

Systematic Approaches for Inventive Thinking and Problem-Solving: Implications for Engineering Education*

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This paper highlights two different outlooks on creative thinking: disordered thinking and idea-generating methods, versus systematic inventive thinking and idea-focusing methods. Several methods of systematic inventive thinking are reviewed and examples are discussed. The experience from industry shows that, through courses for inventive thinking, people observe that this skill can be learned and enhanced. However, methods for systematic inventive thinking complement traditional approaches such as brainstorming or lateral thinking and are not meant to replace them. Teaching methods for inventive thinking are especially important for novice engineers, since only experts develop their own original methods and adjust their behavior to the perceived constraints.

INTRODUCTION

THE TERM CREATIVITY is difficult to explain or define. To create means to cause something to exist, to bring into being, to originate, to give rise to or to compose. The product of a creative process can be an object, an action, or an idea which is new, original, unexpected, or imaginative [1]. Although there is an extensive literature on creativity, and on ways of fostering creative thinking, the questions of how and to what extent creative thinking can be encouraged remain open. This paper highlights the distinction between two different approaches to creative thinking. On the one hand is the traditional approach that connects creativity with disordered thinking and idea-generating. On the other hand is a relatively uncommon approach that emphasizes systematic inventive thinking and idea-focusing. Some aspects of this method are discussed and examples are presented. It will be argued that there is room to teach engineers methods for systematic inventive thinking, since 'disordered' and 'ordered' thinking complement each other, and both are essential for creative design and innovative problem-solving.

FOSTERING CREATIVE THINKING

Creativity is often described as the confluence of many factors. Some writers use the phrase 'the four Ps':

- The Process—the mechanisms and phases involved as one partakes in a creative act.

- The Person—personality traits of creative people are central.
- The Product—the type of expected outcome of the creative action.
- The Place—environmental factors, such as an atmosphere of safety, lack of criticism and teamwork support.

According to Sternberg and Lubart [2], the ability to be creative is determined by several different kinds of intelligence and personality traits: intelligence (synthetic, analytic, and practical), knowledge, thinking styles, personality, motivation (intrinsic and extrinsic) and the environmental context. Amabile [3] found that highly creative projects in industry are characterized by freedom, positive challenge, supervisory encouragement, work group support, organizational encouragement and sufficient resources. Educators strive to encourage students' creativity through responding to all these factors, by replacing the traditional talk-and-chalk lessons with projects, challenging tasks or using computers for teaching and learning. However, programs for direct teaching of innovative thinking are seldom found in K12 education or in engineering education. In order to encourage such programs, we need to look closer at the types of thinking involved in inventive problem-solving and technological design.

CREATIVITY AS UNSYSTEMATIC THINKING AND IDEA-GENERATING

Guilford [4] distinguished between divergent and convergent thinking. Divergent thinking is generative, moves in many directions, can make jumps, lives well with uncertainty, seeks for richness, and

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need not be right at every step. Convergent thinking, on the other hand, is selective, sequential, moves forward in a prescribed path, and seeks the right answer. Although the literature emphasizes that these two types of thinking are both essential to the thinking process, many identify creative thinking only with convergent thinking. Torrance [5], for instance, characterized creative thinking processes by four concepts: fluency, flexibility, originality, and elaboration. These views have led to the appearance of a variety of idea-generating methods, such as lateral thinking [6], synectics [7], mind mapping [8], and brainstorming [9]. These methods adopt a range of common principles, such as: allowing free flow of thought, triggering imagination, using associations, using analogies, avoiding internal and external criticism, postponing judgment, borrowing ideas, paying attention to outrageous ideas, and using humor.

Teaching people to think in these ways seems a difficult mission. How can we teach something that is considered unusual? There is a logical contradiction inherent in trying to induce a spontaneous event. It is difficult to train someone to think in an unexpected manner, or to seek unknown outcomes. Teachers for math and science reward students more for finding the 'right answer' than for richness of ideas, taking risks or coping with the unknown.

