

Integrating Systematic Creativity into First-Year Engineering Design Curriculum*

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Since the lack of creative potential in graduating engineers has been and continues to be a concern for industry leaders, most educators have added a common ideation approach—brainstorming—to engineering design curricula. However, because brainstorming requires the designer to look inward for inspiration, it can be a daunting task, which is not always fruitful. Some systematic creativity methods, on the other hand, use solution patterns derived from problems similar to the one being solved. These methods have typically been introduced in senior or graduate elective courses, if at all. This paper presents the rationale for, and our experience with introducing one of these methods, the theory of inventive problem solving (TRIZ) in a first-year engineering design course. In addition, a study, comparing the ideation quantity in course sections that used TRIZ against control sections that did not, is presented. Results indicate that student teams from sections, where TRIZ was taught, generated substantially more feasible design concepts for an industry-sponsored design problem that was common to all sections.

Keywords: creativity; inventive problems; TRIZ

INTRODUCTION

INDUSTRIAL LEADERS have long expressed a mounting concern about the impact of traditional engineering education on the creative potential of future engineers (i.e., lacking design capability or creativity, as well as an appreciation for considering alternatives). A lack of creativity is viewed as problematic in a rapidly changing technology-oriented world where generating new ideas is essential to survival [1]. Accordingly, a 1995 American Society of Mechanical Engineering report ranked *creative thinking* as 5th of 56 top desired ‘best practices’ for new baccalaureate-level engineers as seen by industry and academe [2]. In the past several years, universities have responded to these challenges by adding more design content and introducing more open-ended design problems into their engineering curricula. Articles discussing the guarded success of these initiatives have appeared in nearly every issue of the *Journal of Engineering Education* and the *International Journal of Engineering Education* over the last 10 years. Yet the need to increase the creative potential of graduates still persists [3]. Recognizing that other factors play a role as well, studies have documented [4]:

1. People whose personality types indicate high levels of creative potential are leaving the major at higher rates than the student body average.
2. Faculty teaching methods lean heavily towards a ‘plug-and-chug’ approach to engineering problem solving, stifling creativity.

Why does the problem of universities churning out

uncreative engineering graduates persist? A possible explanation may lie in the approach to idea generation or creativity that is heavily advocated and commonly used to teach engineering design: *brainstorming* (and its variants). Brainstorming calls upon the designer to look inward for inspiration on creative solutions to problems, by drawing upon past experiences and knowledge. This can be a daunting task that may or may not be fruitful. This is especially true for undergraduate students whose engineering knowledge and experiences are still quite limited. As noted by Wood *et al.* [5], ‘Some students do not adapt well to having extremely open-ended problems as the first assignments they encounter. This may not necessarily be because they have trouble with open-ended problems (intellectual maturity), but because they lack the engineering elements to use for filling the blank sheet with a design.’

Systematic creativity methods such as *the theory of inventive problem solving (TRIZ)*, guide the concept generation process using solution patterns derived from problems similar to the one at hand. These methods have typically been introduced in senior or graduate elective courses, if at all. This paper presents the rationale for, and our experience with introducing TRIZ in the first year of a student’s academic career in a required Introduction to Engineering Design (ED&G 100) course.

The enrolled body of students to the course is divided into 14 sections of 32 students each. Within each section, students are grouped into teams of four. ED&G 100 employs a design-driven curriculum with emphasis placed on skills such as teamwork, communication skills (graphical, oral and written), computer-aided design and analysis tools. The course introduces first-year students to the

* Accepted February 2005.

engineering approach to problem solving with strong references to basic science and mathematics skills, as well as testing and evaluation of design ideas by building models or working prototypes.

Although anecdotal evidence exists stating that TRIZ helps students to be more creative during engineering design, no formal studies have been done. This work, therefore, contributes to the literature by conducting a formal ideation assessment of two cohorts of students in the same course (different sections) working on the same design problem over a six-week period. One set of students is exposed to TRIZ and the other is not.

CREATIVE POTENTIAL AND CREATIVITY PROCESS

What is a person's creative potential? Can it be increased (i.e., can a person learn to become more creative)? First, creativity can be described as a multifaceted ability found in various amounts in everyone [6]. Herman [7] argued that 'each person's experience of [creativity] is so unique and individual that no one can formulate a definition that fits everyone.' As a result, Klukken *et al.* [1] suggest that efforts should be spent on identifying and developing an individual's creative potential. Carlos Santamarina, who has written about and studied the teaching of creativity, states that 'There are skills that can be learned . . . every student can be creative, better at problem solving and invention if they are aware of their own creativity and how to improve it.' [3].

