From Brainstorming to C-Sketch to Principles of Historical Innovators: Ideation Techniques to Enhance Student Creativity

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Abstract

The heart and soul of engineering is innovation and our ability to improve the human condition through design. To enrich engineering education, it is critical that we advance our teaching in innovation and design processes. This research focuses on the ideation component of innovation through the investigation of a suite of concept generation techniques. These techniques have been developed for engineering education across disciplines and at all levels of curriculum. In this paper, we explore this suite of techniques from a method known as C-Sketch to a new method referred to as "principles of historical innovators." Based on the deployment of the techniques, at the freshman- and senior-levels of undergraduate education, we execute a study to understand if the suite of techniques enables students to generate a large quantity of diverse concepts and if the suite enhances the creativity of the students. Our approach is to pre-survey students regarding a self-assessment of their creativity using Gough's list of creativity descriptors. A control and experimental group of student design teams across disciplines and class levels are then asked to develop as many concepts as possible for their course design projects. The control group only executes a single and well-known method from the suite of concept generation techniques, whereas the experimental group employs the entire suite of techniques. The total number of concepts developed by the teams is evaluated, documenting the number of concepts per ideation technique. The teams are also asked to complete a post-creativity survey. The assessment results from this study show a clear and statistically valid enhancement of the students' creativity, a higher quantity of concepts generated from the suite of techniques, and appreciation of atypical techniques such the "principles of historical innovators."

Key Words: *design, active learning, creativity, concept generation, diversity*

1. Motivation and Research Objectives

Innovation and creativity in design are key outcomes for engineering students in our increasingly flat and connected world. The activity of concept generation (CG), or more generally ideation, presents tremendous and unique opportunities for enhancing creativity in students. A variety of techniques specifically to enrich concept generation or ideation inform our research in the context of design processes.

Numerous versions of the "design process" have been proposed(Ullman, 1997; Ulrich & Eppinger, 2000; Otto & Wood, 2001; Dym, 2000). Two examples are captured in Figures 1 and 2. Figure 1 shows the process as depicted by Ullman (1997) and Figure 2 provides a similar description from Ulrich and Eppinger (2000). In both these cases, and in the majority of other portrayals of the design process, one of the key steps in the overall process is identified as "concept generation." As shown in Figure 3 from Otto & Wood (2001) , the CG step itself can be separated into a set of sub-processes. Note the dual paths depicted in the figure, which divide the process into two categories, basic and advanced. Similarly, Shah (1998) uses two categories referred to as intuitive and directed. The upper path in the Fig. 4 corresponds to the intuitive type CG method and the lower path to directed or discursive-bias methods. The goal of the intuitive methods is to create an environment that enhances creativity for the designer allowing for maximum opportunity to produce novel, and ultimately innovative, solutions. Classic examples in the intuitive category include brainstorming, extended brainstorming with mind-mapping and morphological analysis. The goal of the directed methods is to use knowledge or process steps outside the typical background of the designer to develop concepts. Technical information combined with fundamental physical laws and design principles play a key role in this directed method set of CG techniques.

