative solutions were identified. A thorough analysis of these solutions led to the identification of their common features: all of these solutions (apparently non creative although satisfying Altshuller's criterion) involved either the replacement of a technological concept or the addition of new types of components to the original system. A representative example of a solution that incorporates an elimination of a conflict, and yet is not creative is the use of an electric engine as a solution to the problem of car induced pollution.

The conflict in this problem arises between convenience requiring an increase in the number of cars, and the need to avoid pollution requiring the restriction of their number. Equipping cars with electric engines obviously eliminates this conflict (particularly if the electric energy is manufactured in 'clean' ways). But the use of electric engines is obviously not a creative solution in the context of this problem. It is an obvious use of an alternate, well known, and basically inferior power technology. Of course many ingenious and apparently creative engineering solutions were needed for the application of electric engines in cars, but again, the application of the concept in this context is certainly not creative.

3.1.3. Improvement of Altshuller's Theory: the Sufficient Conditions for Design Inventions

Through a modification and extension of the notion of an 'elimination of a conflict' we managed to eliminate its drawbacks. The price paid was that instead of a necessary condition, we arrived at set of two (jointly) sufficient conditions that characterize a (large enough to be interesting) subset of design inventions. The following paragraphs explains these ideas in detail.

3.1.3.1. Solution for the 'Not Well Defined' Problem - The Qualitative Change (QC) Condition

To look for ways to turn 'elimination of conflict' into a well defined criterion we turned to Suh's Axiomatic Design Theory (ADT) that characterizes good design. ADT views design as a process that translates a set of *functional requirements* (represented by the vector {FR}) into a set of *design parameters* (represented by the vector {DP}) through a design matrix (represented by [A]). In terms of {FR}, {DP}, and [A], the process of design can be stated as {FR} = [A] {DP}. Suh offers two axioms that characterize good design. The first, the *Independence Axiom*, states that in a good design, the design matrix [A] should be diagonal. This means that each functional requirement is dependent on a different single design parameter, and not related to any other.

The interesting thing about the *Independence Axiom* is that it is not formulated in terms of the absolute values of either design parameters or functional requirements. Instead, it is formulated in terms of categories of *relations* among them, and therefore it is qualitative in nature. Relations between two (at least ordinal) variables, as opposed to their absolute values, can be categorized a priori independently of the specific content that they represent into three categories: direct relation, inverse relation, or no relation. This lead us to the idea of reformulating Altshuller's criterion as a qualitative change of a *relation* between two causally related parameters that contribute to the undesired effect and intensify the problem. A qualitative change means changing the category of the relation. In the incandescent light bulb for example, the filament temperature is currently inversely related to the endurance of the light bulb. The requirement for a qualitative change of relations, applied to this problem, would require that in the solution, either ‘the filament temperature will not be related to endurance of the filament’ or ‘increasing the filament temperature will result in longer life’. Note that if this requirement is fulfilled the conflict between efficiency and endurance is truly eliminated. A question may arise regarding the range in which the qualitative change should hold. The answer is simple: it should hold in the range around the working point of the independent variable (i.e. temperature in this case), even if it is an infinitesimally small range. In the filament problem, for example, the new relation (reversed, or unrelated) should hold around 1500 degrees Celsius.

3.1.3.2. Solution for the ‘Not Sufficient’ Problem - The Closed World (CW) Condition

The Qualitative Change condition suffers from the same insufficiency problem as the ‘elimination of a conflict’ condition. This problem has been solved by the formulation of a second condition, the ‘Closed World’ condition, that restricts the types of modifications that can be carried out on a technological system. The Closed World condition limits the modifications to those that do not involve the addition of new *types* of components, except for components that reside in the system’s vicinity. Applying the Closed World condition to the car pollution problem, for example, excludes the idea to replace the internal combustion engine with an electrical engine as it’s a new *type* of object. Initially the Closed World condition seems counter-intuitive: whereas creativity is supposedly about freeing oneself from restrictions, here restrictions are added. Furthermore, the Closed World condition dictates a solution that is conceptually similar to the current one, which is again in contrast to the naive view of creativity. The fact that the idea of electric engine as a solution for the pollution problem does not satisfy the Closed World condition does not mean that it is not a good solution, and in fact it certainly is. There are two main problems, however, with the electric engine that are common to many other similar solutions of alternative technologies: the idea is known and therefore the competitors use it too; there are risks and drawbacks in the implementation of a new technology (e.g. an internal combustion engine is currently by far more efficient than the electric engine). An inventive solution that satisfies the Closed World condition is expected to solve both problems: competitors would probably not produce it, and, being based on well tested technologies, it will not suffer from drawbacks and risks associated with the use of a new technology. The rationale that underlies the Closed World condition will be further elaborated in the coming sections. The closed world condition is described formally, and in detail, in section 4.

We conjectured that the two conditions - the Qualitative Change condition and the Closed World condition - form a set of jointly sufficient conditions. In the following sections this conjecture is outlined in detail and defended through illustrative examples, theoretical considerations, and an empirical study.

3.2. The antenna: a case study of a creative solution

This section presents an illustrative example of an actual problem, and some of its possible creative and non creative solutions. The example is used for two purposes: as a means for informally communicating the basic ideas that underlie the sufficient conditions, and for later reference, when the formal aspects of the theory are unfolded.

3.2.1. Description of the Problem and Possible Solutions

A company has won a bid to design and manufacture a mobile military antenna that is to be handled and operated by a single soldier. The antenna system is composed of the antenna itself and a mast that supports it in a high position. The whole system is intended to be left for a period of time in one place, until it should be transferred to another. Once the design was completed, it turned out that when ice accumulated on the antenna it became heavier, causing the mast to collapse (recall that no one is there to remove the ice). The obvious solution, to strengthen the mast through increasing its diameter, would result in a system that is too heavy for one soldier to carry. In summary, if the mast is strengthened it becomes too heavy, if it is not strengthened the antenna is bound to collapse.

'Conventional' Solutions

In one of our preliminary studies the antenna problem was presented to a group of 50 experienced mechanical engineers. The most commonly suggested solutions in the group are presented below according to decreasing frequency of response.

1. Employ composite materials, thus making the mast stronger and lighter.
2. Heat the antenna preventing ice from forming on it.
3. Coat the antenna with a non-sticking material (such as Teflon) to prevent ice formation.
4. Vibrate the mast so that the ice will shatter and fall.
5. Change the structure of the antenna, so that ice will not tend to accumulate on it.
6. Design a lighter antenna, so that the load of the antenna in addition to the ice will not exceed the load that the mast is capable of supporting.
7. Use a balloon instead of, or in addition to, the mast to support at least some of the additional load.
8. Cover the antenna with a plastic dome.
9. Add wheels to the system to help the soldier carry it (not meeting the specifications).
10. Divide the mast into parts, to enable the soldier to carry one part at a time.

A Creative Solution

The following solution was proposed by a single participant of the group, which makes it - by definition - an original solution. In our later study (see figure 3-8, problem 2 solution 1) this solution received an average score of 6.4 in a scale from 1(not creative) to 7(very creative), more than any other solution to this problem.

In this solution ice is made to accumulate not only on the antenna, but also on the mast itself. Thus, the ice itself strengthens the mast. Formation of ice on the mast is achieved by changing its surface structure, so that ice will tend to accumulate there. Note that this solution has a further advantage: when no ice is present, the mast need not be strengthened at all. When the soldier arrives at the antenna site (after the system has been left there for weeks), he simply removes the ice, by knocking at it with a hammer, before carrying the antenna and the mast away. (This solution has been tested using computer simulations, and refrigerator tests on a scale model and it was found that it can work, real life tests have not been carried out.)

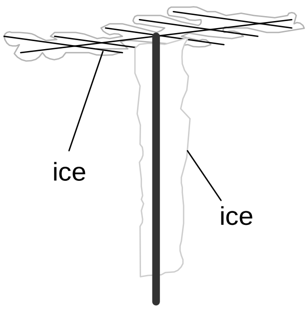

Figure 3-1. The inventive solution for the antenna problem. Ice forms both on the antenna and the on mast, thus strengthening the mast and the system as a whole.

3.2.2. The Sufficient Conditions Applied to the Antenna Problem

3.2.2.1. The Qualitative Change Condition

This problem consists of a system, the antenna-mast system, and two different undesired effects associated with it. The first is the possibility of the collapse of the mast due to ice load (if the mast is not strengthened). The second is the additional load the soldier would have to carry (if the antenna is strengthened simply by adding structural material to the mast). Among others, two relations characterize these undesired effects: the *possibility of collapse* is related to the *amount of ice on the antenna*; *the load on the soldier* is related to the *amount of structural material in the mast*. Both relations qualitatively change from *direct relation* to *no relation* in the creative solution, where it is possible to increase the effective cross-section of the mast, through accumulation of ice, without changing the weight carried by the soldier (the ice that forms on the mast will be removed before the antenna is re-deployed). Furthermore, when weather conditions become more icy, if the mast is carefully designed, the strengthening effect of the ice accumulating on the mast will outdo the burdening effect of the ice accumulating on the antenna - the more ice, the less the antenna is prone to collapse.

3.2.2.2. The Closed World Condition

The Closed World condition is expressed in the creative solution for the antenna problem in the fact that the objects playing a major role in the problem situation - the antenna, the ice and the mast - remain, and no new object is added. The only change is that ice, an object residing in the system’s vicinity and the direct cause of the problem, has a role in the solution - to strengthen the mast.

The only solution for the antenna problem appearing in the list, where both the Qualitative Change and the Closed World conditions were jointly satisfied was the creative solution. The following solutions violated the Closed World condition: in solution 2 a heating system is added; in solution 3, a non-sticking material; in solution 4, a vibration mechanism; in solution 7, the balloon; in solution 8 a plastic dome and in solution 9, the wheels. The following solutions did not incorporate a Qualitative Change: solution 1, the use of composite materials; Solution 5, changing the structure of the antenna; solution 6, a lighter antenna, solution 10, to divide the mast into parts.

3.3. Formal definition of the sufficient conditions

A formal, more precise definition of the two sufficient conditions is presented in this section. We begin with some definitions.

3.3.1. Basic Definitions

Object - an entity that is distinctive from its environment by a set of attributes (e.g. material, form, function, shape, color etc.)

Engineering System - a set of interacting physical objects that satisfy a common purpose.

System Objects – the collection of the *types* of objects comprising an engineering system

Neighborhood (environment) Objects - the collection of the *types* of objects which are not an integral part of an engineering system but reside in the system's proximity or have special affinity to that system (e.g. ice in the antenna problem). (we don't use the term *environment* only because it is now-days a reserved to refer to environmental issues such as pollution global worming et.)

Problem World (PW): the unified set of *System Objects* and *Neighboring Objects* that exist in the problem state (before the solution related modifications have been carried out)

Solution World (SW): the modified unified set of *System Objects* and *Neighboring* Objects that exist in the solution state (after the solution related modifications have been carried out)

3.3.2. The Qualitative Change (QC) condition

Any problem can be modeled as a set of undesired effects (UDEs). Any UDE is characterized by a set of related attributes that correlate directly with the intensity of that UDE. For example, in the problem of car pollution an undesired effect may be defined as “people breath unhealthy air”, problem related attributes are, among others, “number of cars per square mile”, “rate of emission of poisonous gas” and “number of people per square mile”. An increase in the value of each of these attributes represents an increase in the intensity of the above mentioned undesired effect (and hence worsening of the situation in general). Any pair comprising a UDE and an attribute that increases its intensity is called a *problem characteristic*. For example, in our car pollution problem the undesired effect “people breath unhealthy air” and the attribute “number of cars per square mile” constitute a problem characteristic. Any solution in which at least one problem characteristic changes from an increasing relation to either a decreasing or a neutral relation is said to incorporate a *qualitative change*. The Qualitative Change condition is formally presented in Expression (1) in which *r* is defined as a pair of *undesired effect* (UDE) and a related *attribute;* P is defined as the *set of all problem characteristics*.

(1) $\exists r \mid r \in P_{problem} \wedge r \notin P_{solution}$

Expression (1) reads as follows: there exists in the problem state a pair, r, which is a *problem characteristic* and that r is not anymore a *problem characteristic* in the solution state. A UDE-attribute pair can cease to be a problem characteristic only if the undesired effect becomes totally insensitive to the value of the attribute (with which it shared a problem characteristic) or if the intensity of the undesired effect becomes a decreasing function of that attribute). For example in the car pollution problem the problem characteristic involving the undesired effect “people breath unhealthy air” and the attribute *“number of cars per square mile”* ceases to be a problem characteristic if the internal combustion engine is replaced by an electric one. Note that a solution such as catalytic converter in which pollution remains proportional to the number of cars, fails to bring about a corresponding qualitative change.

3.3.3. The Closed World (CW) condition

An engineering system's Closed World is defined as the set of *types* of objects that comprise the system as well as its neighboring objects. The Closed World condition states that the Closed World of the system in the solution state should be identical to, or entailed in, the Closed World of the system in the problem state. In other words, the CW condition simply states that the solution should not incorporate any objects of new type. Expression (2) formally states the Closed World (CW) condition.

(2) $SW \subseteq PW$

Since the building blocks of CW condition are *types* of objects and not the objects themselves and also since the solution's world need not necessarily be identical to the problem's world (only entailed in it) the following modifications are allowed under the closed world condition: addition of new objects of the same type as existing ones; changing an object so long as its *type* does not change; changing the interrelations (e.g. spatial or temporal) among objects; and finally removing an object from the system.   Applying the Closed World condition to the car pollution problem constrains the solution to preserve the engine type (concept) of an *internal combustion engine*. An electric engine, for example, is a new type of object, and thus violates the CW condition. The car pollution problem exemplifies the mechanism of the conditions: the catalytic converter is excluded by the QC condition since it does not bring about a change that is radical enough in eliminating the undesired effect, while the electric engine changes the system's structure too radically, and hence excluded by the CW condition.

3.3.4. Sufficient Conditions For Inventive Solutions

We conjecture that a solution to an engineering problem (involving an *existing* engineering system that suffers from undesired effect) that satisfies simultaneously the Closed World condition and the Qualitative Change condition will necessarily be deemed 'inventive' by relevant experts. The rest of this chapter is dedicated to illustrating the application of the formal definition of the sufficient conditions to engineering problems, and to convincing the reader of their validity. This is done in three different ways: case studies from different engineering domains are presented; the rationale behind the conditions, and their relations with other theories of creativity and engineering design are discussed; and the results of an extensive empirical study aimed at demonstrating the validity of the sufficient conditions are presented

3.4. Detailed examples

This section presents six engineering problems accompanied by several ideas for possible solutions. Each solution is analyzed in terms of the sufficient conditions. The goal of this section is to demonstrate the use of the conditions as a testing procedure, and to show that those ideas that satisfy the conditions do indeed have the 'feel and flavor' of creative ideas.

3.4.1. Solid Fuel Rocket Engine

One of the problems faced by designers of air-to-air missiles was the variability of the thrust supplied by solid-fuel rocket engines during flight. The solid-fuel rocket engine had the shape of a hollow cylinder. Combustion took place in the internal envelope (see Figure 3-2). The problem with this geometry is that after ignition, as the solid fuel material in the internal envelope is consumed, the radius of the cylindrical internal space increases. This causes the internal combustion area to increase, which in turn causes the overall thrust to increase. Non constant thrust means inefficient energy consumption.

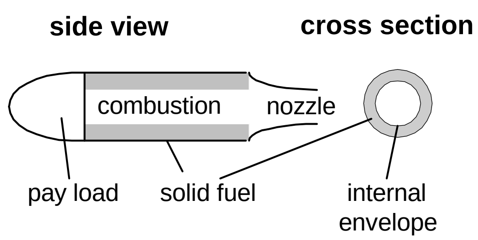

Figure 3-2. Cross-section and side view of a rocket engine

Sufficient Conditions Analysis

Problem World:

System Objects: solid fuel, the missile's body, payload

Neighborhood Objects: atmospheric air, exhausted gases

Problem Characteristic:

UDE: uneven thrust – Related Attribute: diameter difference between the beginning and the end of the flight

Solutions not Complying with the Conditions

Solution 1. Changing the geometrical dimensions of the cylinder so that it will become longer and narrower. These changes maintain the cylinder's total volume and combustion area, but leads to smaller variance due to the smaller difference between initial and final radius.

This solution satisfies the CW condition since no new type of object is. It does not, however, satisfy the QC condition since "uneven thrust" is still directly related to "diameter difference between the beginning and the end of the flight" (although to a lower extent) .

Solution 2. Employing a concept known in the community of missile designers as *cigar burning*. The solid fuel has, again, a cylindrical shape but without the hole. The combustion area is the cylinder's base. As the cylinder becomes shorter with combustion, the cylinder's cross section area remains constant during flight, and so does the combustion area, and thus, the thrust.

This solution does not satisfy the CW condition since the concept of ***fuel in solid state that contains an oxidizer and burns in its internal envelope*** has changed and therefore it is considered a new type of object. The combustion in *cigar burning* engines is not in the internal envelope. The shortcomings of *cigar burning* are that the combustion area is small, and that the solid fuel does not protect the structural elements from overheating. Of course, one has to be an expert in the field to identify and define the concept of cigar burning. A novice may not consider cigar burning a different concept. This solution does satisfy the QC condition as the combustion area is not related to the elapsed time anymore (the attribute "diameter difference" simply becomes irrelevant).

Inventive Solutions

Solution 3. The shape of the cross-section is such that it maintains a constant perimeter. The idea is that the cross-section geometry continuously changes during flight. When flight begins the cross section has a large *perimeter to average diameter* ratio due to its complex shape. Towards the end of flight the shape changes to an almost perfect circle, a form with the lowest possible *perimeter to average diameter*. Thus, although the average radius increases, the perimeter remains constant (See Figure 3-3).

This solution preserves the initial concept of a hollow shape burning in the internal envelope thus complying with the CW condition. Since the variance in thrust is constantly zero, independently of the difference between initial and final radius, the solution satisfies the QC condition as well. Note that, at its time, this solution was a breakthrough in solid fuel engines. In our workshops we see students using the sufficient conditions finding this solution quite quickly.

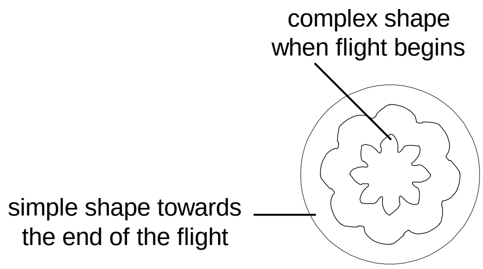

Figure 3-3. The new inner envelope changes from a complex shape to a circle as combustion progresses thus maintaining constant perimeter.

Solution 4: The chemical composition of the solid fuel changes during flight. Those parts of the fuel that burn at the beginning of the flight (small radii) are more energetic thus producing more thrust than the parts that burn at the end of the flight (large radii). In this way constant thrust is maintained.

This solution satisfies the CW condition, as the concept of internal envelope combustion remains the same (Note that changing the type of material from which an object is made is allowed under the CW so long as the object can be considered of the same type, this is not similar to changing an engine from an internal combustion engine to an electric engine because although the two objects fill the same role in the system – producing power – they do it based on a totally different concept). It satisfies the QC condition since thrust remains constant during flight. Note that this solution satisfies only the second component of the QC condition, that requiring qualitative change in the relation between thrust and elapsed time. It does not satisfy the first component requiring a change in the relation between combustion area and elapsed time. According to the definition of the QC condition it is enough to qualitatively change at least one component of the problem characteristic.

3.4.2. The Dangerous Spark

A fuel tank is provided with a device that indicates that the fuel level has reached its maximum permitted value (Figure 3-4). The device is composed of a conductive contact mounted on a float, connected with one wire to a battery. When the float reaches the top of the tank, an electric circuit is closed and an on-line indicator is activated. But, when fuel level increases and the contact approaches the tank, a spark erupts which could possibly cause the fuel vapors to explode. This problem appears in [Sushkov, 1995], but is there treated differently.

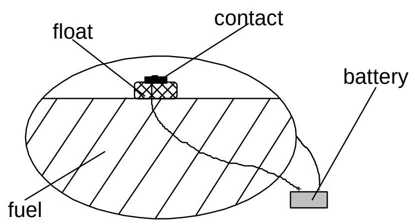

Figure 3-4. Fuel tank and measuring system

Sufficient Conditions Analysis

Problem World:

System Objects: The Signal, electric current, float, battery, container

Neighborhood Objects: fuel, spark

Problem Characteristic:

UDE: a spark erupts in the fuel tank – Related Attribute: battery voltage

Solutions not Complying with the Conditions

Solution 1. To replace the electric current by a sound/magnetic field as a means of transmitting the signal from within the container.

Since this solution replaces the concept of electric current with that of sound or magnetic waves, it does not comply with the CW condition. It does satisfy the QC condition, however, since the battery voltage ceases to be a factor of the problem (there is no battery).

Solution 2. Lower the battery voltage and use more sensitive equipment to detect the signal. This solution does not comply with the QC condition since the problem characteristic still holds - increasing the battery voltage results in an increase in spark intensity.

An Inventive Solution

Solution 3. To make the contact from piezo-resistive material. When not pressed, the material will behave as a complete non-conducting material. Only when the contact is pressed against the container walls, will it start to conduct electric current.