A personality instrument that has been used to loosely measure an individual's creative potential is the Herman Brain Dominance Instrument (HBDI). The scores and profiles from using the instrument reveal four different ways of thinking and 'knowing' [8]:

- A = analytical-logical-quantitative;
- B = sequential-organized-detailed;
- C = interpersonal-sensory-kinesthetic;
- D = innovative-holistic-conceptual thinking.

A longitudinal study, at the University of Toledo conducted on first-year engineers from 1990–1993, revealed a decrease in the extent of B thinking (corresponding to plug-and-chug problem solving) and a corresponding increase in D thinking (creative) from tests conducted before and after the students went through a newly introduced first-year creative problem solving course. The change may have been due to the very plastic nature of the brain that undergoes change with each use, and can therefore result in thinking preferences changes. Preferred thinking modes require less energy in the brain and are usually more enjoyable. Students who enjoyed the design experience in the first-year course may have therefore shifted their thinking preferences to D [4]. This and other studies, such as Wilde's [9], suggest that an increased level of creative

activity in the engineering curriculum may indeed change the way a person thinks, thereby increasing their creative potential.

Creativity in engineering design is mostly predicated on [1, 10]:

1. desire and fulfillment;
2. knowledge of objects and principles possessed or available (knowing how to obtain the needed knowledge and how to use it) that includes tacit knowledge gained in experiences, heuristics, and instinct ('gut' feeling);
3. openness (i.e., a willingness to accept criticisms and ideas from others);
4. knowledge of process, especially design and problem solving processes.

While (1) and (3) are personality traits, (2) and (4) must be learnt, and are typically inadequately developed in students. Traditional idea generation methods, such as brainstorming that rely heavily on (2), when used as the main vehicle to creativity, therefore, often fall short.

The Helmholtz-Poincaré-Getzels model of creativity (initiated in the 19th C by German physicist and physiologist Herman Helmholtz, and later modified by French mathematician Henri Poincaré, and further developed in the 1960s by American psychologist Jacob Getzels) consists of five stages [10, 11]:

- first insight—understanding and formulation of problem;
- saturation—information gathering phase;
- incubation—the mind gets frustrated or stuck and the problem is put aside for a while;
- illumination—the person gets an insight, flash of recognition of the solution during mental down times, for example when showering, eating or jogging: they stumble upon the answer unexpectedly and, therefore, this stage involves an element of luck;
- validation—analytical process to verify solution and put in form others can use. Stages (c) incubation and (d) illumination present the greatest challenge to the novice designer.

The traditional approach to creativity (using methods such as brainstorming, C-sketch [12], morphological charts, SCAMPER [13], etc.) calls upon the designer to look inward for inspiration. TRIZ, on other hand, invites the designer to use a ready pool of knowledge for inspiration. It does not discount the use of the traditional approaches. On the contrary, TRIZ ensures that design teams use these traditional methods in a systematically directed manner by carrying out intelligent idea generation in areas where other people have solved a similar general design problem [14–16].

SYSTEMATIC CREATIVITY WITH TRIZ

TRIZ is a systematic approach for generating innovative designs to seemingly intractable

problems [17]. It was first developed in Russia by Genrich Altshuller in the early sixties and seventies and has been used for many years in Europe and Asia. It is based on the analysis of thousands of patents. These original analyses articulated numerous solution patterns from diverse disciplines. The patterns and the tools are continually being updated by researchers worldwide (for example [18]).

TRIZ has been recognized as a concept generation process that can develop clever solutions to problems by using the condensed knowledge of thousands of past inventors. It provides steps that allow design teams to avoid the 'psychological inertia' that tends to draw them to common, comfortable solutions when better, non-traditional ones may exist. With reference to Fig. 1, a design team using TRIZ converts their specific design problem to a general TRIZ design problem. The latter is based on the analysis and classification of a very large number of problems in diverse engineering fields. The general TRIZ design problem points to corresponding general TRIZ design solutions from which the design team can derive solutions for their specific design problem. The power of TRIZ, therefore, is its inherent ability to bring solutions from diverse and seemingly unrelated fields to bear on a particular design problem, yielding breakthrough solutions.

Despite its strength and potential, several barriers exist, however, to the wider adoption of TRIZ in the engineering design curriculum. These include:

- terminology and modeling methods unique to TRIZ and different from those found in engineering design [19];
- the method is absent from nearly all introductory and capstone engineering design textbooks;
- most engineering design faculty are unfamiliar with the method.