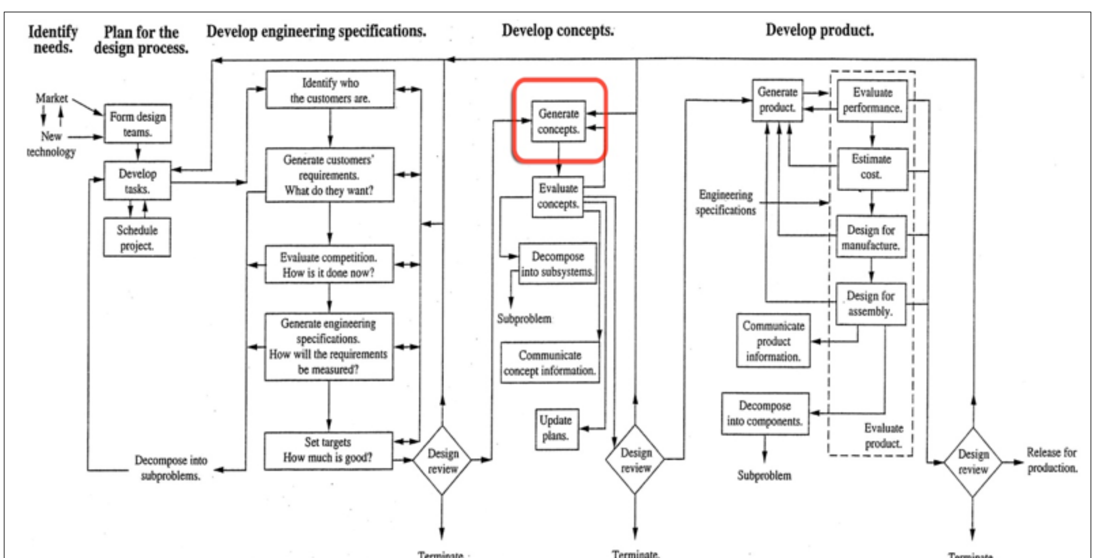

Figure 1. Ullman's (1997) depiction of a design process

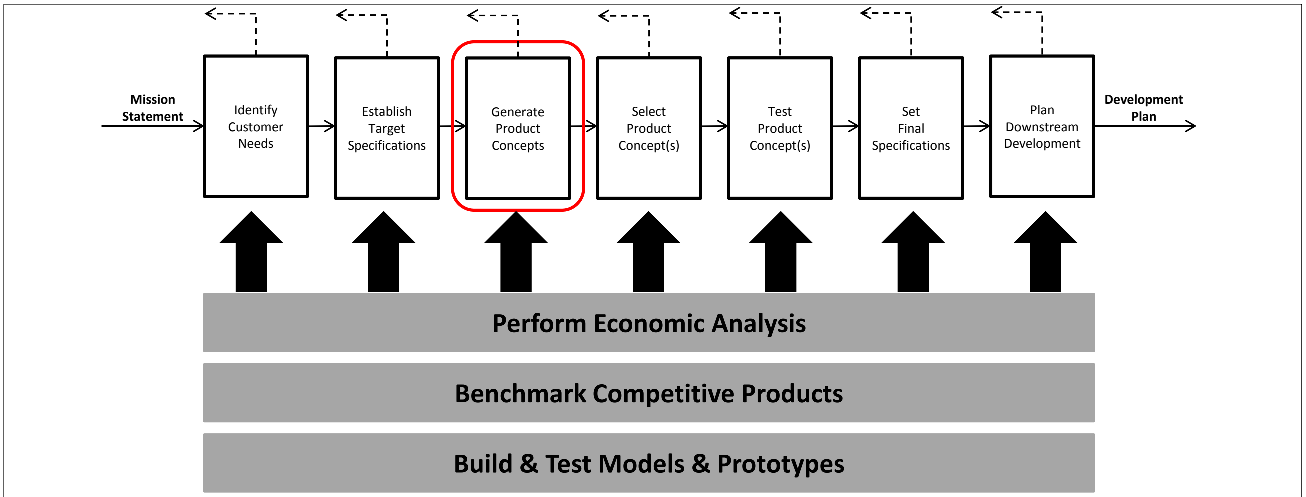

Figure 2. Ulrich & Eppinger's (2000) depiction of a design process

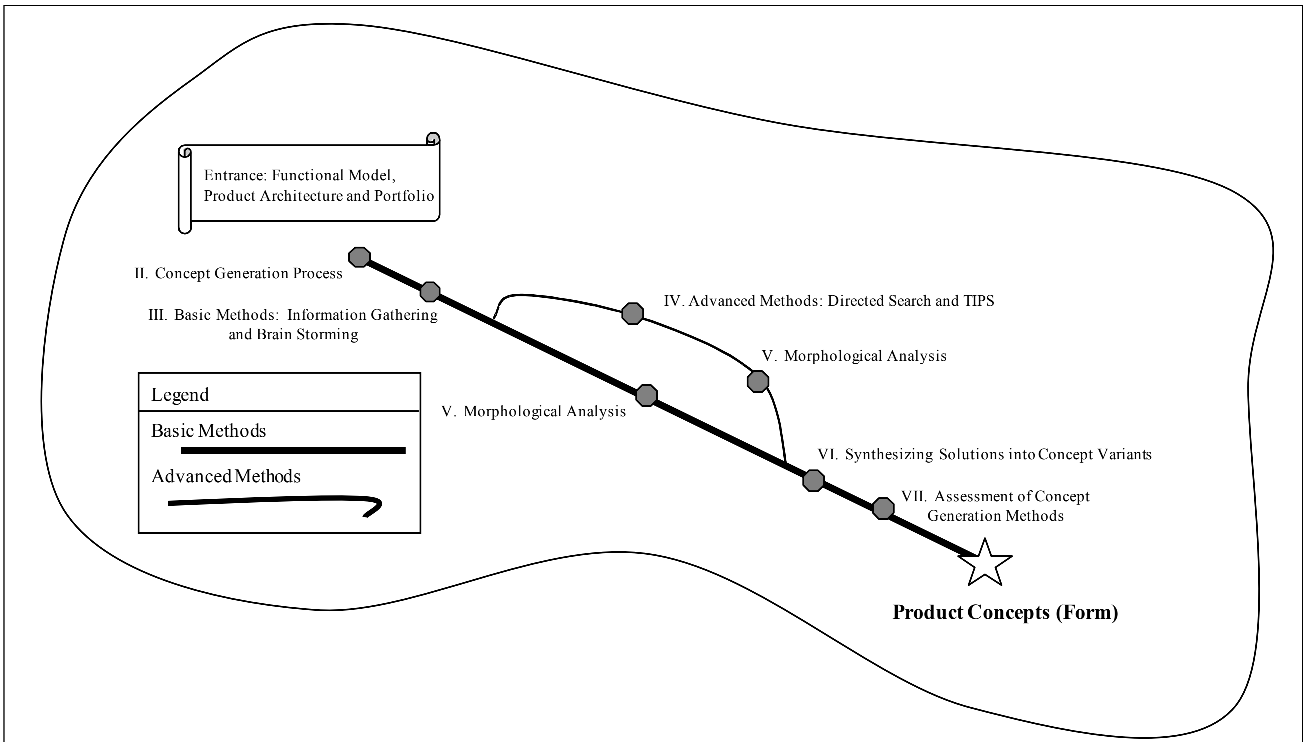

Figure 3. Otto & Wood's (2001) depiction of concept generation

Based on influential ideation techniques, as well as original work we have conducted in this area, we have developed a suite of CG techniques to assist in the design projects (Jensen, Weaver, Wood, Linsey, & Wood, 2009). The techniques include mindmapping, a modified 6-3-5 or C-Sketch technique, functional decomposition combined with morphological analysis, Theory of Inventive Problem Solving (TIPS/TRIZ), a method to produce products with the ability to transform or reconfigure, a search for cross-domain or far-field analogies, implementation of creativity principles from historical innovators, and a design by analogy technique using a WordNet-based search procedure. The fundamental premise of this suite is to enable designers to develop innovative concepts well beyond those that they would have created through ad hoc or singular, intuitive concept generation techniques. Through a suite of techniques, fixation, group think, and other cognitive barriers may be mitigated, we surmise, leading to an enhanced ability to ideate (Linsey, et al., 2010).

To investigate this premise, we designed and executed a study of student design teams. The study focuses on two components: (a) quantitative assessment of a design team's ability to generate concepts using the suite of techniques, and (b) assessment of enhancing students' creativity during ideation activities. These components of the study seek to measure whether a suite of concept generation techniques increases the abilities of design teams to generate ideas, and, in concert, enhance the creativity of student team members. Quantity of concepts, as a measure of a team's ability to ideate, is recorded for teams across multiple education institutions, across disciplines, and across years of study. Student teams are also asked to perform a self-assessment of their creativity characteristics. The teams perform this self-assessment through a pre- and post-survey during the study. Specifically, a creativity measurement instrument is used on both "control" design teams (who did not use the CG suite) and "experimental" teams (who used the complete suite of CG techniques). The