SYSTEMATIC APPROACHES FOR INVENTIVE THINKING

Recently, there has been a growing body of knowledge claiming that disordered thinking is not the best way to foster creative ideas. Lateral thinking or brainstorming methods may not be as productive as predicted. The correlation between divergent thinking tests and creative achievements tends to be low, and the cognitive approach of creative individuals does not differ qualitatively from normal individuals except in the speed and quantity of ideas produced [10]. Goldenberg and Mazurski [11] state: 'research indicates that most brainstorming groups did not generate more ideas than control groups in which individuals worked alone with no contact between them . . . The quality of the ideas themselves and their level of originality were inferior to the ideas generated by individuals working without any group effect.' A creative solution for a problem does not necessarily require a large number of ideas, and postponing judgment does not increase the creative value of ideas. Focused thinking and early judgment of ideas according to well-defined criteria can be a preferred way for finding creative solutions to problems. There follows a brief review of some methods for systematic inventive thinking and problem-solving. According to [12], the existing creativity techniques are not appropriate for use in a technological context due to the mismatch between the playful attitude that belongs to, for

example, metaphorical thinking or mind mapping, and the more formal style of argumentation that is taught in most forms of scientific education.

TRIZ

TRIZ (pronounced *TREEZ*) is the Russian acronym for the Theory of Inventive Problem Solving, which was developed over the last 50 years by Altshuller [13]. Altshuller and his colleagues studied over a million patents and identified a range of principles and knowledge that define the process for inventive solving of engineering problems. Altshuller's method is based on three major principles: (a) the resolution of technical and physical contradictions; (b) the evolution of systems; (c) the reference to the ideal system and ideal solution. The TRIZ method comprises 40 'Techniques for Overcoming System Conflicts', such as (the first 10): Segmentation, Extraction, Local Quality, Asymmetry, Combining, Universality, Nesting, Counterweight, Prior counteraction, and Prior action. TRIZ is gaining increased attention in the world of engineering, design and creative problem-solving, through books, journals and professional institutes. It has been implemented in large corporations such as Motorola, Xerox, Kodak, McDonnell Douglas, General Motors, Ford, General Electric, and Rolls-Royce.

SYSTEMATIC INVENTIVE THINKING

In Israel, Horowitz [14] and his colleagues have been working for about 20 years on developing systematic methods for problem-solving and new product development, entitled Systematic Inventive Thinking, or Advanced Systematic Inventive Thinking [15]. These methods are an attempt to generalize and simplify TRIZ. Academic courses on SIT/ASIT are being offered at Tel Aviv University and in Israel's Open University. Based on these methods, and the roots of TRIZ, Sikafus [16] developed another model, called Unified Structured Inventive Thinking (USIT). This method has been used to train hundreds of engineers at the Ford Motor Company in the USA.

The ASIT version of systematic inventive thinking consists of the following five 'thinking tools' or 'idea provoking' techniques:

- Unification: assign a new function to an existing component.
- Multiplication: introduce a copy (or a modified copy) of an existing object.
- Division: divide an object and reconfigure its parts.
- Object Removal: remove an object from the system.
- Breaking Symmetry: change symmetrical/asymmetrical relationships between system components or functions.

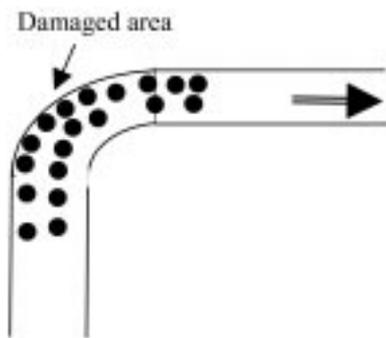


Fig. 1. Flow of grains in a curved pipe.

A central principle in SIT/ASIT is the ‘Closed World’ (CW) principle, according to which a creative solution to a problem relies mainly on the natural components contained in the ‘world of the problem’ or its neighboring environment. Usually, a solution that requires the addition of new elements to a system is not considered creative. Consider the following examples of innovative problem-solving using the ASIT method.

Example 1: The curved pipe problem

This example [17] demonstrates the application of the Unification tool. A corn grain processing plant uses a curved pipe to guide grains propelled by an airstream. The problem is that the grains erode the pipe’s surface at the elbow, as shown in Fig. 1.

A customary solution for this problem is to reinforce the pipe, for instance by adding an erosion-resisting coating on the inside surface. Now let us search systematically for an innovative solution.