Despite the large number of methods that constitute TRIZ, recent efforts at Penn State have focused on only one of the core TRIZ tools: technical contradictions and the 40 design principles. It is the easiest to grasp and can be applied

with limited engineering knowledge, making it ideal for use at the first-year level. A narrative was generated where a few unique TRIZ modeling methods and terminology are replaced by modified versions of those commonly used in engineering design. For example, the use of substance-field modeling (unique to TRIZ) is replaced by EMS models [20] that are based on black-box modeling already taught in engineering design courses. Students therefore do not need to learn radically new modeling methods. The initial results of these efforts have been incorporated into an introductory design text, *Engineering Design: A Practical Guide* [21] and introduced in two sections of ED&G 100 in the 2004 spring semester.

TECHNICAL CONTRADICTIONS AND THE 40 DESIGN PRINCIPLES

Characteristics of engineering systems can be described by a number of parameters that quantify or measure certain aspects of the design (metrics). Based on his analysis of patents, Altshuller developed a list of 39 such parameters (Table 1) [17]. He then reformulated the problems described by the patents in terms of these general parameters and noted their solutions. What began to emerge was that nearly all the solutions could be condensed into 40 general design principles. Next, Altshuller proposed that if most design solutions to thousands of design problems could be condensed to 40 design principles, the reverse should be true: for a current design problem, the 40 principles can be used to find a solution. These principles are summarized in Table 2.

Technical contradictions refer to the standard engineering trade-offs (i.e., changing one parameter to make an aspect of the system better makes another aspect of the system worse). Examples include:

1. Increasing the stiffness of an airplane's wings to reduce vibration during flight (good) increases the weight of the plane (bad).
2. Reducing the engine size in an automobile to decrease fuel consumption (good) decreases available horse-power (bad).
3. Adding more windows to a house to improve passive lighting (good) increases heat loss from the house during winter (bad).

The general parameters used to describe system metrics can be used to formulate the *technical contradictions* within a system. Elimination of the technical contradiction may yield the desired final design. How can one eliminate the technical contradiction easily? Do certain contradictions lend themselves to a particular solution irrespective of the actual problem at hand? These are the questions Altshuller set out to answer. In his patent analysis, Altshuller reformulated the problems in terms of the general parameters listed in Table 1 and noted their

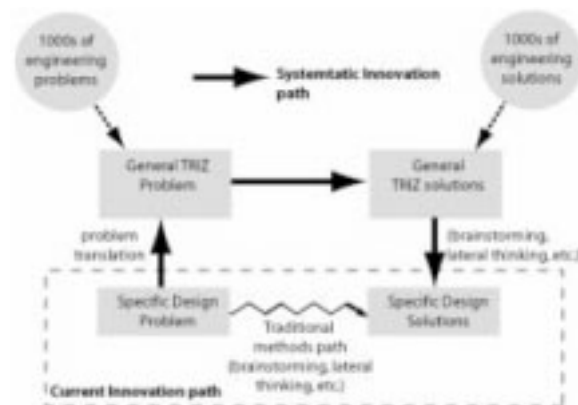


Fig. 1. Generation of design solutions using TRIZ [13].

Table 1. General parameters used to describe engineering systems.

1	Weight of moving object	21	Power
2	Weight of stationary object	22	Energy loss
3	Length of moving object	23	Substance loss
4	Length of stationary object	24	Information loss
5	Area of moving object	25	Waste of time
6	Area of stationary object	26	Quantity of a substance
7	Volume of moving object	27	Reliability
8	Volume of stationary object	28	Accuracy of measurement
9	Velocity	29	Manufacturing precision
10	Force	30	Harmful action affecting the design
11	Stress or pressure	31	Harmful actions generated by the design project
12	Shape	32	Manufacturability
13	Stability of object's composition	33	User friendliness
14	Strength	34	Repairability
15	Duration of action generalized by moving object	35	Flexibility
16	Duration of action generalized by stationary object	36	Complexity of design object
17	Temperature	37	Difficulty
18	Brightness	38	Level of automation
19	Energy consumed by moving object	39	Productivity
20	Energy consumed by stationary object		

solutions. He soon realized certain technical contradictions were associated more frequently with particular design principles than others. He tabulated these observations to create the contradiction matrices.