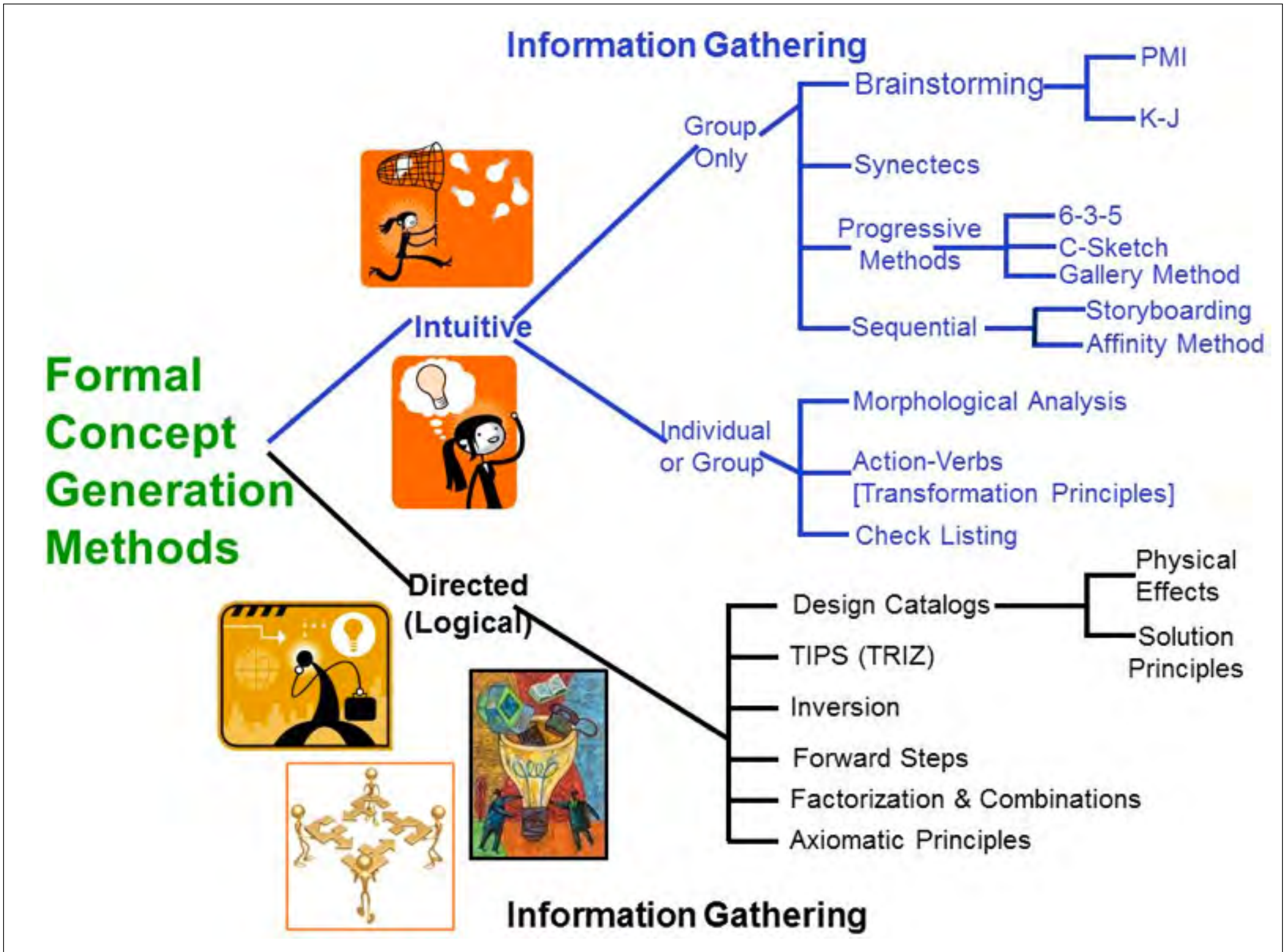

Figure 4. Types and names of concept generation methods (Shah, 1998)

creativity measurement instrument was used both at the beginning and at the end of the CG process so that an increase in creativity could be quantified.

2. Concept Generation Techniques

Concept generation techniques can be separated into directed and intuitive categories. The directed techniques rely heavily on the application of physical laws or other technical or principle insights to the resolution of design conflicts. The intuitive techniques rely more on a divergent thought process to produce new ideas for the solution to a problem based on the collective experience of the designers. Although the intuitive processes are, in many cases, less structured than the directed processes, they are certainly not without a certain level of order. In fact, the challenge in development of innovative solutions to design problems is, at least in part, in structuring a learning environment that will be conducive to this divergent, creative idea generation. It is with this goal in mind that we are implementing the CG suite.

2.1 Morphological Analysis Combined with 6-3-5 C-Sketch / Brainwriting

Functional decomposition is a method that helps designers describe *what* a product will be required to do (functions), *not how* it will accomplish these tasks (embodiment). There are a number of different ways to accomplish this functional decomposition with common methods including function trees and function structures (Otto & Wood, 2001). Functional decomposition combines with morphological analysis to provide a method for organizing potential embodiments for each function. Figure 5 shows a basic morphological matrix for a device to remove bilge water from pleasure boats. The design problem is first broken down into its functions. The functions of the device are then listed in the first column. Solutions (embodiments) that were generated during the concept generation process are then organized by their function in the remainder of the columns, categorized by energy domain.

In the classic method of "brainstorming," a small group of people openly discuss possible new solutions to an existing problem or conceptual solutions for new design problems. While this method may be effective in some forums, it has been shown in many design situations to lack the synergistic effect that is desired. Specifically, groups will not produce more quantity or quality of solutions in this "brainstorming" environment then a group of individuals working alone (Mullen, Johnson, & Salas, 1991). This finding has led many in the design community to the use of a modified brainstorming technique referred to as 6-3-5 / C-Sketh, described graphically in Figure 6 (Otto & Wood, 2001; Linsey, et al., 2011; Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001). In this technique, a small design team (approximately six members) each takes the initial 5-15 minutes of an exercise to develop a small number of concepts

Energy / Sub-Functions	Mechanical		Fluid		Electrical	Misc.
	Principles	Principles	Principles	Principles	Principles	Principles
Capture Energy	Wave – Spring	Moving Column	Wind – Vanes	Reservoir – Rain	Batteries	Solar Panels
	Wave – Pendulum	Mass – Spring	Wind – Cups	Ocean – Pressure	Capacitor	Reactive Compounds
	Wave – Elastic	Salter Duck	Float – Dock	Wave – Bladder		Salt-Water Concentration
	Boat Movement		Multiple Floats	Flowing Water		Delta Temperature
	Torsional Spring		Propeller	Wind Mill		
Transform Energy	Four Bar	Bevel Gear				
	Pendulum	Spur Gears				
	Cam	Belts-Sprockets				
	Universal Joint	Crank Shaft				
		Rack-n-Pinion				
Import Water	Lift	Carousel	Suction			Solidify – Freeze
	Ferris Wheel		Vaporize			Absorb – Sponge
	Archimedes Screw		Atomize			Absorb – Chemical
	Shovel		Syphon			
			Pressure Head			
Transport Water	Ferris Wheel	Spin-Centrifugal	Tube	Water Column		Steam
	Archimedes Screw	Funnel	Pressure	Water Piston		Atomizer
	Piston		Water-Column	Fountain		
			Channel	Squeeze Bladder		
			Weir			
Inhibit Backflow	Actuated Value	One-Way Resistance	Flapper Valve		Solenoid	
			Butterfly Valve			
			Ball Valve			
Prevent Debris/ Impurities	Screen		Skimmer			Absorb – Sponge
	Permeable Membrane					Chemical Bond
						Oil Eaters

Figure 5. Morph matrix: functional solutions for a set of bilge water removal devices (Otto & Wood, 2001)

intended to solve a design problem (Otto & Wood, 2001). These ideas are captured through a combination of sketches and words. Optimally, large sheets of paper and different colored markers are provided for each participant. After this initial 5-15 minutes, participants pass their paper to the adjacent team member. An additional 5-10 minutes are now provided for the members to add to/comment on the ideas of their colleague, or create an entirely new idea as inspired by the sketches passed to them. This rotational review process continues until each member has taken the opportunity to add to the concepts from all other members. No verbal communication is allowed during this entire process until all team members obtain their original concept sheet.

In our particular case, we combine the 6-3-5 /C-Sketch technique with Morphological Analysis and implemented the method following a function structure type functional decomposition of the problem (Otto & Wood, 2001; Stone & Wood, 2000). The ideas developed from 6-3-5 / C-Sketch are arranged in a morphological matrix based on how they met certain functions.

Figure 7 shows a sample result from the first and second round of a 6-3-5 / C-Sketch session. In the first time period, one of the team members drew three different solutions to the problem of a device to shell peanuts for applications in Africa villages. During the second time period, a second team member combined and added to the original set of ideas.

2.2 Transformational Design using Mind-Mapping

We define transformation as changing state in order to provide new functionality; for example, a Swiss army knife. Although products with the ability to transform are not new, until recently there has not been a theory of transformation, nor have there been ideation methods specifically devoted to the development of transformational products. Over the course of the last three years, both a transformational theory and a supporting set of ideation techniques have been developed (Singh et al, 20009; Weaver, Wood, & Jensen, 2008; Weaver, Wood, Crawford, & Jensen, 2010). The transformational theory describes a set of three transformational principles and 20 transformational facilitators. The transformational principles describe how the transformation takes place while the transformational facilitators describe key components of the transformation. These three principles and 20 facilitators shown in Table 1 have been validated through the study of over 300 electro-mechanical devices that have the ability to transform.

The principles and facilitators are used in conjunction with a semantic network technique called Mind Mapping (Otto & Wood, 2001). The technique places key words toward the center of a piece of paper and then organizes related information in categories (meta-analogies). Figure 8 shows a mind map created based on using transformational principles as secondary nodes to generate concepts for a product that transforms from a motorcycle to an ATV.