This solution satisfies the CW condition since no new type of object has been added. It is true that the contact is made from a different material (that has new features) but - and that is what counts – it functions as a *contact* in the very same way as before (a piece of conducting box-shaped material). This solution satisfies the QC condition as spark intensity is now not related to buttery voltage. Before the contact is pressed against the container walls, an increase in current (through increasing voltage) will not result in increased spark intensity, since a necessary condition for the emergence of a spark is that both surfaces be made of conducting materials. After the contact is pressed against the walls there would also be no spark as a necessary condition for a spark is the existence of a gap between the contact and the container walls.

3.4.3. The Flexible Rubber Pipe

A very flexible rubber pipe has to be cut accurately. The cut must be across a straight line that is perpendicular to the surface of the rubber pipe. The current technology is to cut the pipe with a very sharp knife. The problem is that since the knife distorts the pipe before it starts penetrating it, the cut is not as accurate as required (See Figure 3-5).

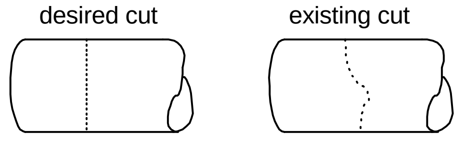

Figure 3-5. Existing and required cuts

Sufficient Conditions Analysis

Problem World:

System Objects: rubber pipe, knife

Neighborhood Objects: none

Problem Characteristic:

UDE: the cut is not accurate – Related Attribute: pipe flexibility

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Solutions not Complying with the Conditions

Solution 1. Use a hot wire to cut the rubber. The advantage of a hot wire is that penetration achieved through melting the material eliminates the need for mechanical force that distorts the rubber pipe. This solution does not satisfy, however, the CW condition since the concept that underlies the cutting tool has changed. Melting is used instead of mechanical force. The QC condition is satisfied since when melting is used the inaccuracy is not related to the flexibility of the rubber.

Solution 2. Use a laser beam to cut the pipe. As in the former solution, the CW condition is not satisfied, while the QC condition is. The arguments, too, are very similar. This is a good example for a solution that does not satisfy the conditions and is nevertheless considered by many to be inventive. The reason is that the use of laser technology (regardless of specific application) is generally viewed as creative.

Solution 3. Use a sharper, better knife to cut the rubber. This solution does satisfy the CW condition since the new knife obviously operates according to the same concept as the old one, however, the relation between flexibility of pipe and the inaccuracy of cut has not qualitatively changed. Increasing the flexibility of the pipe would still result in increased inaccuracy. Thus, the solution does not satisfy the QC condition.

An inventive solution

Solution 4. Before the cut is made the pipe is stretched until the cutting zone becomes a very thin string, so that a delicate touch with the knife suffices to cut it. The cut will be very accurate because the lines of the cut follow the lines of minimum energy. (Note: this solution is used very successfully in the factory of Kibuts Givat Brener.)

This solution complies with the CW condition, as the concept remains that of a simple knife, and no new object has been added (stretching is achieved through existing objects that were also used before). This solution also satisfies the QC condition since the more flexible the material, and the more it can be stretched, the more accurate the cut (this solution is used in practice). The relation between the inaccuracy of the cut and the flexibility of the pipe has been inverted in this case.

3.4.4. The Temperature Regulator Problem

A new device for temperature regulation was suggested. The thermostat would be composed of two materials that change color at the desired maximum and minimum temperatures. A special detector would sense the color change and start/stop the heating process at the appropriate time. In order to select the right materials, a chemical laboratory was asked to determine the precise temperature at which each material changes its color.

The lab developed a measuring process in which the material is gradually heated, while its temperature is continuously monitored . When the color changes, the temperature is noted by a simple thermometer, and recorded. When this process was first tried, a problem emerged. Due to the thermometer's time lag, the measurement was not accurate enough. The measured temperature was actually lower than the required one.

Sufficient Conditions Analysis

Problem World:

System Objects: tested material, thermometer, heater

Neighborhood Objects: all laboratory equipment

Problem Characteristic:

UDE: the measurement is inaccurate – Related Attribute: heating rate

Solutions not Complying with the Conditions

Solution 1. Decrease the heating rate of the material, reducing the thermometer's time lag. This solution satisfies the CW condition as no new types of objects have been added and no concept changed. However, it obviously does not satisfy the QC condition since the relation between heating rate and the inaccuracy associated with the thermometer lag has not been qualitatively changed.

Solution 2. To heat in steps, allowing the temperature to stabilize each time, thus performing the measurement in static conditions. This idea does not satisfy the CW condition since this process requires the introduction of a new control system. The solution also does not satisfy the QC condition since increasing heat rate would still result in reduced accuracy.

Solution 3. To use a measuring device based on a different technology, such as infra-red radiation. This solution does not satisfy the CW condition, since it eliminates the concept of the simple thermometer using a material that expands when heated. It also does not satisfy the QC condition, since any temperature measuring device would still suffer from heat-rate related time and the associated inaccuracy..

An Inventive Solution

Solution 4. Change the temperature in space rather than in time, creating a totally static measurement of the temperature at the point of color change (see Figure 3-6). The idea is implemented by spreading the color on a metal bar and heating to a constant temperature T_1 at one end, and a constant T_2 at the other end.

This solution satisfies the CW condition since the simple thermometer is still used (two heaters are needed but multiplication is allowed). It satisfies the QC condition as well, since the heating rate is totally irrelevant to the accuracy. As soon as the system reaches a stable state, the measurement can be performed using a standard thermometer .

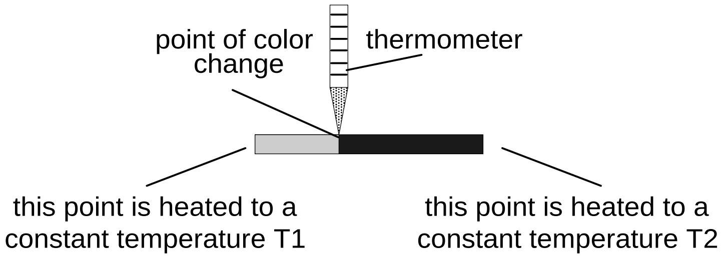

Figure 3-6. The solution to the color change problem - temperature is changed in space rather then in time

3.4.5. The Tumor Problem

This problem, originally suggested by Duncker [Duncker, 1945], was taken from [Weisberg, 1993], where it is mentioned as a problem frequently used by cognitive psychologists in their studies of creativity.

Suppose you are a doctor faced with a patient who has a malignant, inoperable tumor in his stomach. Unless the tumor is destroyed the patient will die. By directing radiation at the tumor at a sufficiently high intensity, the tumor can be destroyed. Unfortunately, at this intensity, the healthy tissue that the rays pass through on the way to the tumor will also be destroyed. At lower intensities, the rays are harmless to the healthy tissue but they will not affect the tumor.

Sufficient Conditions Analysis

Problem World:

System Objects: ray

Neighborhood Objects: tumor, healthy tissues

Problem Characteristic:

UDE: healthy tissues are damaged - Related Attribute: ray intensity

An Inventive Solution

This is a good example of a situation in which nothing but a creative solution can actually solve the problem. The solution is to direct several weak beams at the tumor from different angles, so that they converge at the tumor and develop sufficient intensity there to destroy it (see figure 3-7). Each ray by itself does not pass the threshold value of intensity that can damage healthy tissues.

This solution satisfies the CW condition, since no new type of element has been added (the division of the ray into weaker rays is permitted because each weak ray operates according to the same concept). The QC condition is satisfied since the amount of damaged healthy tissue is now not related to the ray intensity at the tumor. Ray intensity can be increased at the tumor by adding more weak rays without affecting healthy tissues through which these rays pass.

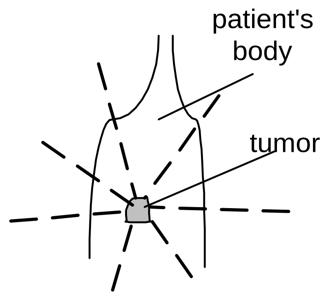

Figure 3-7. Many weak rays are directed at the tumor from different angles.

3.4.6. The Key Distribution Problem

We present the following problem to demonstrate that the principles that underlie the sufficient conditions are applicable also to non physical problem domains, in this case cryptography. It is an accepted assumption in cryptography that one cannot keep secrets for too long. Thus, the security of a system is increased by changing the cryptographic key from time to time. The problem is how to communicate the new key. Using the same channel would of course be too dangerous, in the event that the current key has been broken.

Sufficient Conditions Analysis

Problem World:

System Objects: key, message, sender, reciever

Neighborhood Objects: enemy

Problem Characteristic:

UDE: The key can be broken by the enemy - Related Attribute: the chances the key being intercepted

Note: To satisfy the QC condition the solution has to be such that even if the enemy gets hold of the key, it does not change its probability of decrypting the messages.

Solutions not Complying with the Conditions

To use a human messenger, not satisfying the CW condition

To prepare a set of keys in advance, also not satisfying the CW condition since the initial concept was that the key would be communicated when needed.

***An inventive solution - the public key* [**Diffie, 1976**]**

An asymmetric cryptographic system is used. One key (E) is used for encryption, while another key (D) is used for decryption. The system is designed so that finding D from E is computationally infeasible (e.g. requiring 10^{100} instructions). When A wants to receive messages from B he sends him just E through the existing channels. B uses E to encrypt his messages and A uses D to decrypt them. When it is time to change the key, A creates a new E/D pair and sends E to B. Even if the enemy intercepts E they cannot decrypt the messages and it does not help them to break the code.

The CW condition has been clearly fulfilled, since the key is transmitted over the existing communication line, and no new element has been introduced into the system (the new key is a new element of the same type as the existing one). The QC condition is satisfied, since knowing E has nothing to do with the security of the communication.

3.5. The rationale behind the sufficient conditions

In previous sections the theory of the sufficient conditions has been presented and demonstrated by presenting several case studies. In this section we investigate the rationale behind them. We show, by resorting to other theories of creativity and engineering design, that the sufficient conditions are in line with other criteria and conditions for originality and usefulness of a solution to an engineering problem. As mentioned in chapter 1 the combination of usefulness and originality is considered by most of creativity researchers as a necessary and sufficient condition for a creative solution. This section is divided into two sub-sections: the first ties the theory of the sufficient conditions to theories of originality, and the second to theories of good design.

3.5.1. The Relation Between The Conditions and The Originality of the Solution

3.5.1.1. Functional Fixedness

Functional Fixedness, which was described by Duncker [Duncker, 1945], has since been subject to intensive research in cognitive psychology. Functional Fixedness is a state in which the problem solver cannot conceive of uses for an object apart from its normal use. Ulrich [Ulrich, 1988] mentions Function Sharing, a design process in which an object already carrying out one function is assigned another one, as one of the processes that constitute inventive design. But to identify new functions to be assigned to an object one has to over-come functional fixedness, and few do. The CW condition, by not allowing the introduction of new objects into a system, forces the problem solver to achieve the new functionality needed for a solution using existing objects only. The problem solver is thus forced to search for a solution in areas that others would probably overlook due to functional fixedness. Thus solutions that comply with the CW condition, being rarely attained, are by definition original.

3.5.1.2. Variations on a Theme

The *Closed World* condition restricts the problem solver to variations on existing concepts rather than replacement or the addition of new, formerly non-existent elements. A support for the need for such a restricting mechanism is supplied by Hofstadter in his article 'V*ariations on a theme as the crux of creativity'* [Hofstadter, 1985]. Hofstadter suggests that creative ideas generally arise from variations on existing and known concepts. Concepts are metaphorically viewed as machines with knobs. Variations are produced by playing with the knobs, or by identifying new knobs. Hofstadter writes about this idea: "On the face of it, this thesis is crazy. Aren't variations simply derivative notions, never truly original creations?" (page 233). Through many illustrative examples Hofstadter convinces the reader that it is indeed variations on a concept, rather than 'magic leaps' that constitute a creative act. The CW condition restricts the problem solver to variations on existing concepts and objects, thus compelling him/her to look for a solution, where creative ideas are expected to be hit upon.

3.5.2. The Relation Between the Conditions and the Usefulness of the Solution

3.5.2.1. Modifications Result in Increased Expenses

The Closed World condition restricts the possible solutions to those that do involve new types of objects. Such solutions are on average expected to be more cost effective than those that require new types of objects or new technology (on condition that they indeed solve the problem). Cost effectiveness is achieved as a result of, among others, the following factors: radically modifying an existing system requires investments in production lines, maintenance procedures etc; the behavior of a radically modified system is sometimes unpredictable; the market may reject a product that seems too innovative (customers would not like to be a early adopters of a new technology). follwoing Returning to our example, the problem of car pollution can be solved by replacing the internal combustion design with an electric engine. But the result will be an inferior system in almost any respect but the pollution problem (car manufacturers will have to invest in totally new production lines, new filling stations will have to be built; cars will be slower etc.). Applying the Closed World condition to the pollution problem would restrict possible solutions to those that still use internal combustion technology.

3.5.2.2. Num Suh's Independence Axiom and Taguchi's Robust Design Principles

Suh's theory offers a set of axioms that characterizes good design. The resemblance between the first, the Independence Axiom and the QC condition was illustrated in section 2. Taguchi's *Robust Design* approach [Byrne, 1986] states that good designs are insensitive to variations and changes in the production process or in the operational conditions. Satisfying the QC condition is in line with increasing the robustness of the design. By satisfying the QC condition at least one parameter - one that previously contributed to the undesired effect - becomes totally irrelevant. As a result many related tolerances that had to be kept tight can be loosened.

3.5.3. Failing to find a solution that satisfies the conditions

Looking for a solution that satisfies the conditions should only be the first step in finding a solution. When a problem solver fails to find solutions that satisfy the conditions this may indicate that current concepts are no longer useful and new concepts should be sought. The conditions thus can be viewed both as a tool to aid finding opportunities within existing concepts, and for signaling the need for more profound changes at the conceptual level.

3.5.4. Summary

This section showed that a solution that satisfies the conditions can be expected to be both good and original. The solution is expected to be original as it lies in the search space in areas that, due to functional fixedness, are not explored by the common problem solver and because the solution cannot be generated by routine processes such as optimization. It is expected to be good as the framework of the sufficient conditions is in line with criteria for good design such as Suh's Independence Axiom and Taguchi's robust design principles, and because the solution lies on proven grounds of current technological concepts.

3.6. Empirical demonstration of the relation between the sufficient conditions and creativity evaluation

The purpose of the empirical study was to answer the following question:

> Do domain experts classify solutions that jointly satisfy the *Closed World* condition and the *Qualitative Change* condition as creative solutions?

For the purpose of this study the following definitions were used:

Domain experts	Engineers from any engineering domain (the selected problems did not contain any specialized knowledge that the average engineer is not expected to know.)
Solutions that jointly satisfy the conditions	Solutions that are classified as such by individuals that were trained to apply the criteria of the sufficient conditions to the evaluation of solutions.

Creative solutions Solutions that get a high average score on a scale from 1 (not creative) to 7 (very creative), relative to other solutions, for the same problem. The rating is done by at least 8 domain experts.

To answer the above question a set of 20 problems and their corresponding solutions was used. The solutions were generated in a preparatory study in which experienced engineers (who did not have any knowledge of the conditions) were asked to suggest creative solutions to these problems. See Appendix B for a detailed presentation of the 20 problems and the corresponding solutions. All solutions to every problem were evaluated twice in two different studies. First (in 1) each solution was rated for its average score on the creativity scale. Then (in 2) each solution was checked for its compliance with the sufficient conditions. The integrated results of these two studies can determine whether domain experts classify solutions that jointly satisfy the sufficient conditions as creative.

We used the same set of 20 engineering problems and their corresponding solutions in both studies. The problems were a randomly selected sample from a pretested collection of 50 technological problems, for each of which a solution that satisfies the conditions is known to exist.

The problems originate from different domains such as mechanical engineering, electrical engineering and civil engineering, but they were simple enough for any engineer to understand and deal with. The problems were taken from different sources such as patent literature, the industry, and the authors' own experience. We assume that the set of 50 problems is representative of the kind of problems that commonly crop up in engineering. Each set of solutions included at least one solution that satisfied the conditions as well as other solutions that are commonly offered by engineers (the solutions had been collected in numerous creative problem solving workshops conducted by the authors).[3]

3.6.1. The Creativity Study

As stated above the purpose of this study was to prepare a set of data on the average score of each solution, for each of the 20 problems, in a creativity scale from 1(not creative) to 7(very creative).

Method: Each subject was presented with a description of (only) one technological problem, selected randomly from the set of 20 problems, and a description of its possible solutions. The different solutions were presented to the subjects in random order. The subjects were asked to rate each solution for its degree of creativity (according to his or her own standards) on the 1-7 scale. Each set of solutions for a problem was rated by an average number of nearly 10 subjects.

Subjects: Subjects were experienced electrical (40 %) and mechanical (60%) engineers from various industrial firms. A total of 196 engineers, 176 men and 20 women, participated in the study. Subjects' age varied between 27 to 45 (median 34). Their work experience ranged from 4 to 20 years. These subjects were, of course, not exposed to the theory of the sufficient conditions.

3.6.2. The Conditions Study

The purpose of this study was to prepare a set of data on the classification of each solution for each of the 20 problems as satisfying or not satisfying the conditions.

Method: The study was divided into a training and an evaluation stage. In the training stage each subject was handed a 20-page booklet describing the test procedure for the sufficient conditions, and was asked to learn this procedure. In the evaluation stage each subject was presented with the set of 20 problems and their corresponding solutions. The subjects were asked to check each solution for its compliance with the *CW* condition and the *QC* condition. A solution would be considered *satisfying the conditions* if a majority of the subjects considered it to be satisfying the conditions.

Subjects: Subjects were 3 engineers selected randomly out of 20 students who study for higher degrees at Tel-Aviv University. Two of them study Industrial Engineering and one studies Physics. They were males in the age range of 25-29 years. Note that selecting 3 subjects for this experiment is not designed to extract statistical properties of any random distribution, but simply to enable cross checking of the subject's evaluation. In principle the process of evaluating a solution for its satisfaction of the conditions is a deterministic process, although some margin for error should be allowed.

3.6.3. Integrating the Results of the Two Studies

Given the results of the two studies, the final stage could be worked out by integrating the two sets of data. One set of data (which is the outcome of the creativity study) consists of average creativity scores for each solution. The second set of data (which is the outcome of the conditions study) consists of the tags 'satisfying the conditions' or 'not satisfying the conditions' for each solution.

Figure 3-8 presents the integration of the results of the two studies. The bar graphs numbered 1 to 20 represent the different problems, each bar representing - by its length - the creativity score (1-7) of one solution. The color of the bars represents the classification of the solution in the conditions study. A black bar marks a solution that was agreed to satisfy the conditions both by the authors and the subjects. Gray bars signify solutions classified by the subjects in the conditions study, although not by the authors, as satisfying the conditions. It is interesting to note that there were no solutions that were classified by the authors, but not by the subjects, as satisfying the conditions. The solutions are ordered in a descending order of creativity evaluation scores for ease of reading (although the solutions were presented to the subjects in random order). See Appendix B for a detailed report of the results of the experiment.

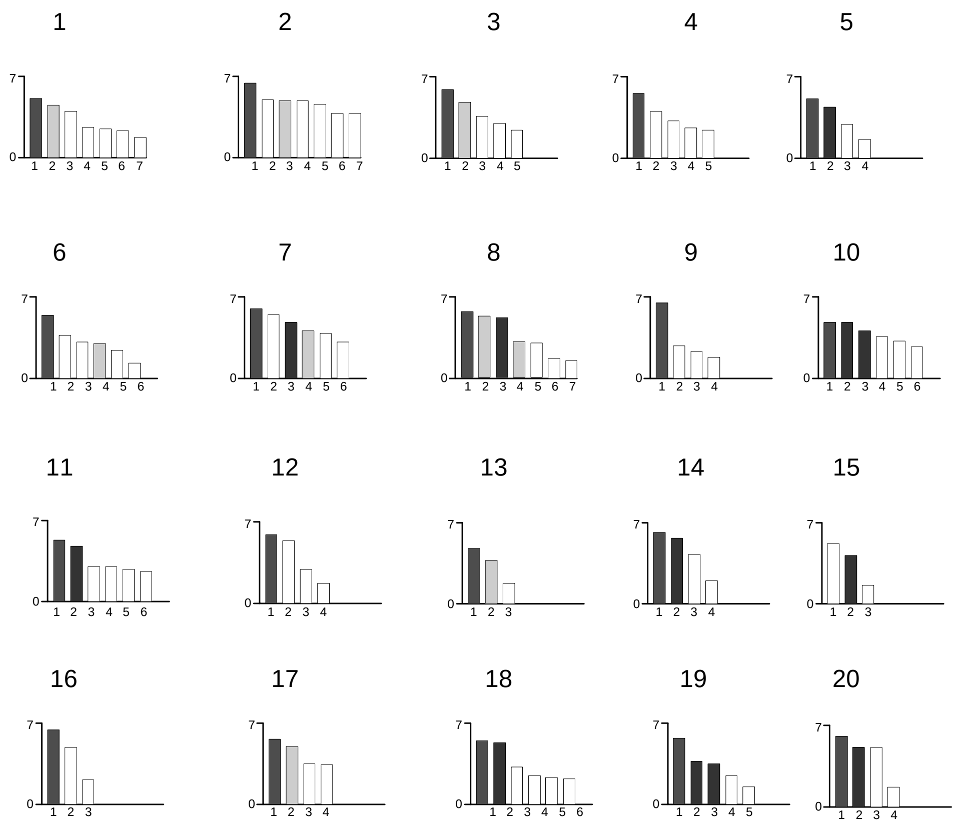

Figure 3-8. Integration of the results of the creativity study and the conditions study. Each bar graph represent a different problem; the length of each bar represents creativity scores in the creativity study (1-7). The color of the bars represents the classification of the solution in the conditions study (see appendix B for a detailed description of the problems, solutions and scores of this test).