Step 1: list all the components of the ‘Closed World’ (CW) of the problem. In this case, these are the pipe, the grains, and the air.

Step 2: formulate the Unification tool sentence: ‘A XXX type component from the CW will be used to prevent (or reduce) the grains from eroding the pipe.’

Step 3: replace XXX each time with another component from the CW. Seek a solution by changing XXX properties.

- 3.1 A *pipe* will prevent (or reduce) the grains from eroding the pipe.

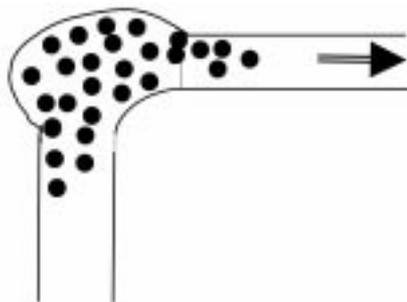


Fig. 2. An innovative method for reducing erosion of the pipe.



Fig. 3. The six glasses puzzle.

- 3.2 *Grains* will prevent (or reduce) the grains from eroding the pipe.
- 3.3 *Air* will prevent (or reduce) the grains from eroding the pipe.

For this example, case 3.2 is the most interesting. How can the grains themselves prevent pipe erosion? How can the grains protect the pipe? The solution is achieved by changing the pipe shape, as shown in Fig. 2.

This example demonstrates the core idea: solving the problem by means of the natural system components. Participants in courses for systematic inventive thinking have suggested other solutions; for example, using the air pressure to reduce the friction between the grains and the pipe surface at the curved area. A similar problem occurs when metal powder flows in a pipe. In this case, a creative solution for reducing the pipe erosion can be magnetizing the pipe elbow (or placing a magnet outside), to create a thin layer of powder that protects the pipe inside.

Example 2: The six glasses puzzle

Puzzles and games are often used in courses for inventive thinking [18]. In this example we are using a well-known puzzle as a second example for using the Unification tool. Six glasses are arranged in a row (Fig. 3). Only the three on the left are filled with a liquid. The puzzle is to arrange the glasses so that they alternate, full and empty, by moving only one glass.

Step 1: The CW components are: glasses, liquid.

Step 2: The Unification sentence is: ‘A XXX component can be used (or modified) to achieve the desired effect.’

Step 3: Replace XXX each time with glass, juice. Seek a solution by changing XXX properties (size, shape, location . . .).

Although this is a quite an easy puzzle, many people spend some time before they see that the solution is to pour the liquid from glass number 2 into glass number 5. Here, the systematic search for the solution guides the solver to the key point—separating the liquid from the glass.

The other thinking tools mentioned above (Multiplication, Division or Object Removal) are used in similar ways, where the words ‘will be used’ in the main sentence are replaced by ‘will be multiplied’, ‘will be divided’ or ‘will be removed’. In more general terms, technological problems might be solved by ‘playing’ with the properties of one of the system components, such as size, color, shape, temperature, or location. The readers are invited to solve the five glasses puzzle, illustrated in



Fig. 4. The five glasses puzzle.

Fig. 4, using one of the tools for systematic inventive thinking. The puzzle is to rearrange the glasses so that they are alternately empty and full. You are allowed to move only one glass.

Consider that a few examples of the other systematic inventive thinking tools might be applied. The *Multiplication* technique is helpful for enhancing or solving problems in technological systems. For example: double glazing, double doors at air-conditioned rooms, or a double-dam system. The *Removal* tool means removing a significant component or function from the system. This approach could have invented the cordless telephone, tubeless tire, no-alcohol pub, non-alcoholic beer, decaffeinated coffee or a cellular telephone for incoming calls only. The *Breaking Symmetry* concept lies behind the idea of allowing only public transportation in some city streets or specific road lanes. Finally, the readers are invited to solve the following question by using one or two of these tools:

The king has a treasure of 10 bags, 100 gold coins in each. A legal coin weighs 100 grams. One of the bags comprises forged coins, each weighing only 90 grams. The king will give all the treasure as a prize to the one who will identify the bag containing forged coins by using a weighing-scale only once!