2.3 WordTree Based Design by Analogy

Using analogy is a powerful method for developing concepts. However, identification of analogies that will prove most helpful can be difficult. Recently, a technique for systematically seeking analogies based on the semantic representation of the functions being solved has been developed (Linsey, Wood, & Markman, 2008; Linsey, 2007). Multiple linguistic representations are created through intuitive brainstorming and using a tool created at Princeton called WordNet (Wordnet, n.d.; Felbaum, 1998). WordNet is similar to a thesaurus, but with far more functionality. The tool takes an input word (which in the case of a design problem could be a key function or key customer need, stated as an active verb) and outputs troponyms and hypernyms. Troponyms are more specific synonyms, and hypernyms are more general synonyms of the input word. By producing troponyms and hypernyms of key functions and customer needs, WordNet provides input to the design by analogy method.

In order to organize the information provided by WordNet, an instrument called a WordTree is developed (Linsey et al., 2008; Linsey, 2007). The word tree organizes the information by simply arranging chosen hypernyms above the input word and the troponyms below it. Additional words found through other intuitive methods can also be added. An example of a word tree using the input word "Track" is given below in Figure 9.

As shown in Fig. 10, the text from the word tree can be combined with pictures to enhance the utility of the method. In this case, the design team was redesigning an automatic cat litter box. The team was searching for ways to clean the litter box. Unexpected analogies generated included dredging, panning for gold and a dump truck tailgate (Linsey et al, 2008; Linsey, 2007).

2.4 Far-Field Analogies

Much of design by analogy is successfully accomplished using biological or biomimetic analogies. If we wish to develop a product with the ability to hop, for example, we might consider how a rabbit or a grasshopper accomplishes this function. If our goal is to develop a product with new visualization capabilities, we might consider how the rods and cones of the human eye function. While biology appears to provide a very fertile set of analogies, it is not clear that this approach is always the most productive realm in which to search for analogies. Perhaps searching in different realms might

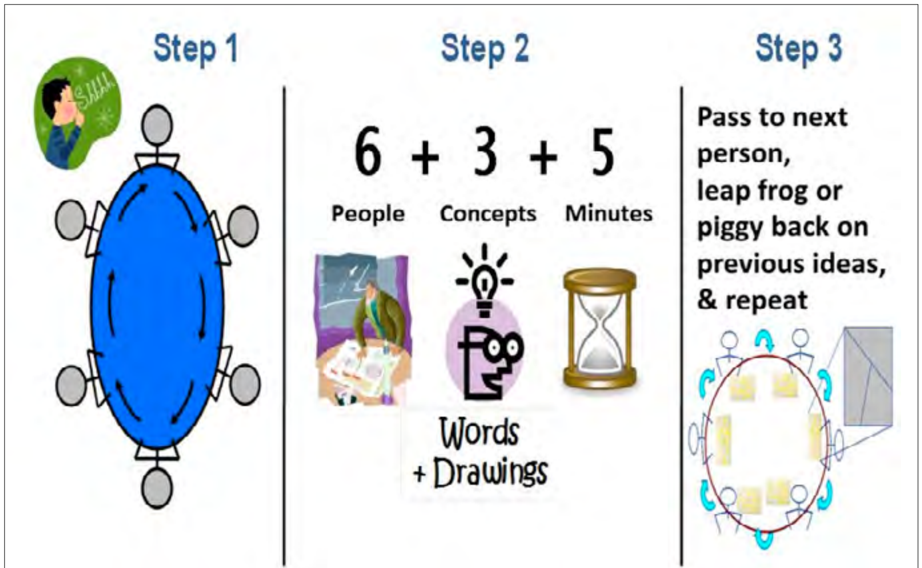

Figure 6. 6-3-5 / C-Sketch concept generation process (Otto & Wood, 2001; Linsey,et al., 2011; Shah, et al., 2001)

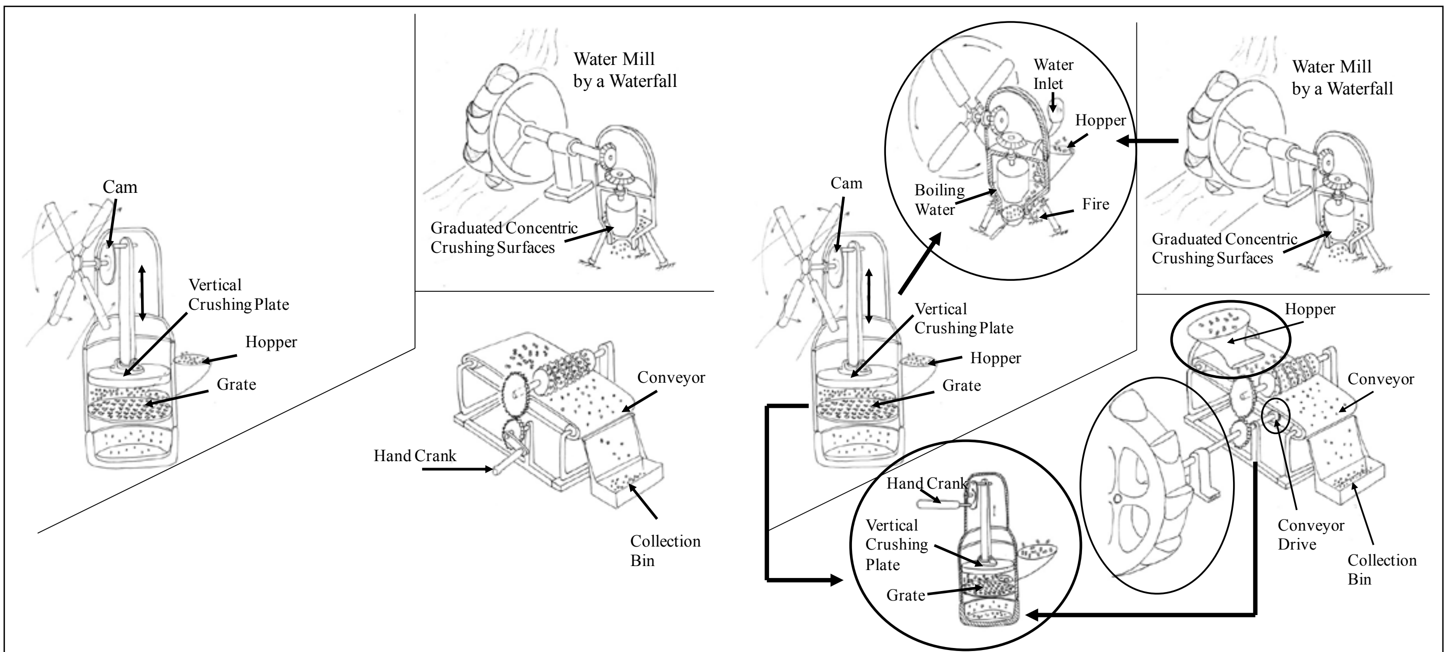

Figure 7. Example results from a first and second round of 6-3-5 / C-Sketch (Linsey, et al., 2011)

PRINCIPLES		
Expand / Collapse	Expose / Cover	Fuse / Divide
FACILTATORS		
Conform w/ Structural	Interchange Working Organ	Share Power Transmission
Enclose	Modularize	Shell
Fan	Nest	Telescope
Flip	Roll/Wrap/Coil	Utilize Composite
Fold	Segment	Utilize Flexible Material
Furcate	Share Core Structure	Utilize Generic Connections

Table 1. Transformational Principles & Facilitators

provide analogies with some different distinctive features.