3.6.4. Analysis of the results

Three different methods were used to analyze the data presented in Figure 3-8: direct observation of the data, computation of the point-biserial correlation coefficient, and analysis of mean differences by using a t-test. The purpose of the correlation test and the t-test was to express in quantitative terms the relation between the evaluation of creativity and the existence of the sufficient conditions for design inventions.

The t-test and the correlation test were not intended to directly support the sufficiency hypothesis. The main goal of these tests is to show that searching for conditions satisfying designs is *practically* a good strategy for finding creative designs. As demonstrated by the results of these tests, the expected creative value of a conditions-satisfying solution is higher than that of one that does not satisfy them.

3.6.4.1. Direct Observation

Scanning Figure 3-8 reveals that in all cases (except for Problem 15) a solution that satisfies the conditions received the best creativity score. In all problems except for problems 6, 8, 13 and 19, the solutions that satisfy the conditions scored higher than 4. In problems 6 , 8 and 13, however, those low rated solutions were not classified as satisfying the conditions by the authors. The results of Problem 19 and Problem 15 are thus left to be explained

Problem 19: No. 19 is the solid fuel problem that appeared as Example 1 in the examples section. The first two bars of graph 19 correspond to the two inventive solutions described in the examples section. Although the two solutions satisfy the conditions, Solution 3 is tighter in conserving the technological concepts than Solution 4. Solution 4 does not conserve the property of homogeneous fuel material. It is probably the difference in conserving the concepts, that accounts for the differences in creativity scoring among the solutions that satisfy the conditions.

Although subjects were not instructed to assign creativity scores in a relative manner, it is plausible that they did, at least partly, refer to the whole list when evaluating a single solution. One explanation for the low scores of solutions 2 and 3 is that the first solution was viewed by the subjects as exceptionally elegant and efficient, and comparing other solutions to the first, made them underestimate the others.

Problem 15: This problem concerned the dynamic sealing of two moving bodies. The highest rated solution for this problem (scoring 5.2) involved the use of a magnetic liquid (a solution which does not satisfy the *CW* condition). Magnetic liquid is a very interesting phenomenon, but its *use* for dynamic sealing is a conventional idea. Since the subjects were not experts in the field of sealing, they probably admired the invention of the magnetic liquid itself regardless of the specific problem.

The results of the conditions study were in accord with the authors' classification of the solutions in more than 90% of the cases. It is interesting to note that in most cases even when the results of the conditions study disagreed with the authors' classification, the particular solution - classified by the subjects but not by the authors as satisfying the conditions - scored relatively high in the creativity study. This demonstrates the fact that the sufficient conditions are not overly sensitive to interpretation errors. The results further demonstrate that the theory of the sufficient conditions is teachable.

3.6.4.2. Point-Biserial Correlation Coefficient

A point-biserial correlation between the dichotomic dummy variable: 0 (= not satisfying the conditions), and 1 (= satisfying them), and creativity scores was computed. A value of 0.7 was obtained. The meaning of this value is that 49% of the variance in creativity scores can be explained by whether a solution satisfies or does not satisfy the conditions. This is considered a very high score in this type of experiment (involving human judgment). It means that with just these two values (of one variable) a very high portion of the variability is cleared. Figure 3-9 presents a graph showing creativity scores in relation to the conditions.

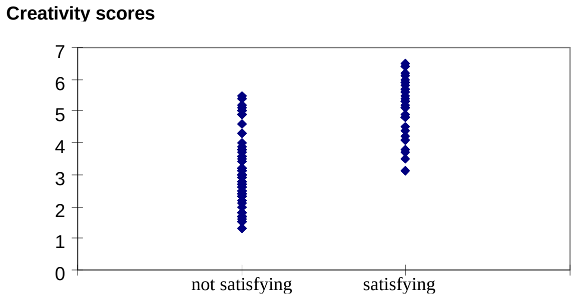

Figure 3-9. Creativity scores in relation to the conditions

3.6.4.3. t-Test

The purpose of the t-test was to show that the average creativity scores of the two sets of solutions are significantly different. In other words, to prove that the two groups represent two different populations. The results of the test showed that the null hypothesis (that the two means are the same) can be rejected with a very high confidence level: $\alpha < 0.0001$. Hence, the mean creativity scores for the solutions that satisfy the conditions differs significantly from the mean creativity scores of the solutions that do not satisfy the conditions.

3.7. Summary of Chapter 3

This chapter presented two jointly sufficient conditions, the *Closed World* condition and the *Qualitative Change* condition, for creative engineering solutions. The conditions were generated empirically through an extensive survey of many creative and non-creative engineering solutions and juxtaposing their features with Altshuller notion of *'overcoming contradiction'* as a necessary and sufficient condition for creative solutions. The result of the study showed that the notion of overcoming contradictions suffers from two main flaws: it is not sufficient, and its test procedure is not well defined. These flaws were ameliorated with the introduction of our two conditions at the price of giving up the necessity of the conditions. Although the conditions are only sufficient and not necessary for a creative engineering solution it is claimed that a large and important sub-set of creative engineering solution are characterized by satisfying these conditions. This fact was demonstrated by the presenting examples from diverse engineering domains.

An engineering solution satisfying the conditions manifests a delicate balance in its distance (in terms of the amount of modifications made on the structure of the engineering system) from the problem situation. The Closed World condition dictates a minimum number of modifications whereas the Qualitative Change condition requires that the solution exhibit a qualitatively different behavior which naturally calls for large structural modifications. The conditions determine the boundaries of a narrow gap in the solution space, overlooked by most problem solvers, in which (almost) the same structure exhibits a qualitatively different behavior. The validity of the conditions was demonstrated through an extensive empirical study in which 200 engineers (unfamiliar with the theory of the conditions) rated solutions to 20 different engineering problems on the basis of their creative merit. The results showed very good fit to the results predicted by the theory of the sufficient conditions - solutions satisfying the conditioned received high scores.

Although the sufficient conditions in their own right can be used to support the search for creative solutions - at least by limiting the search space to those areas were creative solutions are more likely to be discovered - a structured step by step method is still needed. The next chapter presents such a method, whose main components are a set of modification processes (called idea provoking techniques) characterized by the fact that they do not violate the closed world condition. Another important issue that will be dealt with in chapter 5 is the cognitive processes involved in the process of finding a creative solution that satisfies the conditions and their relation to what is known about the creative process in psychology.

THE SIT METHOD FOR CREATIVE DESIGN

Chapter four

This chapter describes SIT (Structured Inventive Thinking), a structured method designed to aid engineers to solve problems creatively. Solutions arrived at by using SIT are characterized by the fact that they satisfy the *Closed World* (CW) condition and the *Qualitative Change* (QC) condition presented in the previous chapter, where it was shown that only (but not necessarily all) creative solutions satisfy them. SIT is applicable to problems occurring in an existing engineering system suffering from known undesired effects. The method is thus most suitable for re-engineering problems, or to development projects in which most of the engineering systems' configuration has been determined.

Section 4.1 outlines the main elements of the method and the rational behind them.; Section 4.2 formally presents the method using a special syntax while in Section 4.3, examples for the application of the method elucidate the concepts presented in previous sections; Section 4.4 presents an experimental study that demonstrates SIT effectiveness in enhancing the creative competence of engineers; Section 4.5 positions SIT in the field of existing methods. Section 4.6 concludes this chapter.

4.1. The underlying principles of the SIT method

SIT was derived by analyzing a large number of solutions that satisfy the CW and QC conditions. For each solution we have examined the main modifications made to the engineering system in the transition from the problem-world to the solution-world. We have observed that these modifications fall into five main operators: *Unification, Multiplication*, *Division*, *Breaking Symmetry,* and *Object Removal.* We have reversed-engineered these archetypes and compiled each of them into a set of guidelines that direct the problem solver step-by-step in modifying his or her system according the one of the five archetypes. We call these sets of guidelines: “idea provoking operators”. The idea behind SIT is simple: the problem solver should systematically try to modify the existing system using each of the five idea provoking operators until he or she hits upon a modified system that represents a solution satisfying the conditions. This section describes the thinking behind the method . The next section (Section 4.2) presents a detailed and formal description of the method.

As mentioned above the SIT method comprises five idea provoking operators (which will be explained below). In order to apply the operators the problem solver must prepare a problem formulation that includes the QC and CW conditions. Two main stages thus make up the SIT method: *preparation* : problem formulation and analysis and *solution* : problem solving. The preparation stage comprises three sub-stages: A. The problem’s closed world is defined by identifying the types of objects that form the given engineering system and those residing in its neighborhood B. To have a better understanding of the rational underlying the system’s design, the problem solver is guided to construct a hierarchical *functional model* of the system (explained below). The functional model is required only when using the Object Removal technique (when an object is removed from the system its important to determine its exact function in the system) and is otherwise optional. C. The problem is analyzed to determine the required qualitative change .

SIT’s solution stage comprises the aforementioned five idea-provoking operators. The five operators are divided into two groups of operators: those resulting in an extension of the functionality of the system (Unification, Multiplication), and those resulting in a restructuring of the system without adding new functionality (Division, Breaking Symmetry and Object Removal). We call each these two groups “solution strategies”. The first is called “Extension strategy”, and the second ”Restructuring strategy”. See Figure 4.1 for a flowchart of the SIT method.

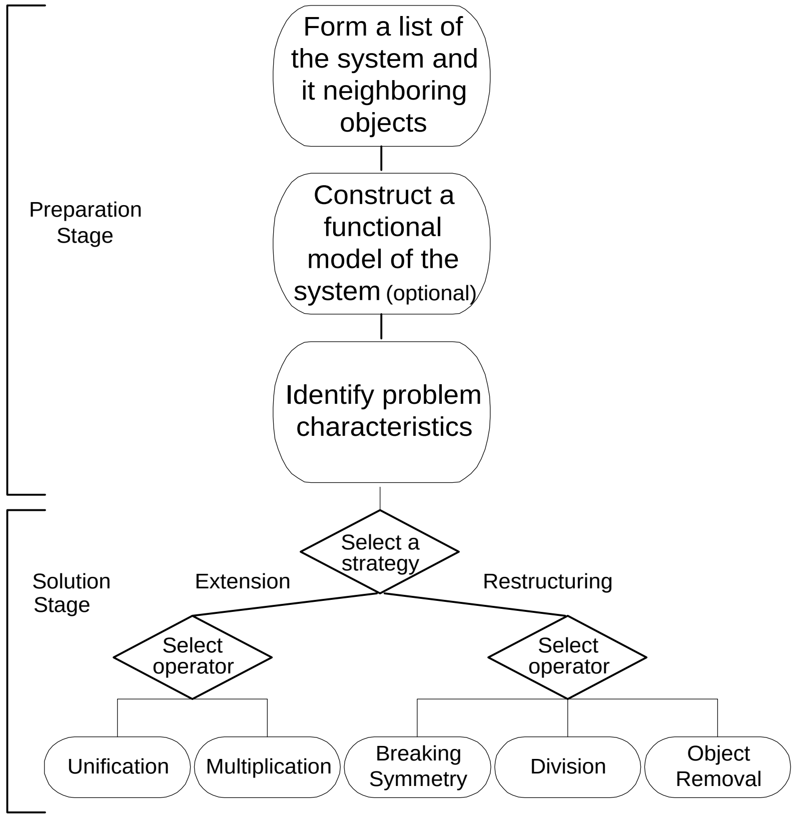

Figure 4-1. A flow chart of the SIT method

4.1.1. The Preparation Stage

In the preparation stage, the problem solver is guided to collecting and organizing information about the given *engineering system, its structure, its neighborhood* and its associated *undesired effects*. The preparation stage consists of three consecutive steps described below (The first two steps are related to the given system itself, the third to the undesired effects associated with the system).

- The problem solver determines the problem's 'world' by forming a list of *system* and *neighborhood* objects.
- The functional interrelations among system objects and their underlying technological concepts are determined through constructing a hierarchical Functional Model of the system. The functional model helps the problem solver recognize the system's design rationale in general, and how each object in the

system operates in particular. In the course of constructing a functional model, the problem solver may discover that one or more system objects are no longer necessary. Understanding the functioning of each object in the system is important in case a particular object is removed from the system and its role fulfilled by another. The functional structure is not a unique construct of the SIT method, and is used elsewhere as well (e.g. [Goel, 1997])

- Identifying as many Problem-Characteristics (see chapter 3 for definition) as possible. The problem-solving goal is determined as qualitatively changing at least one of them.

After carrying out these three steps, the problem solver is familiar with the design-rationale of the system, with its neighborhood, and with various aspects of the relevant undesired effects. Both problem-solving goal and constraints are now determined in terms of the sufficient conditions. At this point the SIT method guides the problem solver to begin searching for solutions.

4.1.2. The Solution Stage

This section explains in detail SIT's two solutions strategies: Extension and Restructuring and SIT's Five Idea Provoking operators: Unification, Multiplication, Division, Breaking Symmetry, and Object Removal.

4.1.2.1. Solution Strategies

Any engineering system can be represented as a *structure* - a collection of interrelated physical objects and their relevant attributes, that support *function* - an operation that changes attributes of physical objects (See Goel, 1997). Consequently, when an engineering system suffers from undesired effects, the problem solver may begin the problem solving process by focusing on either the function or the structure of the system. Beginning the problem-solving process with a focus on *functions*, the problem solver thinks first of a possible new function that can reduce or eliminate any of the undesired effects (bring about a qualitative change in SIT terms). Since the Closed-World condition confines the solution to only modifying (or eliminating) existing objects the new function must be later associated with an existing object (or at least an existing type of object). If the problem solver opts to begin the problem solving process in a focus on *structure*, he or she should first think of a *modification* of the *existing structure* (again, the CW condition confines them) and later verify whether that modification indeed results in a desired qualitative change. These two problem solving approaches, namely beginning with function and beginning with structure are called *solution strategies* in SIT. They are defined as follows:

1st. *Extension strategy*: first extend the functionality of the system by an addition of a new function (operation) that can bring about a desired qualitative change, then identify a closed-world object to carry out this operation

2nd. *Restructuring strategy*: first modify the system's structure, than verify whether the modified system satisfies the qualitative change condition.

The following problem exemplifies the application of the *extension strategy*. Endurance tests are being performed in a vessel, where samples are immersed in an acidic liquid at high temperature and pressure. The vessel cannot withstand the conditions and must frequently be replaced. In this problem, a natural problem characteristic is the relation between the attribute *acid concentration* and the undesired effect *damage to the vessel*. Conceiving an operation that qualitatively changes this relation is fairly straightforward: *to separate the acid from the vessel* (so that there is no contact between the two). This operation extends current system's functionality. Problem solving proceeds now to the selection of a closed world object that will serve as the agent carrying out the operation. For example, the object that will carry out the required operation (to separate the acid from the vessel) can be the sample itself. The required modification of that object is that the geometry of the samples will change to that of small containers in which the acid will be placed.

The following problem exemplifies the application of the *restructuring strategy*. A special type of reinforced concrete beam requires pre-stretched steel bars. The bars are stretched by an electric current that flows through the bars and heats them up. The heat expands the bars which are then fixed, so that their length is forced to remain constant. When they cool off, they are in the required state of tension (See Figure 4-2). A problem arose when a new type of rod appeared. The high temperature of the process dangerously weakened the mechanical properties of these new bars. A close look at this problem reveals that it is impossible to conceive an operation that will break or invert the relation between the natural problem characteristic - *damage to the metal rod* and the *temperature of the rod*. Separating the rod from the heat source, for example, will halt the system's operation. A possible solution to that problem is to fix two bars (old and new) together in a row. The old rod is heated (using the same technology - electric current flowing through the rod), until the two connected bars become long enough. Then their end points are fixed. When the old rod is cooled, it stretches the new one. This solution restructures the system without extending its functionality. A new degree of design freedom is achieved by dividing the rod into a section that is heated and a section that remains cool. It is interesting to note that the restructuring strategy gives rise to a reversed thinking process, in which the structure of the solution is determined prior to understanding its meaning (or function). This reversed thinking process is defined by Finke [Finke, 1992] as a cognitive process of *function follows form (FFF).* As mentioned in Chapter 2, a series of experiments Finke conducted have shown that when people follow this process they produce more creative results. The second strategy then, forces the problem solver into an FFF thinking process

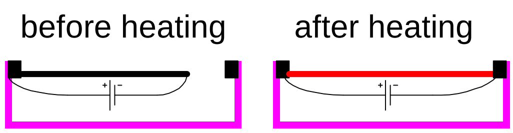

Figure 4-2. The stretching system

4.1.2.2. Idea Provoking Operators

As mentioned SIT’s five idea provoking operators were extracted from numerous exemplars of inventive solutions that satisfy the conditions. The five operators are divided into two groups: Unification and Multiplication belong to the *Extension* strategy – when using them, the problem solver is guided first to conceive an operation that can bring about a qualitative change (by satisfying the QC condition) and later to associate that operation with a closed world object; Division, Breaking Symmetry, and Object Removal belong to the *Restructuring* strategy – following the guidelines of these operators, the problem solver first modifies the existing system (each of the three operators suggest distinct types of modifications) and later verifies whether the modified system satisfies the QC condition (note that the closed world condition is ‘built in’ all of the operators and therefore its satisfaction need not be verified). We will now describe each of the five operators.

Unification directs the problem solver to finding an *existing* system or neighborhood object to carry out the required operation. The object may be modified to adapt to the additional/new task, but must remain of the same type to satisfy the closed world condition. An example may be the following problem: A company develops materials that should withstand extremely harsh environmental conditions. Endurance tests are performed in an oven, where samples (cube-shaped pieces of solid material) are immersed in an acid tank, at high temperature. The problem is that the acid tank, being exposed to the acid at high temperature, does not withstand the conditions and has to be discarded after each test. Using unification the problem solver first identifies the operation “to separate the tank from the acid” and then assigns the operation to the object “samples”. The solution that emerges from this unification of the required operation with an existing object is to drill a hole in the samples, pour the acid into the hole and put the samples in the oven (the tank becomes redundant now).

Multiplication directs the problem solver to search for a new, slightly modified version, of an existing system or neighborhood object to carry out the required operation. (Note that adding new instances of existing types of objects is allowed under the closed world condition). The solution to the following problem is a good example of Multiplication: In a certain area there is a vas number of flies that damage the corps. The operation is “to reduce the number of flies”. A new object of the same type as an existing one is to be added to carry out this operation. This problem was solved by adding sterile flies and by taking advantage of the fact that the feminine of this specific type of fly can mate only once in her life time.

Division directs the problem solver to select one of the objects that belong to the problem’s world, break it down into its parts, and then reorganize the parts in space or in time. For example, consider a tall mast that carries a great number of light projectors. Maintenance cost is very high, since replacing light bulbs requires access to the tall mast. By using the division technique, we may first select the projector as the object for which division is applied. The projector is divided into its two basic components: a light bulb and a reflector. We now have to think of a new organization of the parts (e.g. a new location for each part). A possible idea is the following:the reflectors stay on the mast, and the light source is relocated on the ground. The idea is that there will be a big reflector on the mast and small projectors will be directed at that reflector from the ground. Since the light bulbs are on the ground, the height of the mast will not affect maintenance cost.

Breaking Symmetry directs the problem solver to search for current symmetries (symmetries - in general, not limited to geometry or shape) and to try to recognize new states by breaking them. A symmetry is defined as a pair of unrelated variables (e.g. a circle is symmetrical in terms of *angle* – first attribute, and distance from its center to its circumference – second attribute). Breaking symmetry thus means connecting two hitherto unrelated attributes. For example, a car engine has constant volume in relation to time (it is symmetrical in relation to time). If we let the first attribute to be *engine's volume* and the second to be *time* (now unrelated), we may arrive at the idea of an engine that changes its volume in time, as a function of load, for example. Practically, the change of volume can be achieved through changing the number of operating cylinders.

Object Removal directs the problem solver to remove an object from the system and then search for alternative (*Closed World*) objects to assume the function of the removed object (if necessary), or to restructure the system so that the operation, carried out by the removed object, will not be needed any more. The search for an alternative closed world object is performed with the direction of either *Unification* or *Multiplication*, whereas restructuring the system is conceived with the direction of *Division* or *Breaking Symmetry* (and even by *Object Removal* once again).

4.2. The SIT Method in detail

This section presents the SIT Method in detail. The structured nature of SIT makes it possible to formally present the method using a special syntax, a pseudo- code, describing SIT as an interactive computer program. The rationale underlying such a presentation of SIT is to enable the tailoring of the compositional power of natural language (the fact that the meaning of a sentence is constructed from the meaning of its parts, e.g. the verb phrase and the noun phrase) to the SIT method. The idea is that the SIT method will guide the problem solver to compose meaningful sentences that express information - initially about the problem's world (in the preparation stage) and later about a partial solution concept (in the solution stage). Each sentence is composed of pieces of text supplied by the method, combined with text about the problem supplied by the problem solver. We use a special syntax to present SIT as an interactive computer program that collects information from the problem solver and composes the relevant sentences. This syntax is expected to form the basis for a computerization the SIT method.

We begin with a presentation of the symbols that comprise the syntax used for presenting SIT, followed by a description of the method itself. This section is best understood by referring to the next section, in which the syntax described in this section is used to present examples for using the SIT method.