SCAMPER

SCAMPER is an earlier version of systematic problem-solving, based on the classic work of

Osborn [9], and Eberle [19], provided the acronym. SCAMPER comprises the following techniques:

- *Substitute*: What could be used instead? What other components could be used?
- *Combine*: What parts or functions can be combined? What unrelated ideas or parts can we combine with this?
- *Adapt*: What else is like this? What could be copied? What idea could be incorporated?
- *Magnify*: What can be magnified, made larger, or extended? What can be exaggerated? What can be added? How about greater frequency? What can add extra value? What can be duplicated? How could it be carried to a dramatic extreme?
- *Modify*: Could we change an idea, practice or product slightly and be successful? What new twist can we put in? What changes can be made in plans?
- *Put to other uses*: What else can this part be used for? Are there new ways to use it? Are there other uses for it if modified? What else could be made from this?
- *Eliminate or divide*: What can be omitted or eliminated? What is not necessary? What can be condensed, divided up, split up, or separated into different parts?
- *Rearrange*: What other arrangement might be better? Other patterns? Other layouts? Other sequences? Change the order? Transpose cause and effect? Interchange components?
- *Reverse*: What are the opposites? What are the negatives? Reverse roles? Consider it backwards? Should I turn it around? Do the unexpected?

Kaplan [20] pointed out that ASIT is quite similar to SCAMPER. Horowitz (in Kaplan [20]) compared these two methods and summarized that, in simple words, ASIT = SCAMPER + the Close World condition.

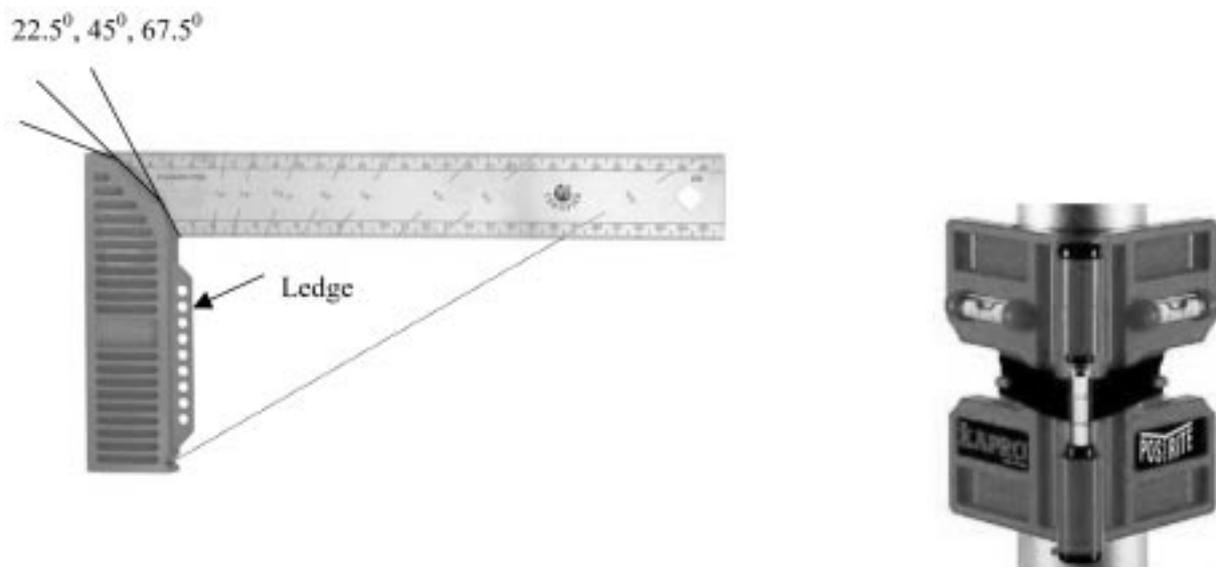


Fig. 5. Examples of KAPRO products.