In light of this, we have developed a relatively unstructured method for encouraging students to search for analogies in other realms. The method is called Far-Field Analogies. The technique considers three distinctly different fields where students might attempt to discover helpful analogies. These fields, along with an example question students can use to lead the discovery of analogies, are shown in Fig. 11. Although we do not propose that these three fields (Physics, Art, and Societal Mechanics) are an optimal set for use in the Far-Field Method, we have used a wide variety of different fields and these appear to be our most useful set to date. Perhaps this is because these three fields are quite diverse. Note that we have had students use this technique with different fields of their own choice with some success as well.

As an example of this method, we are attempting to design products that have the ability to "hide in plain sight." Solutions to this problem would be a distinct advantage for surveillance systems. Using the Far-Field Analogy method, we implement the Far Field Question (Fig. 11) and ask how does music hide in plain sight. We hypothesize that one way this occurs is that the music (see Fig. 11 / Art Category) blends in with surrounding noise. This analogy instigates that next step of inquiring how we can have our surveillance system blend in to its background. In accordance with this we are developing a technique that mounts LCD screens on the edges of the surveillance system, takes a picture of the background behind the system and projects that picture on the screen, causing the edges of the system to blend into their background.

2.5 Principles from Historical Innovators

Although significant questions remain on what precise traits give a person the ability to be creative, there is general agreement that history has numerous examples of individuals who have exhibited tremendous creative accomplishments. The concept generation technique of "Historical Innovators" attempts to capture some of the principles that these extraordinary individuals used to accomplish their innovative feats and then apply these principles to the concept generation process. There are, of course, literally thousands of possible historical innovators that could be used in this endeavor.

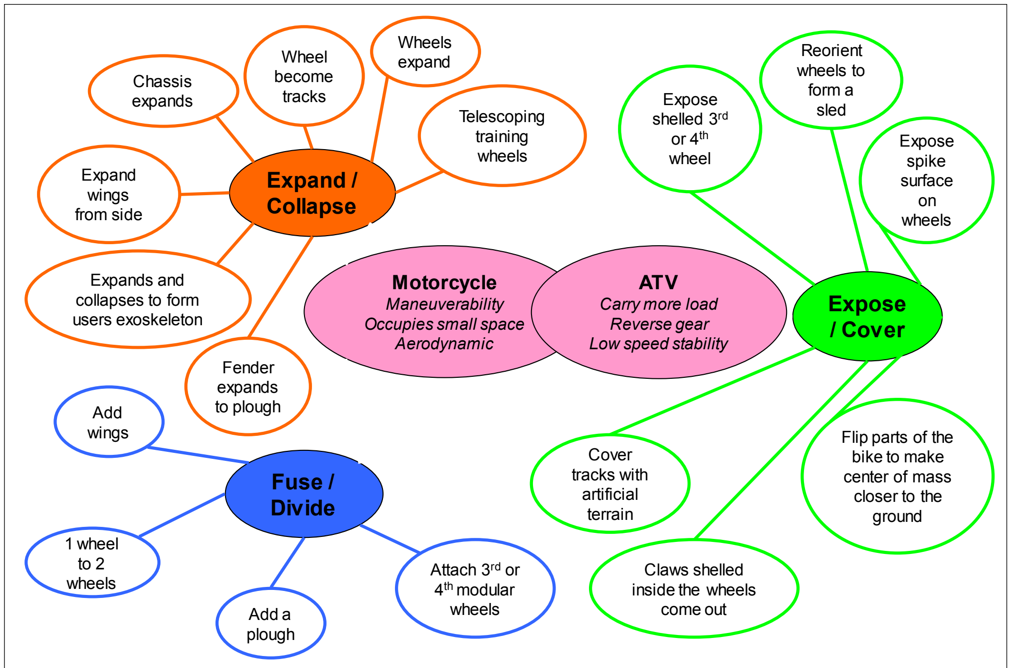

Figure 8. Mind Map using Transformational Principles for a motorcycle / ATV product (Singh et al, 2010; Weaver et al., 2008; Weaver et al., 2010)

Figure 9. Abbreviated WordTree generated using information from WordNet

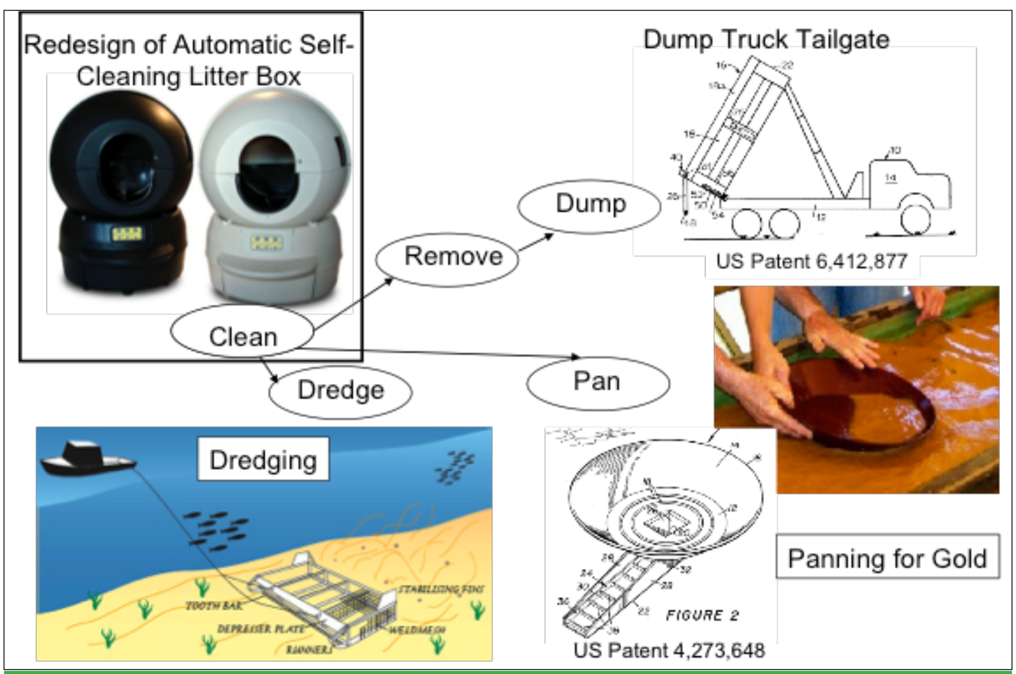

Figure 10. WordTree for cleaning cat litter box [7,10]

On whose Shoulders Do We Stand? Inclusion of Diversity in Our Innovation Giants

Nicolai Copernicus, Christopher Columbus, Plato, and Albert Einstein (Fig. 12) were first chosen as historical innovators in the CG suite. The basis for initially choosing these historical figures was because their principles are quite broad and directly applicable to the CG process. In a concerted effort to consider the inclusion of innovators that can connect to a wide variety of design problems and prompt ideation, we believe that the innovative giants must represent principles and applications that span time and space. Although Copernicus, Columbus, Plato, and Einstein meet those criteria, demographically there is a limit to their representation. It is important that we also include historical innovators that are demographically diverse in gender, race, engineering experiences, and era.