4.2.1. The Special Syntax Used for the Description of the SIT Method

<table>
<tr><td>[text]</td><td>Prompts for free text information entered by the user.</td></tr>
<tr><td>[list, ,]</td><td>Prompts for a list entered by the user containing N entries</td></tr>
<tr><td>{option1| option2| ...}$_{\text{option}}$</td><td>prompts for user selection from fixed system options The selection is stored in “option”.</td></tr>
<tr><td>< list>$_{\text{option}}$</td><td>Prompts the user to select from list entries previously entered. The selection is stored in “option.”</td></tr>
<tr><td>^information^</td><td>Information (user selection or input) copied by the system from one module to another</td></tr>
<tr><td>label</td><td>Address mark</td></tr>
<tr><td>@X</td><td>The information to the left of this sign should be stored in variable X.</td></tr>
<tr><td>|</td><td>Separator for alternatives (exclusive OR)</td></tr>
<tr><td>→label</td><td>Go to the address of label</td></tr>
<tr><td>Bold text/Regular text</td><td>Each SIT element is composed of a dynamic part that can change and a static part that never changes. The dynamic part is presented in bold letters and the static part in regular text</td></tr>
</table>

4.2.2. The SIT method Presented as An Interactive Computer Program

We now use the notation described below to present SIT in pseudo-code as an interactive computer program.

A. Preparation Stage

system objects list

[**system object list, ,**]

Neighborhood Objects List

[**neighborhood object list, ,**]

Functional Structure

[<**system object list & neighborhood object list** >@**acceptors** needs < **system object list & neighborhood object list** >@**actors** to directly perform on it a desired operation: [**operation**]@**operations** which is carried out according to the concept: [**concept**]@**concepts**. This is {**the primary|not the primary**} function of the ^**current object1**^ in the system, ,]

Problem Characteristics

[undesired effects list, ,]

[Increasing the value of the attribute[**Parameter**]@**causes** increases the level of the undesired effect< undesired effects list>@efects, ,]

B. Solution stage

Strategy Selection

{→**extension** | →**restructuring**}

Extension

Conceptual Solution

[The relation **<problem characteristics list>@prob_char** will change from an increasing relation to {**decreasing** | **unchanging**}, if the following operation: [**simple operation**]@**SimpleOperation** is performed, ,].

Extension technique selection

{→**unification** | →**multiplication**}

Restructuring technique selection

{→**division** | →**breaking symmetry** | →**removing an object**}

Extension Operators:

Unification

The object <**system object list & neighborhood object list**>@**SelectedObject** will carry out the operation ^S**impleOperation**^. To do this, the object must be modified in the following way: [**how the object will be modified**].

Multiplication

New object(s) of the same type as <**system object list & neighborhood object list**>@**SelectedObject** will be added to the system. The new object(s) will carry out the operation ^**simple operation**^. To do this, the new object(s) must be different from the original ^**SelectedObject**^ in the following way: [**In what way the new object(s) are different from the original one**].

Restructuring Operators:

Division

The object <**system object list & neighborhood object list**> will be divided into {**its basic parts** | **smaller elements of the same type** | **randomly**}. A new degree of freedom will be achieved by locating each part in a {**different place** | **different orientation** | [**other difference**]}

Breaking Symmetry

Select an object < **system object list & neighborhood object list>**@**SelectedObject** Form a list of important object parameters [**list of parameters of that object**].

The object ^**SelectedObject^** will be modified so that the object's parameter < **list of parameters**> which is currently unrelated to the objects parameter < **list of parameters**> will be related to it in the following way: {**increasing function** | **decreasing function** | [**other**]}

Object Removal

The object <**Object1s**>@**RemovedObject** will be removed from the system. Its operation ^**the operation of the removed object**^ targeted at the object ^ **the target object of the removed object**^ {→**will be carried out by another closed world object** |→**will not be carried out any more, and to compensate, the system will be restructured**}

Will be carried out by another closed world object

The closed world object that will carry out the removed object's function will {**continue**|**not continue**}@Choice to apply the concept: ^**concept of the removed object**^

Idea provoking technique selection

{→**unification (object removal)** | →**multiplication (object removal)** }

Will not be carried out any more, and to compensate, the system will be restructured

{→**division (object removal)** |→ **breaking symmetry (object removal)** }

Unification (Object Removal)

The operation, ^**operation of the removed object**^ targeted at the object ^**target of the removed object**^ , that was carried out by the removed object, ^**removed object**^, will now be carried out by the object <**system object list & neighborhood object list**>@**SelectedObject**. The new object will {**continue**|**not continue**} to operate according to the concept, ^**the concept of the removed object**^. To do this, the object ^ **SelectedObject**^ must be modified in the following way: [**how the object will be modified**].

Multiplication (Object Removal)

The operation, ^**operation of the removed object**^ targeted at the object ^**target of the removed object**^, that was carried out by the removed object, ^**removed object**^, will now be carried out by new object(s) of the same type as <**system object list & neighborhood object list**>@**SelectedObject** that will be added to the system. The new object will {**continue** | **not continue**} to operate according to the concept: ^**the concept of the removed object**^. To do this the new object(s) must be different from the original ^ SelectedObject^ in the following way [**In what way the new object(s) are different from the original one**].

Division (Object Removal)

The object ^**removed object**^ will be removed from the system. Its operation ^**operation of the removed object**^ targeted at the object ^**target of the removed object**^ will not be carried out any more, and to compensate, the system will be restructured in the following way: the object <**system object list & neighborhood object list**> will be divided { **into its basic parts** | **into smaller elements of the same type** | **randomly**}. A new degree of freedom will be achieved by making each object different in {**location** | **orientation** | **property** [**other**]}

breaking symmetry (Object Removal)

Select an object < **system object list & neighborhood object list>@SelectedObject**
Form a list important object parameters [**list of parameters**]$_{\text{Nparameters}}$.

The object ^**removed object**^ will be removed from the system. Its operation ^**operation of the removed object**^ targeted at the object ^**target of the removed object**^ will not be carried out any more, and to compensate, the system will be restructured in the following way: The object ^S**electedObject^** will be modified so that the object's parameter < **list of parameters**> which is currently unrelated to the objects parameter < **list of parameters**> will be related to it in the following way: {**increasing function** | **decreasing function** | [**other**]}

4.3. Examples for using SIT to find creative engineering solutions

This section presents seven examples for using the SIT mechanism to creatively solve engineering problems. The SIT mechanism is presented through the pseudo-code described in the former section. Problems 1, 6 were solved by the authors with the aid of the method; Problem 2 was solved by another SIT practitioner; the solutions to Problems 3 and 5 are known commercial products, Problems 4,7 were taken from [Altshuller, 1985].

Each example demonstrates only one direct path to a creative solution. In real life, the process would be, of course, less straightforward, involving moving back and forth through SIT's routes. When using the method in real situations, the problem solver would use the branching mechanism of SIT and the different possible selections to construct a search tree, which at times may be quite large.

4.3.1. Dipping Wires in Tin

It is necessary to solder electric wires to a post in a switchboard. Best results are achieved if the wires are coated with a thin layer of tin before the soldering process. To coat the wires with a thin layer of tin, they are inserted into a liquid tin vessel so that their tips are coated with a thin layer. To increase the throughput of the process, many wires are inserted at once. But then a problem emerges: due to the short distance between the wires, and the surface tension of tin, some wires stick together when they are lifted from the tin. After separating the wires, their tin layer becomes uneven, and the quality of the soldering process deteriorates.

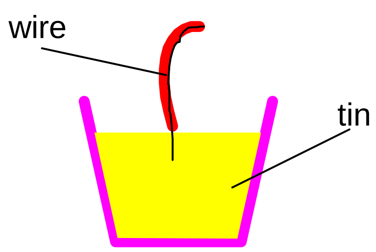

Figure 4-3. The tin coating system

A. Preparation Stage

System objects list

[**wire; insulator; tin, bowl; heat; heat source; worker**]

Neighborhood objects list

[**air**]

Functional Structure

[Tin needs **heat** to directly perform on it the desired operation: **to melt** according to the concept: **melting by heat**. This is **the primary** function of the **heat** in the system.

Heat needs **heat source** to directly perform on it the desired operation: **to generate** according to the concept **electric heating**. This is **the primary** function of the **heat source in** the system;

Tin needs **wire** to directly perform on it the desired operation: **to accumulate** according to the concept: **electric heating**. This is the **not the primary** function of the **wire** in the system]

Problem Characteristics

[tin layer is uneven; wires may be disconnected]

[Increasing the value of the attribute **surface tension** increases the level of the undesired effect **tin layer is uneven**.

Increasing the value of the attribute **unevenness of the tin layer** increases the level of the undesired effect **wires may be disconnected**]

B. Solution Stage

Strategy Selection

{→**<u>extension</u>** | →**restructuring**}

Extension

Conceptual Solution

The relation **increasing the value of the attribute "surface tension" increases the level of the undesired effect "tin layer is uneven"** will change from an increasing relation to **unchanging,** if the following operation: **to not let tin that belongs to one wire be in contact with the tin that belongs to another** is performed.

Extension technique selection

{→**<u>unification</u>**|→**multiplication**}

Unification

The object **insulator** will carry out the operation **to not let tin that belongs to one wire be in contact with the tin that belongs to another**. To do this the object must be modified in the following way: **the insulator needs to be present at the tips.**

Schematic solution

The insulator will not be removed prior to dipping the wire in the tin. As shown in Figure 4-4, the insulator will form a small tube around the wire in which the tin will penetrate. There will be no contact between the tin of one wire and another. Note: this solution has been personally tested by the author and it was found that it is working (producing very high quality soldering) with no undesired side effects

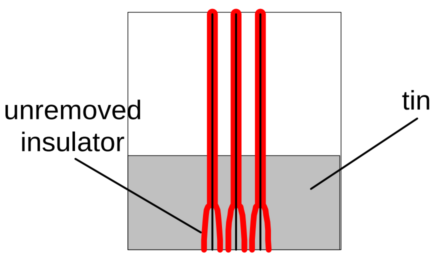

Figure 4-4. The solution to the tin problem

4.3.2. Derailing Detection Device

A train's braking system includes a pipe, that passes along the cars. The air pressure in the pipe is 5 atmospheres. Under emergency conditions (such as derailing), the air must be released very quickly. To ensure sufficiently fast release of the air, it should exit through an opening that is at least 10 cm^2. During normal operating conditions, this opening is closed with a stopper, which is released, when necessary, by the air pressure itself (see figure 4-5).

In normal operation, the stopper is held in place by a derailing detector device. The problem is that the derailing detector can exert only 0.5 KgF, which is insufficient to balance the 50 KgF applied by the internal pressure on the stopper.

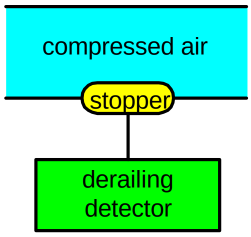

Figure 4-5. The derailing detector system

A. Preparation Stage

System objects list

[**stopper; derailing detection device; pipe, derailing signal**]

Neighborhood objects list

[**air; rails; cars, engine; passengers**]

Functional Structure

[D**erailing signal** needs **derailing detection device** to directly perform on it the desired operation, **to generate** according to the concept, **detection of momentary free fall of one of the wheels**. This is **the primary** function of the **derailing detection device** in the system;

Stopper needs **derailing detection device** to directly perform on it the desired operation, : **to hold in place** according to the concept, **using its compressed spring**. This is **not the primary** function of the **derailing detection device** in the system.

Air needs **stopper** to directly perform on it the desired operation **to not let go out** according to the concept **solid material**. This is **the primary** function of the **stopper** in the system.

Stopper needs **air** to directly perform on it the desired operation, **to open** according to the concept **gas pressure**. This is **not the primary** function of the **air** in the system;]

Problem Characteristics

[force is needed to hold the stopper in place]

[Increasing the value of the attribute **stopper's area** increases the level of the undesired effect **force is needed to hold the stopper in place**.

Increasing the value of the attribute **air pressure** increases the level of the undesired effect **force is needed to hold the stopper in place**]

B. Solution Stage

Strategy Selection

{→<u>**extension**</u>│→**restructuring**}

Extension

Conceptual Solution

The relation **increasing the value of the attribute "air pressure" increases the level of the undesired effect "force is needed to hold the stopper in place"** will change from an increasing relation to **unchanging**, if the following operation: **to exert force that is identical in magnitude and opposite in direction to the force exerted on the stopper by the air pressure** is performed.

Extension technique selection

{→**unification**│→<u>**multiplication**</u>}

Multiplication

New object(s) of the same type as **stopper** will be added to the system. The new object(s) will carry out the operation **to exert force that is identical in magnitude and opposite in direction to the force exerted on the stopper by the air pressure.** To do that, the new object(s) must be different from the original **stopper** in the following way: **its area should be slightly different**.

Schematic solution

The new stopper will be mounted precisely above the original one (see figure 4-6). The two stoppers will be connected by a thin string. The pressure exerted on the new stopper will almost nullify the force exerted on the original stopper by the air pressure.

Note: the same idea is used in many high-pressure systems whenever a small force should keep a stopper in a high-pressure system.

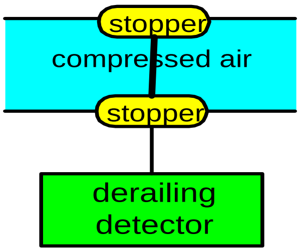

Figure 4-6. The solution to the derailing detector problem

4.3.3. A Simple and Reliable Timing Mechanism

Explosion processes (for example, blowing up a bridge) are very sensitive to the time difference between explosions. It is imperative that the timing mechanism be very accurate, reliable, and simple. In military applications, the mechanism may be buried in the ground for a long time and then suddenly needed.

One possible design is a free falling ball that closes electric circuits located at different heights in a vacuum tube (see Figure 4-7). The problem is that the ball loses some velocity due to friction which degrades the accuracy. It is impossible to simply calibrate the device since the variance in friction is too large.

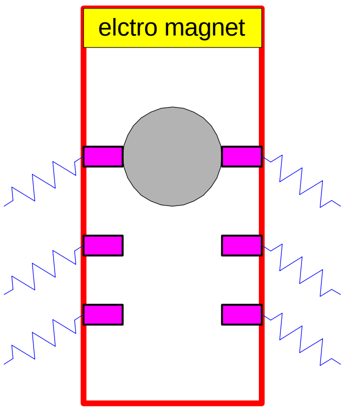

Figure 4-7. The timing device

A. Preparation Stage

System objects list

[ball; electrodes; timing signal; electric current; tube, electromagnet]

Neighborhood objects list

[**air**]

Functional Structure

[Timing signal needs **ball** to directly perform on it the desired operation, **to create** according to the concept **free fall**. This is **the primary** function of the **ball** in the system.

Timing signal needs **electrodes** to directly perform on it the desired operation, **to set intervals** according to the concept, **distance relative to interval**. This is **the primary** function of the **electrodes** in the system.

Timing signal needs **electric current** to directly perform on it the desired operation, **to transfer** according to the concept, **flow of electrons**. This is **the primary** function of the **electric current** in the system.

Electrodes needs **tube** to directly perform on it the desired operation, : **to hold** according to the concept, **mechanical force**. This is **not the primary** function of the **tube** in the system.

Air needs **tube** to directly perform on it the desired operation, **to block** according to the concept, **sealing by solid material**. This is **the primary** function of the **tube** in the system]

Problem Characteristics

[**time intervals are inaccurate; explosions are inefficient]**

[Increasing the value of the attribute **friction** increases the level of the undesired effect **time intervals are inaccurate.**

Increasing the value of the attribute **inaccuracy of time intervals** increases the level of the undesired effect **explosions are inefficient**]

B. Solution Stage

Strategy Selection

{→**extension** | →**<u>restructuring</u>**}

Restructuring

Restructuring technique selection

{→**<u>division</u>**|→**breaking symmetry**|→**removing an object**}

Division

The object **ball** will be divided **randomly**. A new degree of freedom will be achieved by locating each part in a **different place** (see figure 4-8)

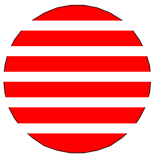

Figure 4-8. The division of the ball

Schematic solution

There will be three different slices having different radii. The gap between any pair of electrodes will be a function. of their heights - higher electrodes, larger gap. Initially the slices will be fixed to the top of the tube (on top the other) through the electromagnet. When the electromagnet is released, the slices will fall together at the same velocity. Each slice will stop at the first pair of electrodes whose gap is smaller that the slice's diameter, without affecting the other slices which continue to free-fall.

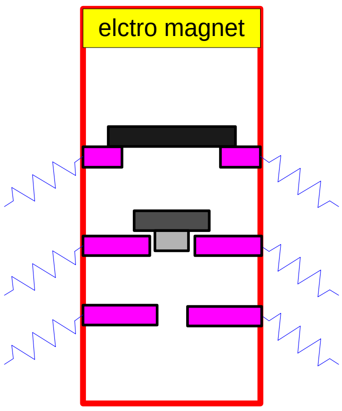

Figure 4-9. The solution to the timing device problem

4.3.4. A Candle Without Wax Spillage

When a candle burns, the wax often flows to the base of the candle. This phenomenon is undesired. especially in birthday candles on cakes.

A. Preparation Stage

System objects list

[wax; wick; flame; light]

Neighborhood objects list

[**air; cake**]

Functional Structure

[L**ight** needs **flame** to directly perform on it the desired operation **to generate** according to the concept **burning**. This is **the primary** function of the **flame** in the system.

Flame needs **wax** to directly perform on it the desired operation **to supply energy** according to the concept **flammable material**. This is **the primary** function of the **wax** in the system.

Flame needs **air** to directly perform on it the desired operation **to supply oxygen** according to the concept **oxidizer**. This is **the primary** function of the **air** in the system

Wax needs **wick** to directly perform on it the desired operation **to transfer** according to the concept **capillary**. This is **the primary** function of the **wax** in the system.

Wick needs **wax** to directly perform on it the desired operation **to hold** according to the concept **mechanical support by solid material**. This is **not the primary** function of the **wax** in the system.

Wax needs **flame** to directly perform on it the desired operation **to heat** according to the concept **direct heating by flame**. This is **not the primary** function of the **flame** in the system;]

Problem Characteristics

[wax flows to the base of the candle]

B. [Increasing the value of the attribute **candle length** increases the level of the undesired effect **wax flows to the base of the candle**] **Solution Stage**

Strategy Selection

{→**extension**│→**<u>restructuring</u>**}

Restructuring

Restructuring technique selection

{→**division**│→**<u>breaking symmetry</u>**│→**removing an object**}

Symmetry Breaking

Select an object **wax.**

Form a list of important object parameters [**radius**, **location along the radius**, **melting temperature, material**].

The object **wax** will be modified so that the object's parameter **melting temperature,** which is currently unrelated to the object's parameter **location along the radius,** will be related to it in the following way: **increasing step function**

Schematic solution

The wax at the outer part of the candle will melt after the wax in the inner parts and a natural bowl are formed (see Figure 4-10). Note: this is a commercial product

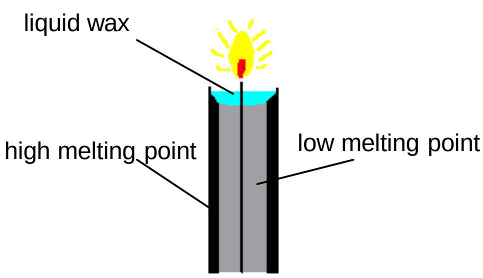

Figure 4-10. The solution to the candle problem

4.3.5. Oil Grains

The ‘residue’ is a by-product of an edible oil production process. The residue that is left after oil extraction from the seeds (corn, soy, beans, etc.) is a viscous substance that is conveyed to other manufacturing processes.

Two processes take place in parallel: 1. Toaster (produces food for animals), 2. Flash (produces milk substitute for babies).

The residue is dropped from a height of several feet into a clapper that divides the residue into the desired amounts for each process (for example, 70% to the toaster and 30% to the flash). The division ratio can be determined by changing the angle of the clapper (see Figure 4-11). If the desired division ratio between the two processes is such that a small amount is directed to one process, the clapper leaves just a narrow gap for the material to flow. In such cases, the residue enters the clapper mechanism, and after a short while it clogs the clapper and blocks the outlet.

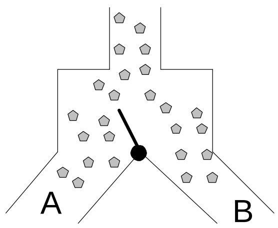

Figure 4-11. The branching point between the two processes

A. Preparation Stage

System objects list

[**clapper; residue; container**]

Neighborhood objects list

[**air; oil**]

Functional Structure

[O**il residue** needs **clapper** to directly perform on it the desired operation **to divide** according to the concept **angular movable mechanical separating point that changes the outlet area of each process** . This is **the primary** function of the **clapper** in the system;].

Problem Characteristics

[there is a probability of blockage]

[Increasing the value of the attribute **stickiness of the grains** increases the level of the undesired effect **there is a probability of blockage**.