The eight-dimensional methodology for innovative thinking

Another example of a systematic approach to creative problem-solving is suggested by Raviv [21], entitled the Eight-Dimensional Methodology for Innovative Thinking, which is applied within a course for systematic problem-solving at Florida Atlantic University. The following are the eight dimensions, with related basic-level questions:

- *Uniqueness*: What is unique about the ‘processes, objects, dimensions, situations, resources, concepts, principles, features, patterns, problems, or solutions’? Could these observations be used to find solutions?
- *Dimensionality*: What could be done with space, time, color, temperature, or any other dimension?
- *Directionality*: Could things be done from different directions or points of view? If so, how?
- *Consolidation*: Would it be helpful to consolidate ‘processes, objects, dimensions, situations, resources, concepts, principles, features, patterns, problems, or solutions’? If so, in what way(s)?
- *Segmentation*: How could division of ‘processes, objects, dimensions, situations, resources, concepts, principles, features, patterns, problems, solutions or dimensions’ help?
- *Modification*: What if modifications to the existing ‘processes, objects, dimensions, situations, resources, concepts, principles, features, patterns, problems, or solutions’ are introduced?
- *Similarity*: Why not look at similar ‘processes, objects, dimensions, situations, resources, concepts, principles, features, patterns, problems, or solutions’?
- *Experimentation*: Could estimating, guessing, simulating, or experimenting help? If so, how?

The Eight-Dimensional Methodology has been taught using hands-on activities that include 3-D mechanical puzzles, games, brainteasers, LEGO® Mindstorms competitions, and design projects, each of which illustrates principles and strategies in inventive problem-solving. According to Raviv [21], ‘this method aims to provide leaders, managers, and other problem solvers with new insights and thinking strategies to solve everyday problems they face in the workplace. The Methodology looks at problems systematically, enhances creative power and innovative skills of problem solvers, helps to generate unique ‘out-of-the-box’, unexpected and high quality multiple solutions, stimulates innovation by generating more and better ideas quickly, and increases productivity of the idea generation process.’ The developers report that the Eight-Dimensional Methodology has recently been evaluated, with encouraging results.

Systematic creativity in management and marketing

Methods for systematic inventive thinking are used not only for problem-solving in engineering,

but also in fields such as management and marketing. For example, Goldenberg and Mazursky [11] incorporated some concepts and principles from TRIZ and ASIT into a framework for product innovation and advertising. Their method consists of the following five templates:

- *Attribute dependency*—changing a key variable of a product.
- *Component control*—changing a product’s links with its environment.
- *Replacement*—substituting part of a product with something from the product’s immediate environment.
- *Displacement*—improving a product’s performance by removing an intrinsic component.
- *Division*—splitting a product’s attributes into parts.

Goldenberg and his colleagues [22] demonstrated that a computer program based on these templates can produce creative advertisements that compete successfully with those suggested by professionals.

We have outlined some techniques or methodologies for systematic problem-solving. Overveld and his colleagues [12] suggest another framework for teaching engineering students design-related creativity techniques, ‘using concepts, attributes and values, together with some structuring devices such as hierarchies, orthogonally and dialectics’ (p. 270). It is obvious that the different methods adopt some similar principles and partially overlap each other. (A detailed analysis or comparison of these methods is beyond the scope of this paper.)

An example of introducing systematic inventive thinking workshops into industry

KAPRO [23] is a medium-sized Israeli plant that manufactures measuring tools, such as spirit levels, measuring tapes, squares and markers, for the construction industry and for domestic use. Barak and Goffer [24] examined the process of introducing workshops for systematic inventive thinking into KAPRO, and the impact of these workshops on the plant. In the late 1990s, tough competition combined with cheap products imported from developing countries posed a threat to the plant’s existence. The plant management decided to compete on the market through innovation, uniqueness and quality, and not in the realm of price. One of the first steps was inviting an external team, which specialized in introducing systematic methods into innovative design and problem-solving, to run in-house workshops for new product development. Participants in these workshops included 5–10 people from the management, design, production and marketing departments. The workshops not only resulted in developing a range of new products, but also contributed to improving internal design and manufacturing processes. Two examples of unique KAPRO products are shown in Fig. 5.