In seeking out additional historical innovators that represent more diversity, we researched repositories that have a focus of marginalized groups in the history of patented inventions in the United States. A few of the repositories included only notable African American inventors, others all female patent holders, and some that are comprised of celebrating salient inventors who are non-White. From these broad lists, we considered ways that we could still represent diversity of engineering experiences, principles, and applications in the resources for the concept generation suite. Ultimately, the historical innovators we highlight in the concept generation suite, in addition to the original aforementioned four, are the following: George Washington Carver, Charles Drew, Stephanie Kwolek and Harriet Tubman (Fig. 13) (White, Talley, Jensen, & Wood, 2010). Other historical innovators such as Marie Curie and Bette Nesmith Graham are included in the CG Suite of resources.

As an example of how this method can be applied, one of our design teams worked with small remote controlled aircraft equipped with small cameras. The systems are used for surveillance missions for the military, fire fighters and natural disaster relief. Unfortunately, these systems are very limited by short battery life. One idea for dealing with this limitation is to give the aircraft the ability to perch. However, the control system to guide, flare wings, stall and grab that is used by most birds is quite difficult to implement in a man-made, mechanical system. While possible, the implementation of this system is likely years away from completion. A principle from the his-

POTENTIAL REALMS FOR FAR FIELD ANALOGIES

Physics: State Changes, Quantum Mechanics, Relativity, Classical Mechanics (fluids, structures, orbital)

Art: Painting, Sculpture, Music, Poetry, Literature, etc.)

Societal Mechanics: Governments, Interpersonal relationships, Family dynamics, Organizational systems (corporate, military, family, recreational…)

Far Field Question:

How does ________ (insert a specific realm here) do ________ (insert a specific Customer Need or Function here).

Figure 11. Overview of Far-Field Analogy concept generation technique

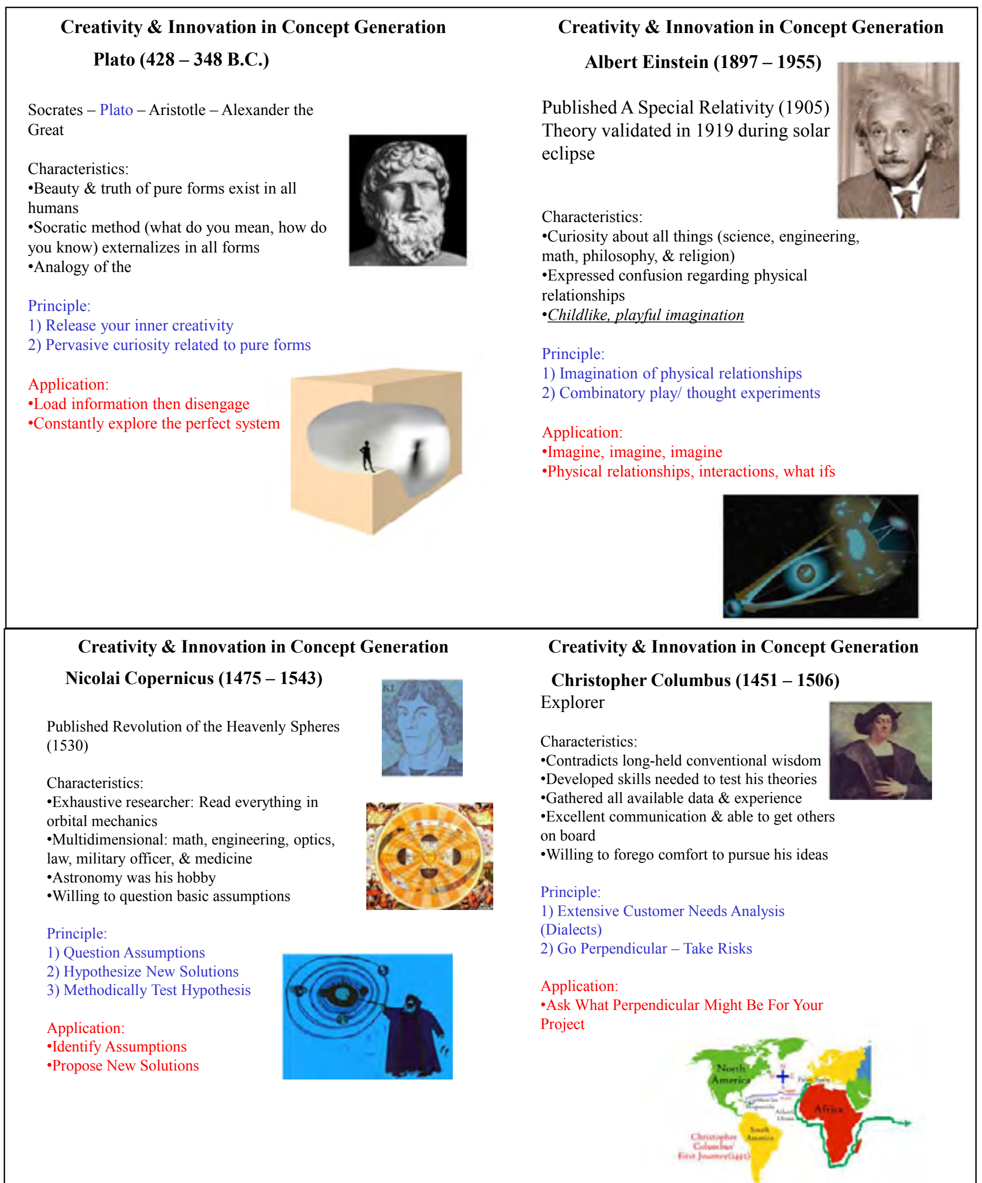

Figure 12. Plato, Einstein, Copernicus and Columbus Historical Innovator Resources (Mullen et al., 1991)

toric innovator Columbus, "go perpendicular - take a risk to shorten the time for completion of your mission," provided the inspiration for an alternative design where the small aircraft simply hits a vertical perch location (like a wall) head on at low speeds, then sticks to the location by means of a "sticky pad" on the aircraft's nose. This risky solution was implemented successfully in a very short period of time (Anderson et al., 2009).

Indeed, during the concept generation process, there are many successful methods within the CG suite yet there are ways to improve each strategy as we continue to learn more about the ideation process. The addition of these historical innovators from traditionally underrepresented groups in engineering may enhance the quantity and quality of innovative ideas because each example, principle, and application represents various facets of engineering design. The likelihood to increase the variety of concepts may be greatly enhanced when, for example, Harriet Tubman's profile is provided in addition to or in complement to Christopher Columbus'. Marie Curie's principle of isolating and characterizing components to study new ideas as she did in discovering the elements Radium and Polonium may be a principle that is applied in generating concepts differently than the original four historical innovators.

2.6 The Theory of Inventive Problem Solving (TIPS /TRIZ)

TIPS is a well documented method for solving conflicts in designs (Otto & Wood, 2001; Altshuller, 1994). Based on a study of thousands of patents TIPS puts forth a set of 40 principles that can be used to inspire creative solutions to conflicts in a design. The designer examines the problem and identifies inherent contradictions in the design requirements. As an example, a designer may want to increase the acceleration of a vehicle. An engine capable of higher acceleration may be used, but this will likely have implications for other system parameters: cost may go up, the system may be larger and heavier, or maintenance needs and durability may be affected. These contradictions may be summed up with general engineering parameters, such as power vs. volume and weight vs. cost.