Increasing the value of the attribute **division ratio** increases the level of the undesired effect **there is a probability of blockage**]

B. Solution Stage

Strategy Selection

{→**extension**│→**<u>restructuring</u>**}

Restructuring

Restructuring technique selection

{→**division**│→**breaking symmetry**│→**<u>removing an object</u>**}

Object Removal

The object **clapper** will be removed from the system. Its operation **to divide** targeted at the object **oil residue** {→**<u>will be carried out by another closed world object</u>** │→**will not be carried out any more, and to compensate for that, the system will be restructured.**}

Will be carried out by another closed world object

The closed world object that will carry out the removed object's function will **not continue** to apply the concept **angular movable mechanical separating point that changes the outlet area of each process.**

Idea provoking technique selection

{→**<u>unification (object removal)</u>** │ →**multiplication (object removal)** }

Unification (Object Removal)

The operation **to divide** targeted at the object **oil residue**, that was carried out by the removed object **clapper**, will now be carried out by the object **oil residue**. The new object will **not continue** to operate according to the concept, **angular movable mechanical separating point that changes the outlet area of each process.** To do this, the object **oil residue** must to be modified in the following way: **all the material will be directed at the higher added value process and only excess material will slip to the other process**

Schematic solution

The outlet of the material will be above the entry to the milk substitute process (process B), which is the higher added value process . Whenever process B can process all the input material, no material will be directed to process A. When the flow of input material exceeds the requirement of process B, the entry to that process will be full and the excess material will flow to process A (see figure 4-12). Note: this solution was implemented in Yizhar company in Ashdod.

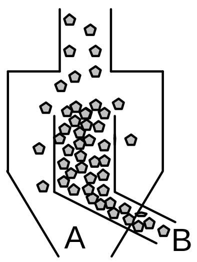

Figure 4-12. The solution to the oil residue problem

4.3.6. Baby Chair

Since tables have different heights, the gap between the height of a baby chair and the table might be too small or large causing inconvenience to the baby.

A. Preparation Stage

System objects list

[**legs; seat; baby; force**]

Neighborhood objects list

[**table**]

Functional Structure

[**Force** needs **legs** to directly perform on it the desired operation, **to transfer from floor to seat** according to the concept **rigid solid material**. This is **the primary** function of the **legs** in the system.

Baby needs **seat** to directly perform on it the desired operation **to support** according to the concept **a planar solid material that distributes pressure**. This is **the primary** function of the **seat** in the system.

Seat needs **force** to directly perform on it the desired operation **to support** according to the concept **mechanical force**. This is **the primary** function of the **force** in the system].

Problem Characteristics

[there is an incorrect gap between the baby chair and the table]

[Increasing the value of the attribute **table height** increases the level of the undesired effect **there is an incorrect gap between the baby chair and the table**]

B. Solution Stage

Strategy Selection

{→**extension** | →**<u>restructuring</u>**}

Restructuring

Restructuring technique selection

{→**division** | →**breaking symmetry** | →**<u>removing an object</u>**}

Object Removal

The object **legs** will be removed from the system. Its operation **to transfer** targeted at the object **force** {→**<u>will be carried out by another closed world object</u>** | →**will not be carried out any more, and to compensate for that, the system will be restructured**}

Will be carried out by another closed world object

The closed world object that will carry out the removed object’s function will **continue** to apply the concept **solid material**

Idea provoking technique selection

{→**<u>unification (object removal)</u>** | →**multiplication (object removal)** }

Unification (Object Removal)

The operation **to transfer** targeted at the object **force**, that was carried out by the removed object: **legs**, will now be carried out by the object **table**. The new object will **continue** to operate according to the concept **solid material.** To do this the object **legs** need to be modified in the following way: **no modification**

Schematic solution

The baby chair will have no legs and will use the table itself for support (See Figure 4-13). Note: this solution is a commercial product

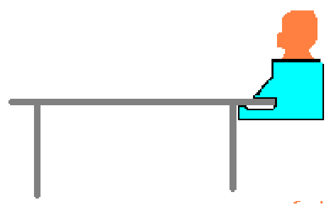

Figure 4-13. The solution to the baby chair problem

4.3.7. Ice breaker

Ice breakers are used to clear the way for tankers. Using its engine power, the ice breaker climbs on the ice layer, breaking the layer in a downward motion by its own weight. The problem with this operational principle is that it is too slow, rendering the process almost uneconomical.

A. Preparation Stage

System objects list

[**ice breaker; freight; tanker**]

Neighborhood objects list

[**sea water; ice**]

Functional Structure

[I**ce** needs **ice breaker** to directly perform on it the desired operation **to break** according to the concept **using the icebreaker's own weight** . This is **the primary** function of the **ice breaker** in the system.

Freight needs **tanker** to directly perform on it the desired operation **to carry** according to the concept **floating on the water** . This is **the primary** function of the **tanker** in the system]

Problem Characteristics

[ice slows the tanker]

[Increasing the value of the attribute **width of the tanker** increases the level of the undesired effect **ice slows the tanker**]

B. Solution Stage

Strategy Selection

{→**extension**|→**<u>restructuring</u>**}

Restructuring

Restructuring technique selection

{→**division**|→**breaking symmetry**|→**<u>removing an object</u>**}

Object Removal

The object **ice breaker** will be removed from the system. Its operation **to break** targeted at the object **ice** {→**will be carried out by another closed world object** |→**<u>will not be carried out any more, and to compensate for that, the system will be restructured</u>**}

Will not be carried out any more, and to compensate for that, the system will be restructured

{→**<u>division (object removal)</u>** |→ **breaking symmetry (object removal)** }

Division (Object Removal)

The object **ice breaker** will be removed from the system. Its operation **to break** targeted at the object **ice** will not be carried out any more. To compensate, the system will be restructured in the following way: the object **tanker** will be divided **randomly**. A new degree of freedom will be achieved by making each object different in **location.**

Schematic solution

The tanker will be divided into two parts. The part of the ship that is above the ice and the part that is below it (see Figure 4-14). The two parts will move, one above and one below the ice. The two parts will be connected by a thin wall that has almost no resistance to ice.

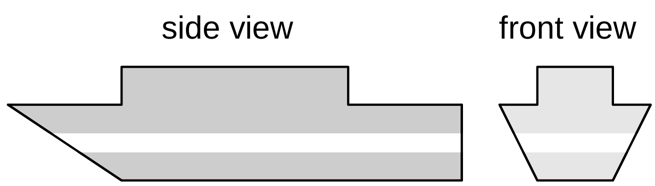

Figure 4-14. The solution of the ice breaker problem

4.4. Empirical demonstration of the effectiveness of the SIT method

The role of the empirical study, presented in this section, is to demonstrate the effectiveness of the SIT method in directing the problem solver towards solutions that satisfy the sufficient conditions. The method's effectiveness is thus measured as the amount of increase in the success rate of finding conditions-satisfying solutions among SIT trainees, before and after SIT training.

The experiments were held in 18 SIT workshops which took place between 1995 and 1997. Each workshop was accompanied by a pre-test and a post-test. The participants were given engineering problems and asked to solve them creatively. Before the course they were asked to use their own understanding of creativity. After the course, they were asked to find conditions-satisfying solutions by using the SIT method. The results of the experiments show a substantial increase in the rate of success in finding conditions-satisfying solutions after SIT training. The rest of this section describes the experiments and their results in detail.

4.4.1. Subjects

The subjects were engineers from various Israeli companies, or Industrial Engineering students just before graduation. All the subjects participated in a 30 hour "inventive thinking course" in which the SIT method was taught and exercised. A total of 180 subjects participated in the experiment.

4.4.2. Method of Experiment

Each subject was given one or two engineering problems prior to the course and one or two *different* problems after the course. Ten real engineering problems were used in the experiment, among them problems 1, 2, and 6 from the Examples Section (Section 3) and the *stretching bars* problem from Section 2. In the pre-test, the subjects were encouraged to suggest creative ideas and to produce more than one solution. In the post-test, subjects were instructed to use the SIT method to find conditions-satisfying solutions. Here, too, they were encouraged to produce more than one solution. Both in the pre-test and in the post-test, time was not limited and most subjects did not need more than half an hour per problem.

It is important to note that the two tests were not held under the same motivational conditions. At the beginning of the course, the only motivation of the subjects was to show that they were creative (the test was not anonymous). At the end of the course the motivation was to show that they had mastered the SIT method. Another important fact is that the number of subjects in the post- test was somewhat smaller than that of the pre-test as a few subjects left the course for various reasons.

4.4.3. How SIT is being taught

SIT is taught in a one–semester, 30 hour, course. First, in the first 10 hours of the course the theory of the sufficient conditions is presented, and then in the next 6 hours the SIT algorithm is presented, using the syntax presented on Section 4.2.2. In class the students view presentations of solved problems. The solve problems themselves in home-work. During the whole course the students solve themselves about 20 problems.

4.4.4. Analysis of the Data

For each problem, a list of 'all suggested different solutions' was prepared. This list contained all the different suggestions for solving a specific problem . Each solution to each problem was assigned an identity number. The response of each subject was coded by fitting a list of relevant identity numbers to his or her responses.

4.4.5. Results

Table 4.1 shows the difference in the rate of success of subjects in finding condition's satisfying solutions. The rate of success is defined as the ratio between the number of *subjects* who succeeded in finding conditions-satisfying solutions and the total number of participants. Note that this definition relates to the rate of successful *subjects* and not to the rate of successful *solutions,* which might be different. The results show a substantial increase in the rate of success in finding conditions-satisfying solutions. Since the study in Chapter 3 has shown a tight relation between the qualities of conditions-satisfying and creativeness, it is fair to say that the subjects managed to produce more creative results after the course.

One exception is Problem 9 for which the pre-test shows a higher success rate than the post-test. Our explanation for this anomaly is that the solution to this specific problem adapts a widely known conceptual idea: saving space by inserting objects one within another. In this case the ability to retrieve that concept was more influential than the hints supplied by the method.

Table 4-1**.** The rate of success before and after the course (See Appendix B for a detailed report of the problems used in this study)

Problem	number of participants (before the course)	rate of success (before the course)	Number of participants (after the course)	rate of success (after the course)	statistical significance level
1	46	0.02	38	0.26	***
2	21	0.00	25	0.48	***
3	32	0.00	21	0.33	***
4	34	0.06	53	0.68	***
5	52	0.00	22	0.41	***
6	18	0.22	26	0.31	insignificant
7	18	0.17	26	0.58	***
8	21	0.05	11	0.55	***
9	64	0.34	14	0.29	insignificant
10	59	0.22	19	0.79	***
Average	36.5	0.11	25.5	0.47	

4.4.5.1. Qualitative Results

The histograms shown in Figure 4-15 demonstrate the distribution of the suggested solutions before the course (the left part) and after the course (the right) part. The darker strips represent conditions-satisfying solutions. All suggested solutions were recorded for the construction of these histograms which means that if a participant produced a number of solutions, they were all taken into account. The solutions in each histogram are arranged according to their frequency in the pre-test.

The histograms show two recurring properties which interestingly shed more light on the effect of SIT creativity training: 1) The variance of the distribution after the course is much smaller, which demonstrates the effect of SIT as a creative filter for solutions. 2) After SIT training, the solutions that were the most popular ones before the course virtually disappeared after the course. This means that even those subjects who failed to produce conditions satisfying solutions managed to use SIT principles to guide them toward more original solutions.

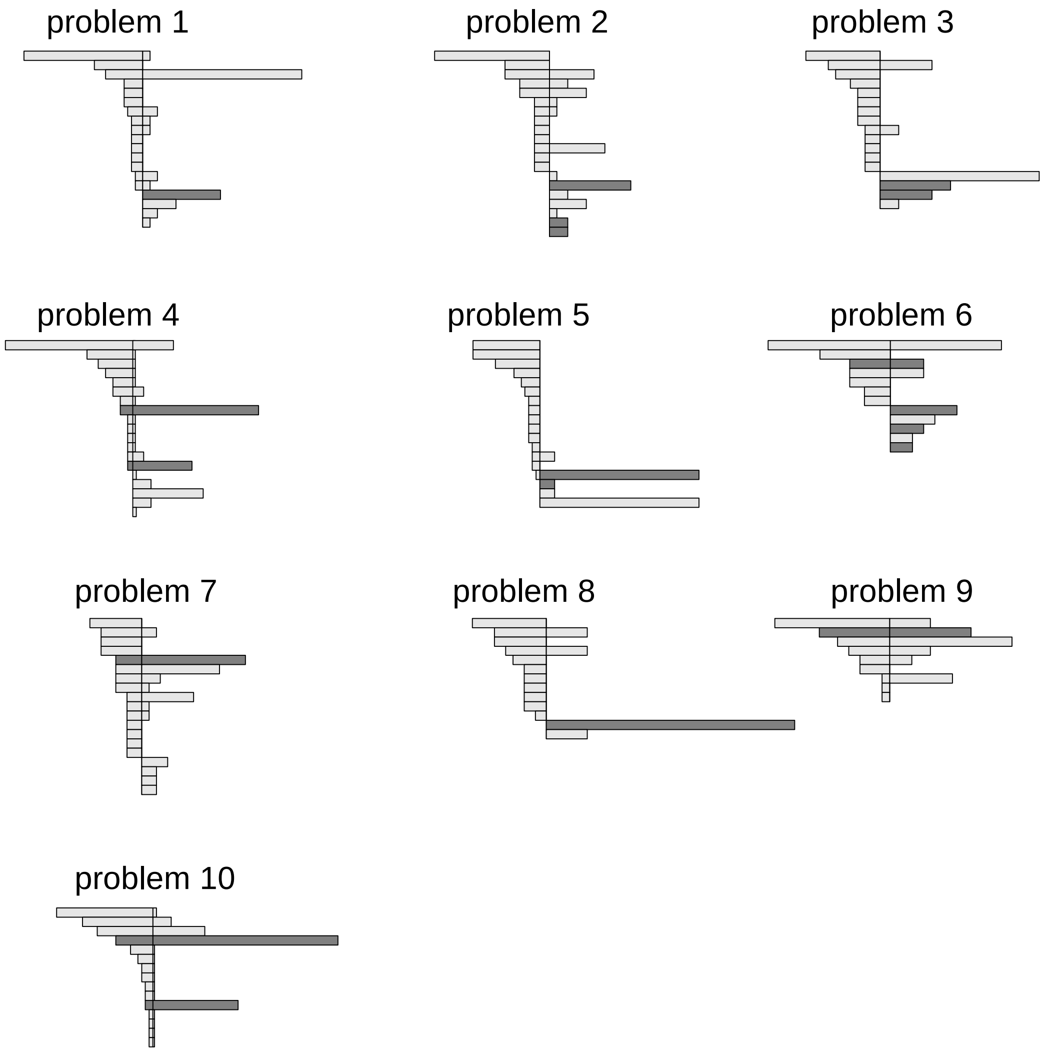

Figure 4-15. Pre-training and post-training distribution of solutions. Gray lines represent conditions-satisfying solutions

4.5. SIT versus other Creative Problem Solving Techniques

This section, which discusses some general features of creativity enhancement methods, is followed by a discussion about the main differences between SIT and other well-known creative problem-solving methods: Brain Storming, TRIZ, and Synectics (See Chapter 2 for a detailed description of these methods).

4.5.1. General Features of Creativity Enhancement Methods

Creativity enhancement methods can be roughly divided into *process level* methods and *content level* ones. Process level methods support the problem solver in the organization and management of his problem solving task, but do not supply tools for analyzing and manipulating content. These methods divide problem-solving into distinct parts, each part characterized by a different set of tasks. The different processes are formulated in general terms, such as problem definition, idea finding and idea evaluation. Many of these methods supply pointers to other more specific methods in each problem solving segment. *Content level* methods operate on the problem content itself. They supply the problem solver with a set of empty templates, or a list of questions to be completed with information about the problem. These templates help the user to reorganize the information at hand, make new associations, draw new meaning out of the same data, and get new hints for the solution.

Content level methods can be further divided along two orthogonal dimensions into *static* versus *dynamic* methods and associative versus non-associative. Static methods incorporate a list of 'ready-made', mostly *what if* questions that the problem solver should try to answer to get new ideas. The prompts supplied by the method are thus not a function of the problem solver's response to previous prompts. An example of such a question is: "*What would happen if an object is removed from the system?*". *Dynamic* methods supply the problem solver with such tools as templates, diagrams, empty forms, prompts, and questionnaires whose contents change in the course of problem solving. *Associative* methods involve mechanisms for associating current problem 'world' with other hitherto unrelated 'content-worlds'. These methods often use elements such as analogy and metaphor to transfer content from one 'world' into another. In contrast, *non-associative* methods operate only on current problem sphere content, and supply the user with tools for analyzing and manipulating that content.

4.5.2. SIT vs. Brain-Storming

Brain-storming, probably the most popular creativity enhancement method, is a *process-level* method. As such it suffers from two main drawbacks. The first is that, due to the lack of criteria for inventiveness, non-creative ideas can find their way through, as the participants tend to promote their natural, non-original ideas. Instead of using the method to find new ideas, the users use the method to justify their old ideas (Sentences such as "this idea popped out in a brain-storming session" are heard). The second draw back is that, by emphasizing quantity, a lot of intellectual effort is invested in non-fruitful ideas. SIT ameliorates this situation by reformulating the problem definition through the framework of the sufficient conditions that ensures both the originality of the ideas and their potential to develop into good engineering solutions.

4.5.3. SIT vs. Synectics

SIT and Synectics are both content-level methods, and therefore most of the differences between these methods are derived from that fact that Synectics is an associative method and draws its power from extracting analogical situations outside the current problem sphere. SIT draws its power from extending and manipulating problem sphere information. SIT advantages over Synectics follow directly from its non-associative mechanism. Finding and using the right analogy is a creative endeavor itself and it has been shown that even if subjects are given a story containing a relevant analogy just minutes prior to a problem-solving session, they fail to recognize its relevance if not explicitly told.

4.5.4. SIT vs. TRIZ

TRIZ is the only known method that, like SIT, is a content-level, non-associative method. SIT differs from TRIZ, however, in the following aspects:

Criteria for inventiveness: SIT uses the framework of the sufficient conditions as a criteria for inventiveness which is an improvement of TRIZ's 'overcoming conflict' criterion as mentioned in Chapter 3.

Compactness: SIT includes a significantly smaller number of operators (5 versus more than 40). The result of this compactness is that after some training the SIT process becomes innate in the problem-solver's mind, rendering it unnecessary to refer to external aids in the course of problem solving. The cost (in terms of efforts, halting the process etc.) of resorting to external knowledge bases (such as printed material, computer programs etc.) is often very high, which results in abandonment of the procedure.

Abstraction level: SIT operators operate on a consistent, content-transcending abstraction level. TRIZ's techniques operate both on a high, content free, abstraction level and on a content expert-system like level. For example one of TRIZ' techniques is the following "If you need to separate a mixture of two materials in a powder form, use vibration”. Table 4-2 summarizes the main differences between the Brain Storming, Synectics, Triz, and SIT.

Table 4-2. A summary of the main differences between the Brain Storming, Synectics, Triz, and SIT

	Brain Storming	Synectics	Triz	SIT
Main creative mechanism	Suspension of Judgement	Analogies	Principles, Standards, Effects	Solution techniques
Number of techniques	No techniques	Small (4 types of analogies)	Large (hundreds)	Small (5 Operators)
Is domain knowledge included?	No	No	Yes (especially in standards and effects)	No
Group or individual	Group	Individual and Group	Individual	Individual
Criteria for inventiveness	No	No	Conflict elimination	Sufficient conditions (CW+QC)
Systematic or Non-systematic	Non	Systematic	Systematic	Systematic
Associative or Non-Associative	Associative	Associative	Non	Non

4.6. Summary and conclusions

This chapter presented SIT, a method aimed at assisting problem-solvers in arriving at creative, conditions-satisfying, solutions. The SIT method consists of a preparation stage in which the problem is analyzed and its closed world as well as the required qualitative change are determined And a solution stage consisting of two solution strategies and five idea provoking operators. SIT was presented t formally by means of a pseudo-computer code. SIT’s effectiveness in increasing the rate of engineers who arrive at a creative solution has been demonstrated empirically.

Although the SIT process is triggered by a description of an engineering system and its associated undesired effects, it can work even when no undesired effect is known, or when no system is given. If no undesired effect is known, it is possible to artificially generate one by hypothetically increasing the system’s performance until undesired effects begin to emerge. If no system is given and only an undesired effect is stated, the closed world condition would allow the creation of a system from objects that naturally reside where the undesired effect has emerged.

SIT's output is a partial solution concept and not a full-fledged solution to a problem. The problem solver remains responsible for elaborating the information supplied by SIT into a detailed solution. SIT, like other known creativity enhancement methods, does not guarantee that all solutions that satisfy the conditions can be derived by the method. Solutions that do not incorporate any of the five idea provoking operators may be missed. Three sets of creative solutions can be defined: solutions derivable by the method $\subseteq$ solutions that satisfy the conditions $\subseteq$ all creative solutions.

Like any other problem-solving aid SIT is not free from limitations and this should be stated explicitly. In order to compile the necessary information from the problem statement into the language of the conditions, the mechanism of the problem itself must be relatively well understood, and the problem must be reasonably well delineated in space and time. When the situation is highly complex, ambiguous, and not confined in space and time SIT looses much of its effectiveness. In such cases it is hard to identify both the objects that comprise the relevant closed world and the required qualitative changes. Another limitation is related to the fact that SIT is geared to support the generation of a specific type of solutions, those satisfying the conditions. Obviously, there may be other solutions. Problem solvers must be aware of this fact, especially if SIT fails to produce satisfactory results.