The POSTRITE is a three-dimensional magnetic

level used for posts, pipes and signs. It folds easily to fit into a toolbox or pocket. The LEDGEND square is unique in that its handle incorporates a Ledge, which avoids the tool from falling and enables hands-free work. In addition, the handle provides reference edges of 22.5° , 45° and 67.5° to facilitate beveling and framing. The arm has signs for marking lines at 60° , 50° , 45° , 36° , 30° , 22.5° , 15° and 10° . Another example of an innovative KAPRO product is a lightweight spirit level called 'Set and Match.' This is a no-body spirit level, consisting of a thin ruler with two sliders holding the horizontal and vertical levels. These sliders enable the user to set a measured distance between two points easily.

Following the success of the new products, systematic inventive thinking workshops were held in the plant 3–4 times a year in the first two years, and 1–2 times a year in successive years. Over a period of four years, the plant delivered dozens of new, innovative products, many of which became commercially successful on the world market. Although most of the new products are patented, more than 40% were duplicated illegally. It should be emphasized that, although the systematic inventive thinking workshops were an important component in the plant's efforts to develop new products, they were only one aspect of the plant's comprehensive strategy to renew and strengthen.

KAPRO is only one example of a range of Israeli companies that incorporated in-house workshops for systematic inventive thinking for senior staff. The author of this article participated in an 80-hour systematic inventive thinking course, together with 12 engineers and senior managers from other Israeli electronics, electro-optics, communications and transportation companies. Among them was KAPRO's quality engineer. All the participants have had previous experience in introducing systematic inventive thinking workshops into their organizations. The aim of the course was to train the participants to run these workshops in their organizations independently. This was a good opportunity to meet several successful, and unsuccessful, cases of attempts to develop new products and to learn of the different ways the plants had run the in-house workshops.

What is a workshop like? A typical workshop lasts one day and, as previously mentioned, involves the participation of senior employees from several departments, such as R&D, production, marketing and sales. The workshop is led by an experienced individual and the other group members gradually learn the technique during work. Each workshop focuses on a particular product or a specific technical problem. The participants try to break down an artifact or system into its basic components and systematically 'play' with the components' attributes and functions in order to achieve new results. Each 'thinking tool' is tested over a period of one to two hours. On the one hand, the participants are directed to focus

on a specific technique. On the other hand, the members are encouraged not to ignore or reject unexpected ideas that suddenly arise, since sometimes these ideas lead to the desired solutions or to new innovative products. The social interaction and teamwork play a pivotal role in the process. When people see that they and their colleagues are able to find original solutions to problems or invent something new, they start believing that inventive thinking is a skill that can be learned and enhanced and not that it is just a 'magic' talent or a mysterious ability afforded to only a few.

CONCLUSION

Despite the wide consensus that engineering education must pay significant attention to developing students' higher-order thinking skills, programs for direct teaching of inventive thinking are infrequent in academia. University programs for management, arts, and in-service courses at workplaces incorporate the study of methods for inventive thinking more often than engineering programs do. We have mentioned two examples of courses aimed at teaching engineering students systematic methods for innovative design and problem-solving [12, 21]. However, these courses are in their infancy and have not been systematically evaluated. In this case, it can be said that engineering education can learn from the industry more than the industry can learn from academia. Clear and simple techniques and 'tools' that help people to quickly reach original and innovative solutions can cause them to feel 'I too am able', and encourage them to continue trying. Following successful experiences, more and more people begin to examine their immediate surroundings—such as artifacts, home appliances, tools, or day-to-day activities—and ask themselves questions such as: Why do actions or objects come to be as they are? Can't we make them in a different way? The psychological literature teaches that creativity is aroused more by intrinsic reward than by extrinsic reward [25].

It should be emphasized that 'systematic' methods for inventive thinking are intended to complement the traditional approaches of non-systematic thinking and free association, and are not meant to replace them. According to Kantovich [26], scientific novelty generated through events dominated by serendipity, tinkering, or random variations is not a marginal phenomenon. Creative thinking is a complex process that involves situations of order and disorder. Numerous scientific discoveries and technological inventions have appeared in an unplanned manner, based upon peoples' intuition. Teaching methods for inventive thinking are especially important for students and novice engineers. Dreyfus and Dreyfus [25] stress that the acquisition of cognitive skills is a continuous and cumulative process. Only

as people become experts do they develop their own original methods and act intuitively, automatically adjusting their behavior to the perceived constraints.

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