The *contradiction matrix* lists the most probable design principles for the solution of a particular technical contradiction. A portion of the matrix is shown in Table 3. Note that the column headings represent the worsening general parameter in the contradiction and the row headings the improving one. The recommended design principles are listed at the intersection of a particular row and column. For example, if the technical contradiction was defined with parameter **2 (weight of a moving object)** as the improving feature and parameter **10 (force)** as the worsening feature, the contradiction matrix recommends design principles **8 (counterweight)**, **10 (preliminary action)**, **19 (periodic actions)**, and **35 (altering an object's aggregate state)**. Then, using the recommended design principles, the design team should use concept generation techniques (for example, *brainstorming*) to

come up with new concepts to address the design problem. Teams must remain disciplined and restrict themselves only to ideas that fall within the current design principle under consideration. In the event that a solution cannot be found from the recommended design principles (recall that these are simply the most probable), the design team should consider all forty design principles in the order of frequency of use as listed in [17].

TEACHING TRIZ IN A FIRST-YEAR DESIGN COURSE AND ITS RESULTS

In the Spring 2004 semester, the authors introduced the developed materials as part of a preliminary module on systematic creativity using TRIZ in two sections (64 students) of ED&G 100 course. During the course, student teams worked on two design projects: redesign of an electric toothbrush, and redesign of the air regulation system of a fume hood. During the first project, students were introduced to traditional idea

Table 2. TRIZ 40 design principles

1	Segmentation	21	Rushing through
2	Removal	22	Turning harm into good
3	Local quality	23	Feedback
4	Asymmetry	24	Go between
5	Joining	25	Self-service
6	Universality	26	Copying principle
7	Nesting	27	Inexpensive short life
8	Counterweight	28	Replacement of a mechanical pattern
9	Preliminary counteraction	29	Hydraulic or pneumatic solution
10	Preliminary action	30	Flexible or fine membranes
11	Protection in advance	31	Use of porous materials
12	Equipotentiality	32	Use color
13	Opposite solution	33	Homogeneity
14	Spheroidality	34	Discarding and regenerating parts
15	Dynamism	35	Altering an objects aggregate state
16	Partial or excessive action	36	Use of phase changes
17	Moving to a new dimension	37	Application of thermal expansion
18	Use of mechanical vibrations	38	Using strong oxidation agents
19	Periodic actions	39	Using an inert atmosphere
20	Uninterrupted useful action	40	Using composite materials

Table 3. Contradiction matrix fragment: parameters 1–2 vs. parameters 1–11; the columns are the generalized performance parameters that deteriorate as the generalized parameters in the corresponding rows are improved

	1	2	3	4	5	6	7	8	9	10	11
1			15 8 29 34		29 17 38 34		29 2 40 28		2 8 15 38	8 10 18 37	10 36 37 40
2				10 1 29 35		35 30 13 7		5 35 14 2		8 10 19 35	13 29 10 18

generation methods. During the second project TRIZ was introduced and used.

During the semester, in sections where TRIZ was introduced, while students learnt and used the method quite well, end-of-semester formal course evaluations revealed some concerns. These concerns were related to difficulty in understanding the method, and some frustration using the contradiction matrices due to the large number of tables and numbers within the tables, coupled with the tedium of having to look up the corresponding design principles from the suggested numbers. In addition, students felt that more examples beyond those contained in the text provided would have facilitated a better understanding of the design principles. As instructors, we observed that students had difficulty in staying focused on their TRIZ design principles during brainstorming. An intervention that worked quite well was to have the students go through a concept generation exercise using TRIZ during class, before allowing them to begin using the method on their projects. During this process, constantly monitoring and correcting student teams when they began to digress helped students to quickly understand the benefits of the method; and thus they remained focused. In the end, we feel that our students gained a new tool to enhance their creativity.

Beyond the anecdotal evidence for the success of TRIZ introduction, however, we sought to answer: Did the introduction of TRIZ really make it easier for the students to generate feasible design concepts? To answer this, the creative output from the 16 teams that used TRIZ (TRIZ teams) were compared with that of 24 teams from three sections that did not use TRIZ (non-TRIZ teams). All teams were working on the same industry-sponsored design problem. The three non-TRIZ sections were selected at random from the 12 non-TRIZ sections. Table 4 illustrates the design concepts (listed by working principle) generated by all teams with the number of unique ideas generated per section.

While there are numerous metrics for ideation effectiveness (e.g., novelty, variety, quality [22]), we would like to report in this paper on the quantity of the design concepts generated by the experiment cohorts. This ideation quantity will cover:

- how many unique feasible ideas were generated per course section;
- how many unique feasible concepts were generated by each team;

- how many feasible design concepts were unique to each experimental cohort (TRIZ teams vs. non-TRIZ teams).

The fume hood design problem, on which the comparison was based, was focused on the regulation of the airflow through the hood to produce a redesigned, cost-effective, efficient, and safe way to offer reliable protection from harmful vapors. Maintaining accurate and constant airflow velocity at the face of the fume hood requires an effective design to account for the changing size of the open face area.