The following points summarize the main features if SIT:

- SIT is a problem-solving method designed to help engineers develop inventive designs
- SIT produces improved solutions within the current domain (and paradigms) that satisfy the Closed World condition and the Qualitative Change condition
- SIT is based on five operators that change the current system without violating the CW Condition
- SIT is structured in such a way that it can be easily develop into a computer aided inventive design system

- Empirical studies proved SIT's effectiveness in increasing the rate of problem-solvers that produce inventive solutions to engineering problems

THE COGNITIVE FOUNDATIONS OF ENGINEERING CREATIVITY

Chapter five

The former chapters focused on objective properties of creative engineering solutions, expressed in terms of two jointly-sufficient conditions, and suggested SIT - a step-by-step method that supports the search for creative conditions-satisfying solutions. The issues were presented with almost no reference to their psychological implications. But these are, of course, crucial to the successful application of the method, as it is humans who learn SIT and apply it to creatively solve engineering problems. Several fundamental issues arise in this respect: the identification of the basic cognitive processes that constitute a successful use of SIT; the psychological profile of a successful (as opposed to a non-successful) SIT user; the way thinking styles change in the course of learning SIT; and the correspondence between the level of success in using SIT and the scores in accepted creativity tests such as the Kogan and Wallach test.

The successful acquisition and use of a thinking method depends on many factors including, among others, personality traits, motivation, cognitive ability, disposition and style. In this chapter we focus, however, only on cognitive aspects of learning and using the SIT method. Two research tools are used in the study: The Kreitler and Kreitler theory of meaning [Kreitler and Kreitler, 1990 a] exposes the main cognitive processes relevant to SIT use and mastery, and the Kogan and Wallach creativity test [Wallach and Kogan, 1965] is used for testing the relations between the theory of the sufficient conditions (and the SIT method derived from them) and the most widely accepted theory of creativity - the theory of divergent thinking.

The results of the study presented in this chapter show that individuals who tend to find conditions-satisfying solutions are characterized by distinct cognitive factors lacking in those who do not. Furthermore, these cognitive factors are easily explained in relation to what is known about creative processes, for example the importance of fluency and flexibility. Theoretically the results support the theory of the sufficient conditions by showing that the conditions constitute a framework of a distinct, creativity-related, and psychologically important set of solutions. Practically, the identification of cognitive processes underpinning the search for creative engineering solutions (using SIT) can serve as the basis for the development of cognitive training programs aimed at preparing individuals for better acquisition and use of SIT.

The results of the study also shed light on some fundamental and bewildering questions accompanying creativity study from its early days: is creativity a general competence across domains or is it strongly domain specific; why does the theory of divergent thinking fail to supply reliable predictions of real life creative performance; and finally, is creative thinking a unique thinking process, or just a particular case of problem solving as maintained by the ‘nothing special’ approach?

The chapter begins, in Section 5.1, by describing the Kreitler and Kreitler theory of meaning including its definition of meaning, meaning variables, meaning measurement through the meaning questionnaire, and how the theory of meaning has been used in previous studies to expose the underlying processes of cognitive tasks; in Section 5.2 the Kogan and Wallach creativity test is described; the experiment and its (raw) results are described in detail in Section 5.3; The results are analyzed in Section 5.4; Section 5.5 concludes this chapter and suggests some practical implications.

5.1. The Kreitler and Kreitler theory of meaning

Meaning has long been viewed by philosophers, linguists, computer scientists and other investigators in the human disciplines as most important in human action. Until the emergence of the Kreitler and Kreitler theory of meaning, however, there were no empirical tools for the characterization and quantification of cognitive content: philosophers treated meaning in unoperational terms, whereas psychological theories such as Osgood’s theory of ‘semantic differential’ [Osgood, 1958] were too limited in their conceptual and methodological scope and therefore in their psychological significance. Kreitler and Kreitler say about meaning that “*to grasp the extent of its importance, one has to recognize that cognitive content is not merely a collection of manipulable items that can be inserted into grammatical slots resulting from phrase-*

structure analysis, or the application of transformational rules, but an active agent guiding human thought and affecting emotions and behaviors" [Kreitler and Kreitler, 1990, p. 16]. This insight lead them to develop their own theory and system of meaning (called here KTM for convenience) that makes it possible to assess meaning so as to empirically study its effects on cognition and other psychological traits.

The major assumptions underlying KTM are first, that meaning is a complex phenomenon with a multiplicity of aspects, which implies that it cannot be wholly reflected in a measure assessed by a single aspect such as actions (in line with the behaviorist tradition). Second, meaning is essentially communicable, because most of the meanings we know have been learned from or through others. Third, meaning can be expressed or communicated by verbal or different non-verbal means. Fourth, there are two types or varieties of meaning - the general, interpersonally-shared meaning and the personal-subjective meaning. And fifth, meaning is referent-bound, that is, meaning is always the meaning of something.

These assumptions made it possible to construct a standard empirical framework for the development of the meaning system whose underlying principles are the following: (1) Raw data are transcripts of individuals' meaning communications in response to a great variety of verbal and non-verbal referents (i.e. explaining the meaning of the referent to an imaginary other, who does not know the meaning of the referent but can understand the communication). (2) Meaning is composed of both personal meaning and generally accepted meaning. (3) The system of meaning is expected to be rich and multi-dimensional. Using their empirical framework Kreitler and Kreitler collected a large amount of empirical data from thousands of subjects differing in age (from 2 to over 80 years), gender, cultural background, mental health, intelligence, and education.

On the basis of the empirical data and theoretical considerations, meaning was defined as a referent-centered pattern of meaning values. In this definition, the *referent* is the carrier of meaning, which can be anything, including a word, an object, a situation, an event, or even a whole period, whereas *meaning values* are cognitive contents assigned (by the 'meaning processor' - usually a human being) to the referent for the purpose of expressing or communicating its meaning. For example, if the referent is 'table', responses such as 'made of wood' or 'stands in a room' or 'I have one' or 'a piece of furniture' are four different meaning values. The referent and the meaning value together form a *meaning unit* (e.g., table - a piece of furniture). It is important to note that in the course of communicating meaning the referent does not necessarily remain identical to the input stimulus. For example, in communicating the meaning of the input ‘table’ someone may shift to communicating the meaning of the term ‘furniture’. When coding the data the referent was identified by asking “What does the subject communicate about ?” whereas the meaning value was identified by asking “What does the subject communicate about the referent”. Kreitler and Kreitler developed a meaning system in which meaning units are characterized in terms of five sets of classification schemes. Each classification scheme consists of 11 to 22 predetermined variables. Each meaning value (and recall that a referent can be assigned several) can thus be assigned a point in a five dimensional space. The following section describes the five sets of meaning variables.

5.1.1. The Meaning Variables

Analysis of the empirical data made it possible to define five sets of variables for characterizing the unit of meaning: 22 *Meaning Dimensions*; 4 *Types of Relation*; 12 *Forms of Relation*; 12 *Shifts of Referent*; and 5 *Forms of Expression*. These variables are described in the following section(for a more detailed description see [Kreitler and Kreitler, 1990, pp. 19-31], for a full list of variables see Appendix A).

5.1.1.1. Meaning Dimensions

Meaning Dimensions characterize the contents of the meaning values from the viewpoint of the specific information communicated about the referent. The meaning dimensions were derived by asking, in regard to the subject’s response, questions such as “What does the subject communicate about the referent?”, “What kind of information about the referent is stated ?”. These questions provided a tool for identifying units (i.e. unit = referent (subject) + communicated content (predicate)) within the subject’s response and for categorizing them. Although meaning dimensions divide content into categories of meaning their conception is not limited to that of a static classification scheme, as they can be conceived also, dynamically, as thought processes. For example the meaning dimension *Contextual Allocation* corresponds to processes of classification and categorization. Meaning values fall into

22 categories called meaning dimensions. A partial list of meaning dimensions includes:

Dim 1. contextual allocation: The superordinate system of items or relations to which the referent belongs or of which it forms part (e.g. *car* - a means of transportation; *wall* - part of a house).

Dim 3. Function, Purpose, or Role: The uses to which the referent is usually put, or the usual activity (or activities) that it does or that may be done with it (e.g. *book* - carries information; *army* - defends the independence of a country).

Dim 7. Consequences and results: Consequences, results or effects of whatever nature and order that derive directly or indirectly from referent's existence, occurrence or operation (e.g. *inflation* - increases poverty).

Dim 10. Structure: The interrelations between the parts or the elements of the referent; the placement or position of the elements relative to each other (e.g. *table* - a flat board on top three or more legs).

Dim 15. Locational Qualities: The place, address, or domain in which the referent exists, occurs, lives, operates, is located, can be found and so on (e.g. *book* - can be found in a library).

Dim 19. Sensory Qualities: The sensory qualities that characterize the referent, that is, those that others perceive in the referent and the referent experiences or could experience. Sensory qualities include *visual* (e.g., *grass* - green), *form and shape* (e.g. *table* - usually a rectangular shape), *auditory sensations* (e.g. *dog* - barks), tactile sensations (e.g. *silk* - smooth), *smell and odor, temperature, internal sensation* (e.g. pain, arousal), *moisture*.

Dim 21. Feelings and Emotions: Feelings, emotions, and moods that the referent evokes or may evoke in others and those that the referent experiences or could experience (e.g., Storm - scary).

Dim 22. Cognitive Qualities and Actions: The cognitive qualities (e.g. bright, witty, silly, interesting) and actions (e.g. thinking, remembering, imagining) evoked by or through the referent in others, and those that characterize the referent.

5.1.1.2. Types of Relations

Types of Relations characterize the manner in which a meaning value is related to the referent. The four types of relations are listed below.

TR 1. *Attributive relation*: the meaning values are related to the referent directly as qualities, features, attributes, properties, events, actions, or other characteristics (e.g., Summer - warm).

TR 2. *Comparative relation*: the meaning values are related to the referent indirectly through the mediation of another referent, which is typically on the level of generality or abstractness similar to that of the original referent (e.g., Summer - warmer than spring).

TR 3. *Exemplifying-Illustrative relation*: the meaning values are related to the referent as examples (e.g., Country - Zimbabwe).

TR 4. *Metaphoric-Symbolic relation*: The meaning values are drawn from domains that do not belong strictly to the referent's conventional spheres of connotation or denotation but relate to the referent metaphorically, through the intermediation of another referent, mostly more concrete or specific than the original referent (e.g. *happiness* - like a blue sky).

Modes of meaning: The four types of relations give rise to a division of meaning values into two modes: *lexical mode* - communicating interpersonal meaning and characterized by the attributive and comparative types of relations; and *personal mode* - communicating personal or subjective meaning and characterized by the exemplifying-illustrative and metaphoric-symbolic types of relations. This distinction is based on empirical findings that the lexical mode predominates when subjects are asked to communicate interpersonally shared conventional meaning, whereas the personal mode predominates when they are asked to communicate subjective meaning.

5.1.1.3. Forms of Relation

Forms of Relation characterize the relation of meaning values to referents from a logical-formal point of view - how the relation between the referent and the cognitive contents is regulated in terms of its validity (positive or negative), quantification (absolute, partial), and form (factual, desired or desirable). A partial list of the forms of relation is:

FR 1. Assertion or Positive relation: The meaning value refers positively to the referent.

FR 2. Negative relation or Denial: The meaning value refers to the referent negatively (e.g. Iraq - is not a democracy).

FR 4. Conjunction: At least two stated meaning values apply jointly to the referent (e.g. basketball - I like to play and watch)

Fr 5. Disjunction: Of two stated meaning values, only one applies to the referent, but not both (e.g. Food is either healthy or tasty).

5.1.1.4. Referent Shifts

Referent Shifts characterize the relation between the referent and the presented input (the initial stimulus for the meaning assignment process), or - in a chain of responses to some input - the relation between the referent and the previous one. Referent shifts occur in the course of meaning communication when the subject assigns meaning values to a referent that is different from the input, or different from the referent that the subject was communicating about in the previous meaning unit. Referent shifts indicate the kind and amount of cognitive flexibility or as strategies for extending the scope of meaning assignment. The whole list of referent shifts is now presented because of the importance of this set of meaning variables to our study:

SR 1. Identical: the actual referent is identical to the input or the previous referent.

SR 2. Opposite: the actual referent is the negation, the inverse, or opposite of the presented or previous referent (e.g., the referent was “democracy” and the subject speaks of “dictatorship”)

SR 3. Partial: the actual referent is part of the presented or previous referent (e.g., when the presented stimulus was "U.S." and the subject responded by saying "I love New York"). **Note**: It is important, at this point, to emphasize the difference between the meaning dimension *Dim 2a* in which the subject characterizes the referent in terms of its parts (e.g. a car has four wheels) and the shift of referent *SR 3* in which a part of a previous referent serves as the *subject*, the *referent*, of the current meaning unit (e.g. wheels used to be made of wood).

SR 4. Modified by adding another meaning value: the actual referent includes the presented or previous referent and another meaning value (e.g., when the presented stimulus was “dog”, and the subject speaks of “cats and dogs”).

SR 5. Previous meaning value: the actual referent includes whole or part of a previous meaning value (e.g., the subject was speaking of New York: “New York is in US”, then turned to speak of the US: “US is the only superpower in the world”).

SR 6. Associative: the actual referent is related to the presented or previous referent only by association.

SR 7. Unrelated: the actual referent is not related to the presented or previous referent in any obvious way.

SR 8. Grammatical variation: the actual referent is a grammatical variation of the presented or previous referent. Variations may involve shifts in terms of parts of speech across the categories of noun, verb, adjective, adverb, gender, number (singular, plural), tense, declension and so on.

SR 9. Linguistic label: the actual referent is the presented referent treated as label. This can occur when a subject shifts from communicating about the content denoted by the label to communicating about the characteristics of the label itself.

SR 10. Combined previous meaning values: the actual referent is a combination of several previous meaning values.

SR 11. Superordinate category: the actual referent is a superordinate category of the presented or previous referent. (e.g., the previous referent was “Jerusalem”, and the current is “city”).

SR 12. Synonym: the actual referent is a synonym of the presented or previous referent

5.1.1.5. Forms of Expression

Forms of Expression characterize the forms of expression of the meaning units (e.g., verbal, denotation, graphic) and its directness (e.g., actual gesture or verbal description of gesture).

5.1.2. The Meaning Questionnaire

The *meaning questionnaire* was developed for assessing individuals' tendencies to use the different meaning variables. The test includes 11 standard stimuli (*to create, street, life, bicycle, feeling, to take, friendship, art, to murder, ocean, telephone*) and requests the subject to communicate the interpersonally-shared and personal meaning of these stimuli to someone who understands language as a means of communication, but does not know the specific meanings, using any means of expression that seem adequate. Coding the responses in terms of meaning variables yields the subject's *meaning profile* which summarizes the frequency with which the subject used each of the meaning variables.

The analysis of the questionnaire consists of the following steps: dividing the material into meaning values; coding each meaning value by assigning to it five scores, one of each type of meaning variables (e.g., when the referent is "Eyes" and the meaning value "blue", the coding on meaning dimensions is Sensory Qualities, on Types of Relation - exemplifying-illustrative, on Forms of Relation - positive, on Referent Shifts - identical to input, and on Forms of Expression - verbal); finally computing the frequencies of the occurrence of each meaning variable. The results of the analysis of the meaning questioner constitute the individual’s meaning profile. Kreitler and Kreitler state [Kreitler and Kreitler, 1990, p. 32] that students regularly learn to apply the meaning system to the actual coding of materials in a matter of several hours.

5.1.3. The Relations Between Meaning Variables and Cognitive Processes

Previous studies by Kreitler and Kreitler showed that meaning plays a crucial role in cognition, in regard to both the processes involved and the domains of contents in which the processes are activated. When individuals assign meaning to a referent, they apply to the task a certain selection of the meaning variables at their disposal. The meaning variables that an individual uses frequently reflect his or her cognitive tendencies and style. Studies showed that there is a good correspondence between the competence of individuals in cognitive tasks, and their preferred, frequently used, meaning variables. It is thus possible to characterize cognitive tasks in terms of the meaning variables that were significantly more frequently used by individuals who score high on some task-related scale (in relation to those who don’t). For example an individual who tends to use Dim15 *Locational qualities* frequently is expected to perform well in cognitive tasks involving location, such as solving Poretus mazes; subjects who use the meaning dimension *temporal qualities* frequently tend to structure their behavioral plans chronologically more often than those who use this dimension infrequently. The variables frequently used by high scorers in a cognitive task are labeled the *meaning profile of the cognitive task.*

The relations between the meaning profile of a cognitive task and the meaning profile of an individual are, as many studies have shown, bi-directional: training individuals in the frequent use of those variables that constitute a task's profile improves their performance in this task, while training individuals directly in a cognitive task strengthens specific meaning variables involved in performing it. This practical implication of using KMT for devising basic training programs was one of the main reasons for its selection as a cognitive analysis tool in this study.

As mentioned above, the meaning system has been used to study many types of cognitive tasks. Three of these studies involved tasks that are related to creative behavior, and hence are worth describing in some detail here. The first was a study of the *cognitive determinants of exploration*; the second study tested the effectiveness of a meaning training program aimed at reducing *Functional Fixedness* effects (see chapter 3 for a description of the phenomenon), and the third dealt with the psychosemantic foundations of creativity and analogical thinking.

5.1.3.1. Meaning and Exploration

Exploration plays an important role in creativity as emphasized by Finke [Fink, 1992]. In Finke's *geneplore* model creative thinking consists of a *generation* stage in which *pre-inventive forms* are elicited, followed by an *exploration* stage in which the forms are organized and meaning is assigned to them. Kreitler and Kreitler [Kreitler and Kreitler, 1994] summarizes a study aimed at clarifying the cognitive determinants of exploration. Preliminary studies described in the paper showed that exploration is a differentiated rather than a homogenous phenomenon. Five types of exploration processes were identified: *manipulatory exploration* (focused on exploring by means of motor actions); *perceptual exploration* (focused on exploring by means of viewing listening or smelling); *conceptual exploration* (focused on exploring by checking meanings and their interrelations, and by asking questions); *exploration of the* *complex or ambiguous* (exploring especially the complex aspects); *adjustive-compliant exploration* (exploring in line with obvious demand characteristics of the situation, and especially when expected or stimulated to do so).

In the main study reported in [Kreitler and Kreitler, 1994], the meaning system was used to identify those meaning variables that play an important role in each of the five modes of exploration. The subjects were administered the standard meaning questionnaire and a set of tasks especially designated to measure performance in the five exploration modes. In order to characterize the exploratory modes in terms of meaning variables, correlations were computed between the subjects' meaning profile and their scores on exploratory variables. The results of the study showed that indeed each exploratory mode was characterized by a different subset of the meaning variables.

Interpretation of the results indicated that subjects with high scores on *manipulatory exploration* are concerned especially with how objects function (Dim 5) , what can be done with them (Dim 4), their weight, quantity, sensory qualities (Dim 12, 13, 19 res.) , but not their cognitive qualities (Dim 22). They focus on concrete examples (TR 3a), dwell on the similarities between referents (TR 2a), and tend to qualify their statements (TR 1a) . They also tend to shift attention form the given referent to a combination of the given and other referents (SR 10). In contrast, high scorers on *perceptual exploration* have meaning assignment tendencies closely related to perception such as sensory qualities (Dim 19), locational qualities (Dim 15) and size, material, and structure (Dim 13, 9, 10 res.). They tend to focus on differences between referents (TR 2b) and stick closely to the presented referent (with some occasional associative shifts away, SR 6). High scorers on *conceptual exploration* tend to focus on the conceptual classes the referent includes (Dim 2a), the manner in which it operates or occurs (Dim 5), its causes and results (Dim 7) and other aspects which indicate tendencies for analytical, logical and consistent thinking (e.g. FR 3, 4 and 5). They have tolerance for ambiguities and tend to shift from given to modified referents (SR 5, 10 and 4). High scorers of *complexity exploration* reveal concern with internal sensations (Dim 19), evaluations (Dim 21), feelings and emotions (Dim 20). They tend to avoid concrete examples (Dim TR3 a neg.) and to redefine input (SR 8, 6, 4, and 9). Finally, high scorers on *adjustive-compliant* exploration tend to pay attention to practical aspects of reality such as belonging of things (Dim 17 b). They reveal tendencies for rigidity, low tolerance for ambiguity, and conformity (this is deduced from the fact that no positive referent shifts were identified).

5.1.3.2. Meaning and Functional Fixedness

Functional Fixedness (FF) is a cognitive phenomenon detrimental to problem solving that consists in focusing on a specific function of an object while overlooking another function required for the solution. The concept was introduced by Duncker [Duncker, ,1945]. FF is an important cognitive set that occurs in a great variety of contexts. In terms of the system of meaning FF can be described as focusing on particular meaning values of the meaning dimension *function, purpose, or role*.

Arnon and Kreitler [Arnon and Kreitler, 1984] used meaning training to broaden the range of meanings the subject hitherto assigned to referents in a problem. The meaning training was designed to promote the assignments of 10 *meaning dimensions* and one *type of relation* variables. The meaning dimensions were *contextual allocation; function, purpose, or role; actions and potentialities for action; range of inclusion; sensory qualities; material; weight and mass; locational qualities; domain of application*; The type of relation is *comparative type of relation-similarity*. The assumption underlying the selection was that each of the selected meaning variables may potentially have a specific contribution to reducing FF. For example, promoting the use of Dim 2, *range of inclusion,* may compel the problem solver to focus on different parts of the referent, which may be crucial to a solution (Note that this process is very similar to the *refinement* process of the SIT method described in chapter 4). Arnon and Kreitler's findings show that meaning training, especially when focusing on problem sphere referents, is effective in overcoming FF.