A conventional approach may simply attempt to compromise in these tradeoffs, finding a Pareto frontier design that is "good enough" with respect to all the conflicting parameters. TIPS, however, guides the designer toward specific design principles that can resolve or eliminate these conflicts. This approach is done through a matrix that tabulates all combinations of contradicting engineering parameters and lists the principles used to creatively resolve them. To continue the previous example, identifying the contradiction between power and volume would lead to, among others, the principle of "*universality: make a part or object perform multiple functions; eliminate the need for other parts*." This may lead to an attempt to in-

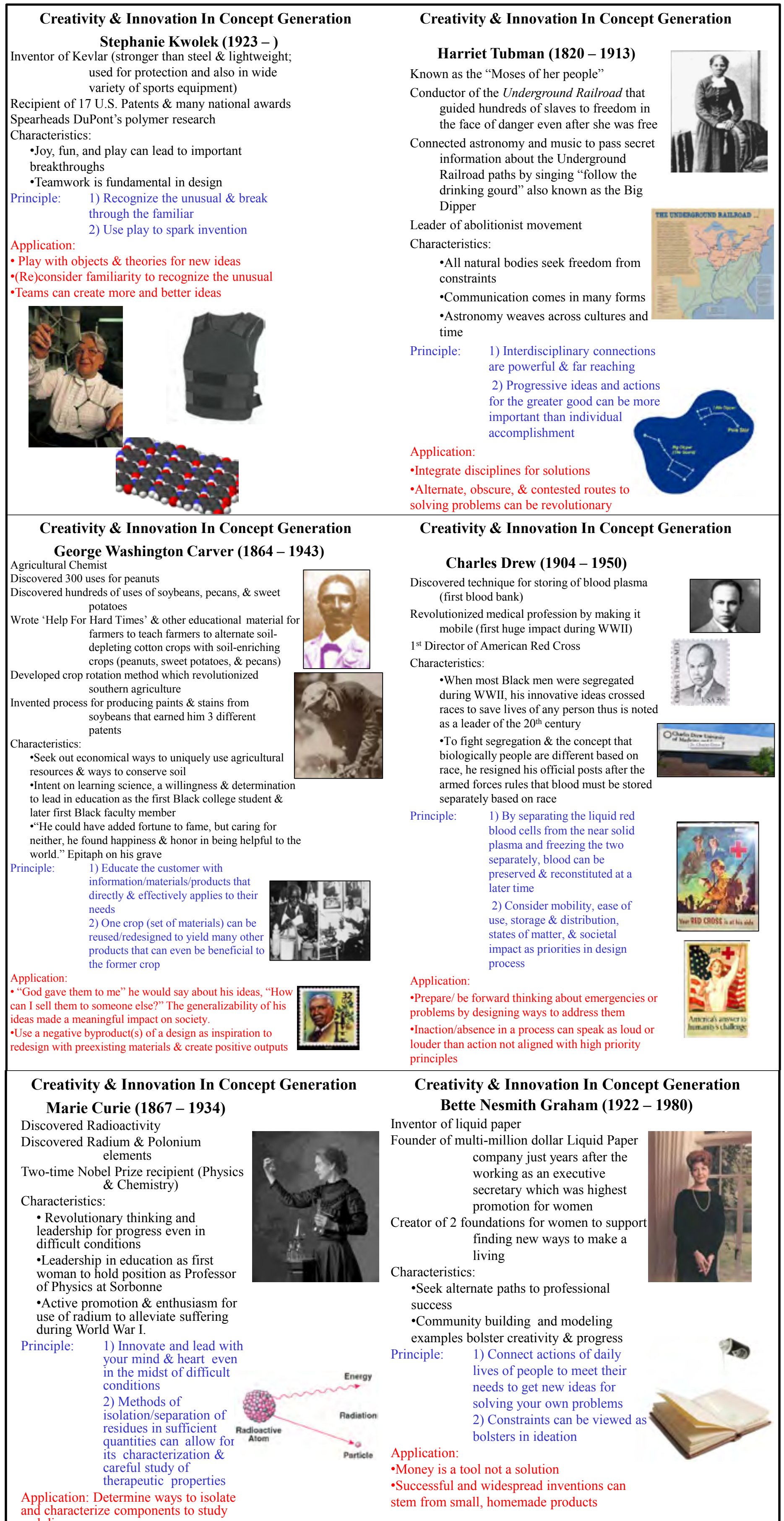

Figure 13. George Washington Carver, Charles Drew, Stephanie Kwolek, and Harriet Tubman Historical Innovator Resource (White et al., 2010)

crease function sharing and decrease the number of components in the engine and surrounding system, minimizing the additional volume resulting from the increase in power. While this method is normally included in the concept generation stage of design, to some extent it requires embodiment solutions to already be conceptualized. A design conflict must be identified (which is more readily apparent in fleshed-out embodiments) before the TIPS method can suggest a path to a resolution. Therefore, we have tended to use this method at the end of the concept generation process. Otto and Wood (2001), as well as other sources, provide details needed to implement this concept generation method.

3. Background on Measurement of Creativity

The measurement of creativity is elusive at best. Although the research in this area is quite substantial, even the definition of creativity remains in question among various researchers. Kerr and Gagliardi (2009) provide a wonderful overview of the research in this area. Often the measurement techniques are used to identify people (usually children) that have high potential to be creative. However, the correlation between those who "score" high on these creativity measures and then later manifest this creativity is not always very high (Plucker & Ranco, 1998). There are a variety of hypothesized reasons for this lack of correlation and researchers are working diligently to investigate this phenomenon. One such effort is the work by Csikszentmilhalyi (1996) where the correlation between creativity and the mastery of a specific domain's knowledge was investigated. Others have investigated psychological variables that can block creativity, environmental variables that enhance creativity, and task motivation that drives creativity (Pritzker, 1996; Piirto, 1998; Johansson, 2006; Hennessey & Amabile, 1998).

Two of the most common methods for measuring creativity are divergent-thinking testing and creativity-trait testing. Divergent thinking is a process that allows for various, sometimes seemingly unrelated, streams of thoughts that produces innovative solutions to a problem. Runco (1998) explains, "Because some of the resulting ideas are original, divergent thinking represents the potential for creative thinking and problem solving" (pp. 577). Divergent testing is thus testing that attempts to measure the ability of an individual to think in this divergent manner. Torrance produced a set of divergent thinking tests that are probably the most widely used and also are supported by a wide range of validity assessment data Torrance, 1998; Khatena, 1989). However, the use of testing like Torrance's requires extensive time, resources and the support of experts who have been trained to exclusively evaluate the tests' results (Kerr, Shaffer, Chambers & Hallowell, 1991). This makes these sorts of testing procedures less functional in an academic environment.