From the data in Table 4, we can see that each TRIZ section produced an average of 35 unique solutions, a two-fold increase over non-TRIZ sections that averaged 16.3 solutions per section. A comparison of the number of unique feasible concepts produced per team can be found in Table 5. As shown, TRIZ teams averaged 8.94 feasible concepts per team, a two-fold increase over non-TRIZ teams that averaged 4.42 feasible concepts. Finally, in Table 4 we also see that TRIZ teams generated 21 unique design concepts that none of the non-TRIZ teams thought of, in comparison to eight for non-TRIZ teams. If one takes into account the fact that there were 96 students in non-TRIZ teams and only 64 in TRIZ teams, the effectiveness of TRIZ in providing a tool to help designers enlarge their solution space by generating ideas that are not thought of by designers who are not using TRIZ, is very significant. Overall, we report that the introduction of TRIZ to first-year engineering students was not only possible, it helped design teams to generate more feasible design concepts, and more unique design concepts that students who did not learn TRIZ did not think of.

CONCLUSION

The results from this study indicate that first-year students are able to learn and successfully implement systematic creativity methods such as TRIZ. Technical contradictions and the contradiction matrix present concepts easy enough for first-year students to grasp and immediately begin to implement despite their limited engineering knowledge. The results from the formal assessments between students introduced to TRIZ and those not, clearly indicate that TRIZ makes it easier for students to generate feasible concepts

Table 4. Comparison of feasible concepts generated by teams in each section

Concepts	# Groups in Each Section using a Particular Concept				
	1	2	3	4 (TRIZ)	5 (TRIZ)
Pressure transducers to measure, ΔP	***	*		****	****
Measure sash position with lasers	*****	**	***	*****	*****
Use of magnetic field		**	**	***	*
Wire/cable wound around roller			**	**	*
Strain gauge			****	*	*
Mechanical arm				*	
Rack and pinion		*	***	**	*
Ultrasonic sensor	***	*****	*	***	
Torque about and axis					
Discrete electrical switches	***	*	**	***	****
Track ball/mouse ball			*		
Optical mouse			*		
Multiple sash doors			**	*	
Camera		*	*		
Manual speed adjustment	*			**	**
Pin wheel/Rotary sensors		*	*	*	*
Hydraulics		*	*		
Variable input fan			*		
Resistive strip	***		*	*	***
Drag element	**				
Bar code scanner		*			
Reconfigurable fan blade size					*
Accelerometer/Motion sensor		*		*	*
Infrared		*****		**	*
Measure evaporation (air velocity)					*
Anemometer (air velocity)	*****	*****		****	****
Pitot-Static tubes (air velocity)	***			**	*****
Laser doppler (air velocity)	*				*
Venturi (air velocity)				*	*
Vibration of string across entrance (air velocity)					*
Propeller to measure air velocity	****			**	**
Airflow through fixed opening	*				
Telescoping button					*
Series of optical sensors	**	*	*	*	**
Automated sash (like car window)				*	**
Pulleys and belts	*	**	**		****
Multiple fans			**	*****	*****
Multiple ducts				***	
Compressed air				*	
Thermistors				*	
Fume hood material neutralizes bad gases				*	
Phase change bad gases				*	
Audio sensor					**
Segment sash				*	*
Hand holes			*		*
Nested chamber				*	**
Nested doors				**	**
Resistor pads			*		***
GPS sensors					**
Measure exhaust fan velocity					*
Solar power for exhaust fan				**	*
Wind power for exhaust fan				*	
Potentiometer (on Sash) directly changing exhaust fan speed				**	*
Flapper valve				**	**
Number Unique Ideas	14	15	20	34	36

Table 5. Number of feasible concepts for each team in all sections

Team Number	Section 3	Section 4	Section 5	Section 10	Section 12
1	3	3	5	8	13
2	5	4	4	6	8
3	6	3	6	13	10
4	4	5	6	7	9
5	4	4	4	5	6
6	8	4	5	9	7
7	5	4	3	11	10
8	4	3	4	8	13
Average	4.88	3.75	4.63	8.38	9.50

to design problems. This can easily be seen in the increased number of feasible design concepts per design team, and the increased number of unique design concepts in TRIZ teams in comparison to non-TRIZ teams. Accordingly, as engineering

educators we believe that introducing our students to TRIZ will help them to be successful in today's technology innovation driven economy, and we make TRIZ a permanent topic in our engineering design teaching.

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