5.1.3.3. Meaning and Creativity

In a study reported in [Kreitler and Kreitler, 1990], the aim was to test meaning impact on analogical thinking (believed to play an important role in creative thinking), and creativity as manifested by scoring on the Kogan and Wallach Creativity Test (see next section). The results showed that scoring on an analogical thinking test was significantly correlated with, TR 2, the *comparative type of relation* and with the specific meaning dimensions underlying the structure of the analogy (e.g., in the analogy ‘A river is related to a brook as an ocean is to...’, the relevant meaning dimension is *size*). The results concerning the creativity test showed that scoring on *flexibility* correlated significantly with TR 3, *exemplifying-illustrative type of relation;* and scores on *originality* correlated significantly with the *metaphoric-symbolic* type of relation. The studies were extended to test the effect of meaning training on performance in analogical thinking and creativity test and the results showed positive effects.

5.2. The creativity test

The creativity test used in our study was Kogan and Wallach’s version of Guilford's divergent thinking test (see chapter two for the theory of divergent thinking). The test is based on both verbal and visual procedure formats. The verbal tasks consist of a *possible uses* test in which subjects are requested to suggest many possible uses for a simple object (e.g. find many possible uses for a cork), and a *possible similarities* test in which subjects are requested to propose possible similarities between two objects (e.g. train and tractor). In the visual task the subjects were requested to propose an interpretation or meaning for each of various abstract visual patterns and line forms. In this study the test consisted of eight tasks: two possible uses; two possible similarities; two visual patterns; and two line forms. The tests were coded on the basis of three out of the four Guilford divergent thinking factors: f*luency* - the total number of responses; f*lexibility* - the number of different categories of responses (e.g. a subject suggesting possible uses for a brick - build wall, build a ceiling, and use as weight for pendulum, would score 3 on fluency and 2 on flexibility, as only 2 categories of ideas were suggested); *originality*: the number of unique ideas suggested by less than 5 percent of the subjects.

5.3. A description of the study

In the current research the cognitive task was defined as ‘the capacity of an individual to use SIT to find conditions-satisfying solutions to engineering problems’. The subjects were engineering students, in their fourth year, who participated in a one-semester Inventive Thinking course. All subjects were administered the Meaning

Questionnaire and the creativity test twice - pretest before the course and post-test after the course.

5.3.1. Subjects

Subjects were 57 industrial engineering students, 15 girls, 42 boys, aged 21-28, who participated in two fully credited academic ‘Inventive Thinking for Engineers’ course. The subjects voluntarily selected the course.

5.3.2. Method

As mentioned above, the subjects were administered the meaning questionnaire and the creativity test twice: at the beginning of the course (pretest) and at the end of the course (posttest). At the beginning of the course they were also asked to suggest creative solutions to two engineering problems presented to them. The assessment of their acquisition and mastery of the SIT method, and their capability to successfully use it to find conditions-satisfying (and hence creative, according to Chapter 2) solutions was based on their final course examination. In this examination they were asked to solve creatively, by using the SIT method, 4 real-life engineering problems (different problems for each of the two groups). Their score was computed on the basis of the number of suggested conditions-satisfying solutions.

5.3.3. Procedure

All meaning questionnaires were coded by an experienced investigator, and the subjects’ (pretest and post-test) meaning profiles were extracted. On the basis of their scores in the SIT test the group was divided into two subgroups: 35 subjects who scored high on the test (the ‘inventive’ subjects) , and 22 subjects who scored low (the ‘non-inventive’). Three different meaning profile and creativity test scores comparisons were computed: between the inventive and the non-inventive based on their pretest meaning profile and creativity scores; between the inventive and the non-inventive based on their post-test meaning profile and creativity scores; and, between pretest and post-test meaning profiles and creativity scores. The meaning variables that differentiated the groups in each comparison were computed through a standard t-test. Significance level of 95% was regarded a threshold for significant difference.

5.3.4. Results

Tables 5-1 through 5-3 present the results of the meaning tests. All variables appearing in the tables are characterized by a significant level beyond 0.9, entries with significant levels of 0.95, 0.99 are marked by '*' and '**' respectively. Table 5-1 details the differences in meaning assignment between inventive and non-inventive subjects based on post-training meaning test. The results show that inventive subjects scored significantly higher on total number of different meaning values; number of different meaning dimensions; SR 8 - shift to a grammatical variation; FE 2 - graphic form of expression; and number of different S (sensory qualities, e.g., vision, smell, taste etc.) used by the subject. Table 5-2 details the differences in meaning assignment between inventive and non-inventive subjects based on the pre-training meaning test. In this test (those who were later to be classified as) inventive problem solvers scored significantly higher on total number of meaning values; number of different TR (type of relations); TR 2a - comparative similarity; number of different SR (shifts of referent); SR 3 - shift to part of referent; SR4 - shift to a modified (by adding a meaning value) referent; SR 9 - shift to a linguistic label of the referent; SR 11 - shift to a higher level referent. In contrast to these results Inventive problem solvers scored significantly lower on Dim 10 - structure. Table 5-3 details the results of the differences between pre-training and post training showing that training increased significantly the use of Dim 22a - cognitive qualities evoked by the referent; TR 1 (a + b) - attributive type of relation (a - qualities to substance, b - actions to agent); and the use of general, lexical meaning. On the other hand training decreased the use of TR 3 - exemplifying illustrative type of relation (3a - exemplifying instance, 3b - exemplifying situation, 3c - exemplifying scene) and the use of personal meaning.

Table 5-1. Significant differences between inventive and non-inventive problem solvers, based on post-training meaing profile

	Inventive (n=35)		Non-inventive (n=22)		t-test (df=55)
	Mean	StD	Mean	StD	
No. of meaning values	165.971	57.030	123.636	54.100	2.78**
SR8	.022	.020	.012	.016	2.10*
No. of different SR	6.886	1.510	6.045	2.035	1.79
Dim8b	.099	.026	.111	.027	1.69
No. of different Dim	23.857	1.700	22.727	2.453	2.05*
No. of different Dimm	19.114	.993	18.500	1.406	1.93
TR2c	.028	.015	.035	.016	1.71
FR5	.031	.023	.042	.022	1.73
FE2	.058	.077	.026	.046	2.01*
FE10	.000	.000	.001	.003	1.83
No. of different S	3.514	1.721	2.545	1.101	2.59*

* p < .05** p < .01

Table 5-2. Significant differences between inventive and non-inventive problem solvers post-training, based on their pre-training meaning profile

	Inventive (n=34)		Non-inventive (n=22)		t-test (df=54)
	Mean	StD	Mean	StD	
No. of meaning values	173.529	73.890	138.000	55.524	1.93
No. of different SR	7.029	1.586	5.591	1.869	3.09**
No. of different TR	7.941	.952	6.909	1.231	3.53***
SR3	.016	.022	.006	.009	2.38*
SR4	.023	.022	.006	.008	4.08****
SR9	.031	.023	.014	.020	2.83**
SR10	.185	.042	.211	.047	2.10*
SR11	.003	.008	.001	.001	2.13*
Dim10	.011	.009	.018	.015	2.09*
Dim12	.001	.001	.002	.003	1.91
Dim13	.015	.011	.007	.010	2.55*
Dim19b	.001	.002	.003	.006	1.92
Dim21a	.033	.020	.023	.019	1.88
TR2a	.007	.006	.002	.005	2.95**
TR2c	.027	.013	.034	.016	1.72
TR2d	.018	.014	.012	.013	1.68
FR7	.001	.002	.000	.000	1.77
S3	.093	.151	.187	.220	1.88
S8	.023	.052	.000	.000	2.54*
S10	.239	.238	.118	.153	2.09*

* p < .05** p < .01 *** p < .001 **** p < .0001

Table 5-3. Significant differences between problem solvers pre- and post-training

Variable	Pre (n=33)		Post (n=33)		t-test (df=32)
	Mean	StD	Mean	StD	
SR3	.017	.022	.011	.015	1.76
SR9	.032	.023	.024	.022	1.78
Dim7	.015	.012	.011	.009	1.92
Dim22a	.009	.010	.014	.009	2.87**
TR1a	.651	.067	.673	.060	1.74
TR1 (a+b)	.797	.063	.831	.043	3.38**
TR2b	.036	.016	.043	.016	1.88
TR3a	.089	.046	.061	.037	4.01****
TR3b	.010	.016	.004	.007	2.52*
TR3 (a+b+c)	.099	.055	.064	.040	4.15****
No. of different TR	7.909	.947	7.454	1.175	2.09*
General meaning	.886	.059	.922	.043	4.10****
Personal meaning	.114	.058	.078	.043	4.09****
FR5	.041	.029	.031	.023	2.19*
S2	.067	.096	.029	.066	2.86**

* $p < .05$ ** $p < .01$ *** $p < .001$ **** $p < .0001$

The next three tables, 5-4 through 5-6, present the data of the creativity test. Table 5-4 details the differences in creativity scores between Inventive and non-Inventive subjects based on pre-training creativity test and shows no significant differences (Inventive subjects scored higher on fluency almost significantly). Table 5-5 details the differences creativity scores between Inventive and non-Inventive subjects based on post-training creativity test showing that Inventive problem solvers scored significantly higher on flexibility and almost significantly higher on fluency. Table 5-6 details the results of the differences between pre-training and post training showing that training decreased originality significantly. Table 5-7 summarizes all significant results of all tests (including meaning and creativity).

Table 5-4. Significant differences between inventive and non-inventive problem solvers, based on creativity test pre-training

Variable	Inventive (n=18)		Non-inventive (n=17)		t-test (df=33)
	Mean	StD	Mean	StD	
Fluency	6.069	1.784	5.073	1.665	1.70$^{\pi}$
Flexibility	5.072	1.395	4.426	1.446	1.34
Originality	2.256	1.448	1.676	.963	1.38

$^{\pi}$ $p = .098$

Table 5-5. Significant differences between inventive and non-inventive problem solvers post-training, based on Creativity Test post-training

Variable	Inventive (n=20)		Non-inventive (n=17)		t-test (df=35)
	Mean	StD	Mean	StD	
Fluency	5.950	2.315	4.757	1.401	1.85[π]
Flexibility	4.900	1.664	3.926	.803	2.32*
Originality	1.544	1.197	1.294	.733	.75

[π] p = .072   * p < .05

Table 5-6. Differences between Problem Solvers Pre- and Post-Training on Creativity Test

Variable	Pre (n=36)		Post (n=36)		t-test (df=35)
	Mean	StD	Mean	StD	
Fluency	5.576	1.750	5.458	2.058	.36
Flexibility	4.758	1.416	4.490	1.440	1.17
Originality	1.972	1.236	1.451	1.018	3.14**

** p < .01   *** p < .001

Table 5-7. Summary of all (0.05) significant results

variable	Posttest Vs. Pretest	inventive vs. non-inventive (based on pretest)	inventive vs. non-inventive (based on posttest)
No. of meaning values		↑#	↑↑
No. of different dim(dimensions)			↑
No. of different S(sensory qualities)			↑
Dim 10 Structure		↓	
Dim 13 Size and Dimension		↑	
Dim22a Cognitive Qualities	↑		
No. of different Types of Relations.		↑↑↑	
TR1a Qualities to substance	↑		
TR1(a+b) b - Actions to agent	↑↑		
TR2a Comparative - Similarity		↑↑	
TR3a Exemplifying instance	↓↓		
TR3b Exemplifying Situation	↓↓		
TR3(a+b+c) c - Ex. Scene	↓↓↓		
General meaning	↑↑↑↑		
Personal meaning	↓↓↓↓		
No. of different Shits of Referent		↑↑	↑#
SR3 Partial		↑	
SR4 Modified		↑↑↑↑	
SR8 Grammatical Variation			↑
SR9 Linguistic Label		↑↑	
SR10 Combined meaning values		↓	
Fluency - number of responses		↑	↑

Flexibility - number of categories			↑
Originality - n. of uncommon res.	↓↓		

↑# $p < 0.1$, ↑ $p < 0.05$, ↑↑ $p < 0.01$, ↑↑↑ $p < 0.001$, ↑↑↑↑ $p < 0.0001$, arrows pointing upward represent inventive subjects (or posttest) scored significantly higher than non-inventive (or pretest). arrows in opposite direction represent the opposite.

5.4. Analysis of the results

The differences between inventive and non-inventive subjects, in terms of meaning variables and creativity scores, based on their pretest and post-test meaning profiles, point at the cognitive processes underlying effective acquisition and mastery of the SIT method. Since SIT is a procedure supporting the search for conditions-satisfying, and hence creative, solutions, the identified cognitive processes are expected to teach us about creative processes in general. The differences between pretest and post-test results show SIT's training effect on cognition.

The results of all three meaning tests summarized in Table 5-7 show three distinct clusters of differences, in line with the different sets of meaning variables, between inventive and non inventive problem solvers, and between pre-training and post-training: the first, in the set of *meaning dimensions,* includes total number of meaning values, total number of meaning dimensions and three specific meaning dimensions (Dim 10 - structure (neg.), Dim 13 - size and dimension, Dim 22a - cognitive qualities); the second set, the *type of relations* set, includes the total number of different types of relations, TR 1 - the attributive type of relations (TR 1a - qualities to substance, TR 1b actions to agent), TR 2a - the comparative type of relation that focuses on similarity, and TR 3 - exemplifying-illustrative type of relation (TR 3a - exemplifying instance (neg.), TR 3b situation (neg.), TR 3c exemplifying scene (neg.)), and finally the results in this set show increase in general meaning and decrease in personal meaning; the last set, the *shift of referent* set, includes the total number of different referent shifts and SR 3 - shift to a part of the referent, SR 4 - shift to a modified referent, SR 8 - shift to grammatical variation, and SR 9 - shift to a linguistic label. In what follows these three sets of meaning variables, representing three distinct types of cognitive processes, will be analyzed separately followed by an analysis of the creativity test results. The discussion will focus on relating the results to the theory of the sufficient conditions and the SIT method.

5.4.1. Meaning Dimensions

Post-training results (Table 5-1) show that inventive problem solvers tend to assign more *meaning dimensions* to the input and use more *meaning values* in their meaning assignment. Using more meaning dimensions represents an individual's mastery of more content categories and his or her flexibility in switching attention between them. The number of meaning values represents the problem solver's fluency in assigning meaning and is dependent, of course, also on the number of meaning dimensions at his or her disposal. The ability to view the input from a larger spectrum of meaning variables and meaning values forms the basis of the problem solver's ability to focus on more diverse aspects of closed world objects and to find ways of using them in the solution. In other words, the closed world condition compels the problem solver to extend the search space by playing with different meanings of the same set of objects, rather than by extending the set of objects. For example, a common SIT task is to find a closed world object to carry out an operation (mainly in the Unification and Multiplication operators). The appropriateness of an object for carrying out an operation can be due to only a few of its possible meaning dimensions, and a subject overlooking these dimensions would fail to use the object. Another aspect of inventive problem solvers' tendency to use more meaning values is that their thinking is more fluent, helping them exhaust the different routes offered by SIT in a problem solving session. Another result, in line with the above results, is the inventive problem solvers' utilization of a more diverse set of different sensory qualities (No. of different S) in their meaning assignment, showing, again, their ability to view the referent using a wide spectrum of information channels.

Pre-training results also show that inventive problem solvers tend to use more meaning values (but less significantly), but no significant differences in meaning dimensions were found. These results can be explained by the SIT training effect of increasing inventive problem solvers' flexibility in using diverse meaning dimensions. In other words, those who started SIT training equipped with a potential to become inventive problem solvers benefited more in terms of its psychological side effect of increasing their thinking flexibility. A very interesting, yet explainable, result is inventive problem solvers reduced focus on *structure* of referents (Dim 10). Inventive problem solving, especially that invoked by SIT's restructuring strategy, involves breaking up a structure by reorganizing its elements (SIT's Division technique), or removing an element (SIT's Object Removal technique). A problem solver who tends to focus on structure of referents is expected to think more rigidly and be less prone to modify or even break this structure. It is interesting to note that in the post-training test this result was not duplicated. We suspect that this means that SIT training decreased the use of structure among those who originally tended to use this dimension more frequently, namely the non-inventive problem solvers. Comparing the meaning profiles pre- and post-training of the non-inventive group revealed that, indeed, their use of structure in meaning assignment decreased significantly.

Pre Vs. Post training results show that the only significant effect of SIT training (affecting all subjects) in using meaning dimensions was the increased use of Dim 22a - cognitive qualities evoked by the referent. This result can be explained by the effect of SIT training stimulating meta-cognitive control of the thinking process.

5.4.2. Types of Relations

Pre-training results show that inventive problem solvers tend to be more diverse in their selection of types of relations, a fact indicating their more flexible meaning assignment mechanism. Inventive problem solvers also tend to use more frequently TR 2a - the type of relation focusing on similarity. This fact can be explained by the fact that 'similarity analysis' is necessary for finding solutions constrained by the Closed World condition. This allows to extend the problem's framework only by the addition of objects that are similar, but not necessarily identical, to existing objects.

Pre Vs. Post training results show the most notable differences in the frequency of the use of types of relations. Training increased the use of TR 1 - attributive type of relation and decreased TR 3 - the exemplifying-illustrative type of relation. More generally, SIT training increased the frequency of the lexical, interpersonal mode at the expense of the personal mode. This result may be due to the fact that training involved learning a general, highly constrained procedure that does not favor the use of personal knowledge and associations.

5.4.3. Referent Shifts

Pre-training results show that inventive problem solvers tend to switch more frequently from the given referent to another one, a fact that can be attributed, again, to their more flexible, less conforming thinking. It is plausible that the inventive problem solvers use their aptitude to shift from one referent to another in order to manipulate the input information so as to reformulate problem definition. The specific referent shifts that were found to be significant in this test – SR 3 (shift to part of referent); SR 4 (shift to a modified referent) and SR 8 (shift to a grammatical variation of the referent); as well as SR 9 (linguistic label), significant in the post training test – are characterized by their intermediate distance from the input. The following shifts of referent - SR 1 (identical), SR 5 (Previous meaning value), SR10 (combined previous meaning values), and SR 12 (synonym) - are semantically close to the given referent because the subject does not switch to a meaning variable that was not mentioned previously. In contrast, SR 6 (associative) and SR 7 (unrelated) are semantically distanced from the given referent since there is no definite link between the modified and the given referents. This result – that the significant shifts of referent are the intermediate ones – is completely in line with the framework of the sufficient conditions which encourages making qualitative changes in the behavior of a system, while limiting the changes that can be made to its physical structure. Small changes in the system's structure fail to bring about a qualitative change in its behavior, whereas large changes violate the closed world condition. The cognitive qualities required for an effective acquisition and use of the SIT method are those that support the flexibility to modify the referent as much as possible to the extent that does not go beyond its 'semantic closed world'.

A closer look at the specific referent shifts that characterize the difference between inventive and non-inventive problem solvers reveals an interesting correspondence to the underlying processes of the SIT method. SR 3 (shift to a part of the referent) can be seen as related to the Division technique - restructuring an object by focusing on its parts and rearranging them; SR 8 (grammatical variation) is related to the Multiplication technique - using another instance of an existing object, as one form of grammatical variation, among others, is to shift to a plural instead of singular form; SR 9 (shift linguistic label) is related to the ability of the problem solver to shift attention between the meaning of a referent (the *function* of an object in engineering systems) and its label (the form of an object) which may in turn help to access new aspects of the referent (new uses for the form). This ability is important in applying the Unification technique, that requires the ability to shift focus from the function of an object (be it currently useful, neutral, or harmful) to its form, and utilize previously overlooked aspects (meaning dimensions or meaning values) of that form to carry out a new, needed function.

Post-training results show that the differences between inventive and non-inventive subjects in terms of referent shifts have disappeared. On the other hand the referent shift to a grammatical variation which was not significant in the pretest became significant. A closer look at the results reveals that the total number of referent shifts is still a factor, though the significance level is reduced to 90%. These results show that the effect of SIT training is to reduce the differences between the inventive and the non inventive subjects in their capability of using referent shifts. Still those who came to the course equipped with the competence to closely modify the referent did better than those who acquired it during the course.

5.4.4. Creativity Study

Pre-training results show that inventive problem solvers score higher on fluency (almost significantly) and on flexibility, but do not score higher on originality. These results are in accord with the meaning study's results that inventive problem solvers tend to assign more meaning values (fluency) and more meaning dimensions (flexibility). Also *Post-training results* show that inventive problem solvers are more fluent (almost significantly), but not significantly more flexible and original. *Pre Vs. Post training* results show a seemingly counter intuitive result: SIT-training does not affect fluency and flexibility but reduces originality. This result is, however, in accord with the previous finding, in the meaning test, involving the decrease in using personal modes and increase in the use of general interpersonal lexical mode, and can be explained accordingly.

5.5. Summary and conclusions

Using Kreitler and Kreitler's meaning system and Kogan and Wallach's creativity test, some of the cognitive processes underlying the learning and application of the SIT method were identified. The results show that inventive problem solvers are more flexible and fluent thinkers: they have at their disposal a more diverse set of meaning dimensions; they ‘communicate’ with the referent through a wider spectrum of sensory qualities; they do not fixate on the given referent, but rather tend to modify it in a way that is neither very close to the given referent (and therefore not interesting), nor too distanced from it (so as to traverse the boundaries of its semantic closed world); they pay less attention to the structure of the referent so as to be in a better position for thinking about restructuring it; finally, they score higher on fluency and flexibility in the creativity test. SIT training decreases problem solvers’ reliance on personal experience and associations, while increasing their use of interpersonal common knowledge and procedures. Training also reinforces meta-cognitive control processes.

The results of both the meaning study and the creativity study are interestingly related to some of the theories of creativity mentioned in Chapter 4. The theory of divergent thinking as *competence* (rather than as *performance*) is supported by the finding that on the one hand inventive problem solvers’ ideation is more fluent and flexible, but on the other hand SIT training, while significantly increasing actual performance in creative problem-solving, did not increase ideational fluency and flexibility. On the basis of these results it is possible to suggest a solution to the divergent thinking paradox: the fact that the theory of divergent thinking has been widely accepted (and even equated with creativity), and yet, divergent thinking tests fail to reliably correlate with real life creativity. Divergent thinking may be an important low level skill underlying creative thinking, but one that is silent until it is invoked by a higher level strategy such as the SIT method. Another explanation may be that divergent-thinking skill is useless when not operated within an appropriately constrained framework such as the one formed by applying the sufficient conditions to a specific situation. The Gestalt view of creativity - breaking one Gestalt in favor of another - is related to the finding that inventive problem solvers tend to pay less attention to structure rendering them more prone to breaking the structure and reorganizing the parts, as often required under the constraints of the closed world condition. Meaning dimensions, especially those initially hidden from the problem solver, can be viewed as representative of Hofstadter’s knobs. Following this analogy, ‘variation on a theme’, is achieved by inserting different meaning values to a ‘slot’ created by a particular meaning dimension. Similarly, inventive problem solvers’ wider spectrum of meaning dimensions can be viewed as the underlying mechanism for expanding the search-space in line with Boden's model of creativity. The specific role of shifts of referents in the meaning profile of engineering creativity is in accord with Duncker's view that the capacity to reformulate the given input is an important factor in establishing a creative solution. The fact that SIT training increased the lexical-interpersonal mode of meaning at the expense of the personal mode, is in contrast to the view that private personal factors underlie creative processes, and thus does not support the theories such as Mednick's that emphasize the associative nature of creative thinking.

Regarding some of the big questions concerning the understanding of creativity the results support the view that creativity is a general competence across different domains. Domains are supposed to be characterized by a specific pattern of meaning dimensions, but in this study, although dealing exclusively with the engineering domain, no particular meaning dimensions were identified as contributing to creative performance (except for structure and cognitive qualities that are relevant to any domain). Another issue that the results of the study may relate to is the question whether creative thinking is a unique process (as held by the Gestalt school for example) or 'nothing special' (as strongly claimed by Weisberg). We believe that the unique pattern of meaning variables that were found to characterize engineering creativity support the 'uniqueness' view of creativity.

The results of the study also add another dimension to the proof of the validity of the sufficient conditions as a framework for creative engineering solutions. The theory of the sufficient conditions is supported by the fact that subjects who succeeded in finding conditions-satisfying solutions were characterized by creativity-related traits. As mentioned before, these subjects scored higher on flexibility and fluency in the creativity test, used more meaning dimensions and referent shifts and paid less attention to structure.

Practically, and maybe most importantly, the results of this study suggest an approach for the design of basic training for preparing an individual for SIT learning. Although beyond the scope of this research, it is obvious that training should include (among others) the following elements: aquatinting subjects with all 22 meaning dimensions, and exercising them in communicating the meaning of diverse, and preferably task specific, referents using as many meaning dimensions as possible (and as many meaning values as possible for each meaning dimension); training in the ability to shift between referents in line with the findings; and training in breaking structures of specific referents (e.g., “describe the structure of a common table and find new uses for a table in which the structure is modified”).

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Chapter six

This summary chapter presents the main ideas of this thesis and suggests topics for further research. Section 6.1 summarizes the results of our study of the sufficient conditions for engineering solutions, the SIT method, and the meaning profile of SIT. Section 6.2 reviews some of the theories of creativity mentioned in Chapter 2 and ties them to the theories, methods, and empirical results of this work; Section 6.3 suggests topics for further research. Section 6.4 concludes this thesis.

6.1. Product, process, and person

As mentioned in the introduction, *product*, *person* and *process* are the primary, commonly accepted approaches for the study of creativity in general, and the study of engineering creativity in particular. The main chapters of this thesis (chapters 3, 4, and 5) reflect these approaches.

Chapter 3 studied the unique characteristics of creative engineering *products*, as opposed *to* conventional or routine ones. The results took the form of two jointly-sufficient conditions that characterize a large set of creative engineering solutions that fall into the category of 'inventions within a paradigm'. The first condition - the Closed World condition - constrains the solution to not incorporating new *types* of object that were absent from the initial engineering system and its neighborhood. The second condition - Qualitative Change - requires that the solution incorporate a qualitative change in at least a single *relation* (between an undesired effect, and an attribute that currently increases the severity of the undesired effect) that characterizes the problem. "Qualitative" means here that a relation changes its trend from a direct-relation to either no-relation or inverse-relation. Setting problem-solving goal in terms of relations rather than absolute values requires major changes in the behavior of the system. This, in conjunction with the constraints posed by the Closed World condition, creates a problem-solving task solvable only by creative operators. The joint sufficiency of the Closed World condition and the Qualitative Change condition was established empirically: ratings on a 1-7 creativity-scale of more than 100 engineering solutions by 200 engineers fit very well the sufficient conditions framework.

Chapter 4 dealt with the creative engineering *process*. It developed SIT, a step-by-step, systematic strategy that supports the search for creative engineering solutions satisfying the sufficient conditions. The method is based on five operators: Unification, Multiplication, Division, Breaking Symmetry, and Object Removal. Common to all these operators, called idea-provoking operators, is that applying them to a given problem's world does not involve adding new types of objects and thus the Closed World condition is satisfied.

The five idea-provoking operators are divided into two main strategies that reflect two different cognitive approaches to problem-solving. In the first, the *extension* strategy, a top-down process is applied in which the problem solver first determines *what* to do and then *how* to do it. With the second approach, the *restructuring* strategy, a bottom-up, function-follows-form process is applied in which the system is first restructured (by modifying the interrelations among its parts or attributes) followed by an attempt to assign meaning to the new structure. In the restructuring strategy, the *how* precedes the *what.*

In its initial stages SIT guides the problem solver in analyzing the problem's world: to prepare a list of system and neighborhood objects; to determine the functional relations among system objects; and to identify the problem characteristic relations. Empirical pre-training and post-training studies demonstrated that, indeed, the rate of conditions-satisfying solutions increased drastically through SIT training and application.

Chapter 5 dealt with the creative *person*. It studied the cognitive mechanisms that differentiate inventive problem solvers (those successful in using SIT for creative problem solving) from non-inventive ones, as well as the change in cognitive processes induced by SIT training. Research tools such as the Kreitler and Kreitler meaning system and the Wallach and Kogan creativity test were used. The results indicate that successful SIT users tend to score significantly higher on ideational flexibility. They use more meaning dimensions and shift more often from current referent in their meaning assignment process; they are less committed to current referent's structure (the interrelations among its parts); and they score higher on flexibility in the creativity test. The significance of these results is twofold: first, they point to the way in which pre-SIT training can be carried out; and second, they reconfirm the relation between the sufficient conditions and creativity. Ideational flexibility (one of the factors of divergent thinking) has long been associated with creative processes and, as the empirical study indicates, it is also the cognitive ability required for finding solutions that satisfy the sufficient conditions.

6.2. Theories of creativity revisited

Chapter 2 described 15 theories of creativity and 4 engineering design theories of creativity. References to these theories, that tie them to the theories and methods developed in this work were made throughout this thesis. It would be, however, worthwhile at this point to review all the relevant relations between the results of this work and the terms it uses and the ideas expressed by other investigators and the terms they use. Table 6-1 summarizes these relations.

Table 6-1. Summary of the relations between other theories' concepts and the concepts of this work

Investigator	Main concepts	Related concepts in this work	Explanation
De Bono	Provocation	QC condition	QC condition generates a provocative problem-statement
Altshuller	Overcoming conflicts	QC condition	A state of conflict is a private case of the QC condition. If the independent variable in a problem-characteristic is related to the system's functioning, it reflects a conflict between improving functioning and increasing undesired effects.

Num Suh	Independence Axiom	QC condition	Independent Axiom is similar to QC condition in its requirement to make design parameters independent of each other.
Wazlawick Change	Second order change	QC condition	QC condition inhibits more-of-the-same solutions (which are given as counter-examples for second order changes by the authors)
Guilford	flexibility	strategies, techniques, objects, meaning dimensions, referent shifts, decreased focus on structure	Flexibility is the ability to switch between SIT's strategies and operators. Flexibility is the ability to switch between objects (in the framework of the same technique). Flexibility is the ability to switch between meaning dimensions (in the framework of the same object). Flexibility is the ability to shift from current object (the current referent) to its parts, to a linguistic label of the object, to grammatical variation, or to a modified object. Flexibility is the ability to change the structure of an object.
Guilford	fluency	object, meaning dimension	Fluency is the ability to refer to an object from the viewpoint of many *meaning values* within the framework of same meaning dimension.
Hofstadter	variations on a theme	the Closed World condition	Here theme = problem's world. The Closed World condition allows only variations on problem's world.
Hofstadter	knobs	meaning dimensions	A new knob is like viewing a concept from the viewpoint of new meaning dimensions
Duncker	functional fixedness	Closed World condition, Unification technique	The Closed World condition compels the problem solver to assign unusual uses to existing objects. Unification technique is SIT's tool for overcoming functional fixedness.
Gestalt school	Restructuring	restructuring strategy	The restructuring strategy helps problem solvers break current structures and reorganize them

Finke	Function follows form	restructuring strategy	SIT’s restructuring strategy guides the problem-solver to first change form, and than assign function to the new form.
Boden	Search space expansion	Sufficient Conditions	The Sufficient Conditions compels the problem solver to search for the solution in hitherto overlooked portions of the search-space.
Schank	the importance of failure	Sufficient conditions	The framework of the Sufficient conditions create a task for which initial attempts to solve are likely to fail
Boden	heuristic: changing the value of numerals in problem space	Multiplicatio n	Multiplication draws problem-solver’s attention to the possibility of increasing the number of objects of the same type.
Lenat	heuristic search and creativity		SIT’s five techniques can be viewed as heuristics.
Koestler	Bisociation	Unification	The Unification procedure results in connecting two previously unconnected elements: an object and an operation
Perkins	Isolation problem, Oasis problem	Sufficient conditions	The sufficient conditions create a framework that directs the problem solver towards isolated areas of problem-space and away from the (tempting) oasis.
Ulrich	function sharing	Unification, Object removal	When an object is removed from the system, another object may share its function.
Cagan and Agogino	Design space expansion through introducing new variables	Breaking Symmetry	Breaking Symmetry connects two previously unconnected variables (say Z and W) resulting in the formation of a new variable (dZ/dW)
Wallas	Preparation (that begins with failure)	SIT’s preparation stage	Forming a list of system and neighborhood objects. Constructing the Functional Structure and Determining problem characteristic relations are SIT’s preparation stage. The result is a problem definition based on the sufficient conditions that inhibits routine ideas.
Wallas	Incubation	Search through SIT’s	

		strategies and techniques	
Wallas	Illumination	Hitting upon a successful technique	
Wallas	Elaboration	The schematic solution	

Several theories mentioned in Chapter 2 – the creative use of *analogies*, Weisberg's *'nothing special'* approach, design *from first principles*, and *cased based design* – are not presented in table 6-1 for reasons explained below. Analogies are not represented because SIT does not make use of analogies, although SIT's five idea-provoking techniques can be viewed as 'ready-made abstract templates' drawn from many analogical sources. A SIT user is thus free from the need to identify a source analogy and to extract an abstract template for mapping it into his target domain. He or she is only responsible for the last stage of analogical thinking: applying an abstract template (one of SIT's five techniques) to the problem at hand. Weisberg's view, that creativity is just a form of routine problem solving, is not supported by the results of this work which found that inventive problem solvers are characterized by unique cognitive qualities that are in line with the theory of divergent thinking. The theory of case-based design is actually an implementation of analogical thinking to design and it is absent from Table 6-1 for the same reasons that analogical thinking is. The theory of design from first-principles deals mainly with design-from-scratch, while the theory presented in this work deals with design problem solving.

Chapter 2 ended with the following paragraph that suggested the possibility of selecting and integrating different theories of creativity in order to arrive at a concrete set of instructions for directing problem solving towards creative solutions.

> Set the problem solving goal as *overcoming a contradiction* or *second order change*, but confine your search-space to *variations on a current theme* (rather than abandoning current theme and moving to another one). This may lead you to a temporary state of *failure* which is a good starting point for the creative process. Draw on your *divergent thinking* ability and skill, mainly *fluency* and *flexibility,* to *expand the search-space.* Be aware of the possibility that the solution lies in an *isolated* area of the search space due to functional and structural *fixedness.* Use heuristics such as *reversal*, *dropping constraints*, *function-sharing*, and *changing the value of a numeral*.

Using this work's terms and concepts, this paragraph can be translated into the following set of instructions showing the close correspondence between our theory and (an integration of many) previous ones:

> Set the problem solving goal as *qualitatively changing at least one problem-characteristic unit,* but confine your search-space to *the current Closed World*. This may lead you to a temporary state of *failure* which is a good starting point for the creative process. Explore *SIT's strategies and techniques: Unification, Multiplication, Division, Breaking Symmetry, and Objet Removal,* focus on *different objects*, and try to view each from the viewpoint of *different meaning dimensions.*

6.3. Suggestions for further research

6.3.1. Non-Closed-World Creative Engineering Design

The framework of the sufficient conditions characterizes a large set of creative engineering solutions but not all. Creative engineering solutions exist in which new types of objects are added to the system. More research is needed for characterizing such solutions. One hypothesis may be that in creative solutions, when incorporating non-closed world objects, the new object forms a special type of *interaction* - yet to be discovered - with the given system.

Another type of engineering problem for which the framework of the sufficient conditions is currently not inapplicable is design-from-scratch problems in which the problem's world is simply not yet defined. Great inventions such as the telephone, the laser, the light bulb fall into this category. Although we believe such inventions stem from different creative mechanisms – dependent on the development of basic technologies, chance, spirit, and large-scale social trends – it would be interesting to look for common patterns for these types of engineering problems as well.

6.3.2. Computerization

An important aspect regarding the tools and methods developed to support engineering thinking is their amenability to computerization. Computer programs have become the engineer's apprentice in many areas of design and thus engineers expect methods such as SIT to be coded into computer programs. Capturing SIT in a computer program that would support collaborative engineering problem solving is a promising future research area.

6.3.3. Pre-SIT Training

SIT is a high-level thinking strategy. As such, successful acquisition and application of SIT draws on lower level cognitive processes and abilities as demonstrated in Chapter 5. The identification of the meaning variables that differentiate a good SIT practitioner from a not-so-good one point to the cognitive training processes that are expected to enhance inventive problem solving through SIT. A future research topic will incorporate the design and empirical testing of such a training program.

6.3.4. Motivational Aspects of Engineering Creativity

A subject's cognitive abilities (expressed by his or her meaning profile) as well as motivation, are the main factors in predicting his or her success in performing a cognitive task. Kreitler and Kreitler's theory of *Cognitive Orientation* (Kreitler and Kreitler, 1976) and its operational measuring tool, the CO test, can be used to analyze subjects' motivational factors in relation to a cognitive task. A combined CO and Meaning test can, as demonstrated in past studies, supply a very good tool for predicting a subject's success in a cognitive task. An interesting future research topic is the application of the CO test to predict success in SIT use. The results of such a study will also have practical implications since they will point to the way in which subjects can be motivated to learn SIT and apply it to their engineering work.

6.3.5. New Domains

Most of the presented examples dealt with problems of a physical nature. A future research topic may be the extension of the theory to other fields, such as management, business strategic planning, marketing, advertising, and new product development. The main difficulty in applying the framework of the sufficient conditions to these new domains will be the formulation of the Closed World condition. The challenge will be to replace the notion of physical objects, which currently constitute the core of the closed world, to other, more abstract constructs.

6.4. Concluding remarks

Only 50 years ago, the prevailing view was that human creativity, by its own nature, is not amenable to scientific study. Since then, investigators of creativity, from various domains, such as psychology, artificial intelligence and engineering have worked to show that this view is wrong. This work joins the collective efforts to prove that creativity is a legitimate subject of scientific study. This does not mean that investigators of creativity should not develop their own specialized scientific tools. Our choice of formulating *sufficient conditions*, rather than (the mathematically stronger) *necessary conditions,* is an example of a research method that is more suited to the study of creativity. Whether necessary conditions for creative products will ever be found remains an open question. We suspect that it might be impossible to capture the phenomenon of human creativity through necessary conditions.

It is hoped that this work, and possibly other works that deal with engineering creativity, will pave the way for incorporating engineering creativity training in the curriculum of engineering studies. This may help to train better, more creative, and more productive engineers.

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Appendix A - The Meaning System

Meaning Value	Example
I. MEANING DIMENSIONS (Dim)	
1. Contextual allocation	car - a means of transportation
2. Range of inclusion	
2a. Subclasses of referent	car - sport car
2b. Parts of referent	car - has 4 wheels
3. Function, purpose and role	knife - used for slicing bread
4. Actions & potentialities for action	
4a. By referent	knife - can injure people
4b. To/with referent	Ski - taking it to the cable car
5. Manner of occurrence or operation	Ski - first you have to purchase skis than take lessons
6. Causes and antecedents	Ski - you have to be in good physical shape
7. Consequences and results	Puzzles - making you more intelligence
8. Domain of application	
8a. Referent as subject	Beauty - related to a woman
8b. Referent as object	Eating - fruit, meat
9. Material	Table - made of wood
10. Structure	Table - a board is on top four legs
11. State & possible changes in state	Water - liquid state, solid state
12. Weight and mass	Car - weighs 4 tons
13. Size and dimensionality	Car - 6 feet long
14. Quantity and number	Car - there are many of them during rush hours
15. Locational qualities	House - very beautiful in the mountains
16. Temporal qualities	Exams - there is never enough time for completing
17. Possessions & Belongingness	
17a. of referent	Car - in the past only reach people owned cars
17b. by referent	American - usually possesses a personal computer
18. Development	Organization - always increases in size
19. Sensory Qualities	Man - evolved from apes
19a. Of referent	Sea - is salty
19b. By referent	Dog - smells very well
20. Feelings & emotions	
20a. Evoked by referent	Dog - makes you happy when it is happy
20b. Felt by referent	Dog - very glad each time his master comes home
21. Judgments and evaluations	
21a. About referent	War - should be avoided by diplomatic efforts
21b. By referent	Car - is always evaluating its driver
22. Cognitive qualities	
22a. Evoked by referent	Book - sometimes make you think hard to understand
22b. Of referent	Citizens - often have short memory
II. TYPES OF RELATION (TR)	
1. Attributive	
1a. Qualities to substance	Eyes - blue
1b. Actions to agent	Policemen - catch criminals
2. Comparative	
2a. Similarity	Israel - its population is similar to Denmark
2b. Difference	Day - the opposite of night
2c. Complementarity	Friends - help each other
2d. Relationality	Sea - smaller than an ocean
3. Exemplifying-illustrative	
3a. Exemplifying instance	Cars - my neighbor's car never moves
3b. Exemplifying situation	Sadness - when you watch a tragic movie
3c. Exemplifying scene	War - a doctor tries to reach a wounded soldier

4. Metaphoric-symbolic	
4a. Interpretation	Sea - symbolizes freedom
4b. Conventional metaphor	Mind - works like a computer
4c. Original metaphor	Mind - works like termite nests
4d. Symbol	Love - fire that creates and destroys

MODES OF MEANING

Lexical Mode: Attributive + Comparative

Personal Mode: Exemplifying-illustrative + Metaphoric-Symbolic

III. FORMS OF RELATION (FR)

1. Positive	Sky - is blue
2. Negative	Oil - do not contain cholesterol
3. Mixed positive & negative	Wine - is good in small quantities but not in breakfast
4. Conjunctive	Apple - is red or green
5. Disjunctive	Cars - are pollutant and dangerous
6. Combined positive & negative	Cars - convenient, but not environment friendly
7. Double negative	Television - neither interesting nor reliable
8. Obligatory	Crime - must be fought
9. Question	computers - what is their role in society ?
10. Absolute, general	Big cities - always polluted
11. Desired	Money - people want a lot of it

IV. SHIFTS OF REFERENT (SR)

1. Identical	Car - a car is a means of transportation
2. Opposite	Murder - birth is a wonderful thing
3. Partial	Car - it is good to cover the wheel in summer
4. Modified	
5. Previous Meaning value	Car has four wheels; wheels are made of rubber
6. Associative	Car - its not easy to drive in England
7. Unrelated	Car - I love ice cream
8. Grammatical Variation	Car - cars are expensive
9. Linguistic label	Car - ‘car’ has three characters
10. Combined meaning values	
11. Superordinate category	
12. Synonym	Car - there are two many automobiles in the street

V. FORMS OF EXPRESSION (FE)

1. Verbal
   - 1a. Direct
   - 1b. Verbal description of explanation, interpretation
2. Graphic
   - 2a. Actual
   - 2b. Verbal description of drawing or painting
3. Movements, gestures & facial expressions
   - 3a. Actual enactment
   - 3b. Verbal description of movements, gestures and facial expressions
4. Sounds and voices
   - 4a. Actual voicing
   - 4b. Verbal description of sounds and voices
5. Denotation of object or situation
   - 5a. Actual presentation
   - 5b. Verbal description of object or situation to be presented