Creativity trait testing is based on the hypothesis that people who are creative share a common set of personality traits (King & Pope, 1999; Feist, 1999; Piirto, 1998). For example, a specific characterization from the Myers-Briggs personality tests has been correlated positively with creativity (Myers & McCaulley, 1985). There are a variety of instruments used to provide the Myers-Briggs type data. A web version commonly used in academic settings has been developed by Kersey (Human Metrics, 2009). The test provides four personality descriptors. A person is either "extroverted" or "introverted," "sensing" or "intuitive," "thinking or "feeling," and "judging" or "perceiving". The strength of one's preferences is also delivered by the test. Across a variety of fields including managers and teachers those individuals who are "introverted," "intuitive," "thinking" and "perceiving" tend to be more creative than those with other Myers Briggs designations (Fleenor & Taylor, 1994; Houtz, LeBlanc, Butera & Arons, 1994). This Myers-Briggs data appears to be a useful way to measure creativity in an academic setting and in this light has been used to develop a team formation and team coaching strategy (Jensen, Wood & Wood, 2003).

In the present work, we seek to measure fluctuations in an individual's creative ability. This desire is obviously based on a belief that, while some creative ability is likely intrinsic to the person's personality and mental capabilities, it is possible to ***develop*** creative capabilities as well, or at least bring awareness of creativity to the individual. In order to measure changes in an individual's creativity, we have chosen to use an established set of "creativity descriptors." Gough's (1960) list of 18 descriptors has been evaluated across multiple fields using over 1700 subjects. These 18 adjectives have been shown to positively correlate to creativity (as measured by experts in the different fields). The list of descriptors is shown below in Table 2. Our assessment strategy entails asking the students to self-evaluate in these 18 areas both before and after they are exposed to the set of concept generation techniques described previously. We propose that the difference between their before and after assessment in these 18 areas is a measure of their increase or decrease in creative ability. Both a control group and experimental group are used as described in detail in the assessment sections below.

4. Assessment of the Concept Generation (CG) Suite

4.1 Overview

In an effort to assess the ability of these techniques to enhance creativity in our students, a survey is designed and conducted to gauge creative ideas before and after the students learned to use the CG techniques. We apply this assessment, as well as concept generation metrics, to a range of inventive design problems solved by our students. Our results show that the implementation of the suite of CG techniques increases the creativity of the students, and produces an increased quantity and variety in concepts. The assessment also indicates that exposure to these CG techniques increases creativity when compared to a control group that were not exposed to the full suite of CG techniques.

4.2 Methodology

Teams of undergraduate engineering students are formed at the US Air Force Academy (USAFA) and the University of Texas at Austin (UT for Major Design Experiences (a.k.a., Capstone) in the students' last year of undergraduate work. Teams of students are also created as part of a freshman signature course at UT, entitled "The Engineered World: Products and Innovations" and are composed of multiple disciplines (typically not engineering) from across the university. The USAFA and UT teams were formed to meet the following goals:

1. Intrinsic student motivation. Students' desires to work on a particular project or to solve a chosen inventive problem were taken into account.
2. Equitable distribution of high and low academic performers. The average GPA of each team was a factor in distributing students among the teams. (USAFA only.)
3. Diversity of personality. Complementary MBTI and 6-hat scores were taken into account when forming teams [49-53,58].

Capable	Egotistical	Informal	Interests wide	Reflective	Sexy
Clever	Humorous	Insightful	Inventive	Resourceful	Snobbish
Confident	Individualistic	Intelligent	Original	Self-confident	Unconventional

Table 2. Gough's (1960) List of Creativity Descriptors

4. Diversity of academic background. The majority of each senior-level team contained Mechanical Engineering majors. A variety of students from other majors also participated. These other majors (e.g., electrical engineering, biology, human factors, management) were distributed as evenly as possible, considering other factors such as student desire, and the project's unique requirements. Each team had at least one management major (USAFA) and usually one or more other students from other technical degree programs.

At USAFA, design teams worked on a variety of projects ranging from the Society of Automotive Engineers Formula Car Intercollegiate Competition to various smaller projects sponsored by the Air Force Research Laboratories (AFRL). Team sizes ranged from 12 (for the formula team) to six (for the smallest AFRL team). Half of these groups served as a "control" group, only using 6-3-5 / C-Sketch for concept generation. These three teams included the SAE formula car, a project to design a "quiet" Baja-type vehicle, and a project to design an exercise machine for rehabilitating the walking gate of those with neuro-muscular diseases. The other three teams utilized the complete suite of six CG methods detailed in section 2. Two of these teams worked on different aspects of a project to enable UAVs to tag and track targets, while a third worked on the previously mentioned project to enable UAVs to perch.

At UT, design teams worked on an innovative sensor system for the oil field applications, a intelligence-surveillance-reconnaissance application for AFRL, and inventions for new products based on the students' life experiences. Five experimental teams, with five to eight members each, were formed from a multi-disciplinary senior design course with the industry sponsored projects. Seven additional experimental teams, with two members each, were formed from the freshman signature course.

Based on this team distribution, the experimental teams execute the suite of concept generation techniques, and the control groups execute an abbreviated set (such as a focus on the 6-3-5 / C-Sketch method only). Prior to applying the suite of techniques, team members complete a self-assessment of creativity based on a pre-survey from Gough's creativity descriptors. The difference between the before and after assessment in these 18 areas is a measure of the increase or decrease in their creative ability. Both a control group and experimental group were used as described in detail in the results sections below.

In addition to an assessment of creativity enhancement, the number of non-redundant, unique concepts generated by the control and experimental teams was recorded. This quantity measure provides an indication of the successfulness of the design teams to generate innovative solutions to their design problems. The quantity of concepts generated correlates with the novelty, diversity, and quality of the set of the concepts.

4.3 Analysis and Results

Tables 3 and 4 list the number of concepts generated by the different teams broken down by the different CG methods. Table 3 shows the results for the senior-level teams, where the first three teams are from USAFA and the latter five teams are from UT. Table 4 shows the results from the freshman signature course at UT. For each method, the teams had approximately 30-60 minutes of training on the use of the method followed by approximately 30-90 minutes of time to implement the method. Therefore, the use of the 6 methods represents about 3- 9 hours of total time.

Table 3 shows that the average number of concepts generated by each senior-level "experimental" group through the use of the six CG methods is 88. As teams were instructed to only "count" concepts that were distinctly different from their other concepts, we believe this to be an extremely positive result. The three USAFA "control" teams, using only the 6-3-5 / C-Sketch method, generated an average of approximately seven (7) concepts. Of course, this result is not directly comparable to the 88 concepts generated by the experimental group, as the control groups spent only a fraction of the time spent by the experimental teams on concept generation. However, a quantitative measurement can be developed noting that the experimental groups developed an average of 14.7 ([average of 88 concepts] / [6 CG methods]) new concepts per CG method while the control group developed only seven. This result is even more persuasive when one considers that the experimental teams might tend to experience some "burn-out" of their creativity as they proceed through the suite of CG techniques. As shown from the table, the number of concepts generated generally decreases as one moves down a team's column in the table. This, we hypothesize, is because, in general, the teams used the techniques in chronological sequence from the top row to the bottom row, or, alternatively, the teams selected the CG techniques that were most appealing to them. The table also shows the "top" producing CG methods (red numbers in the table) varied across the teams. This result might indicate that the team dynamics for each team or the type of design problem presented created different levels of productivity for each CG method. The use of multiple methods thus has an advantage of being able to access the unique strengths of the different teams/

	Number of Concepts								
CG Technique	Team 1	Team 2	Team 3	Team 4	Team 5	Team 6	Team 7	Team 8	Avg.
6-3-5 + Morphological Analysis	16	3	**43**	**47**	25	**42**	**32**	12	28
Transformational Design +Mind Maps	23	1	10	25	**29**	30	18	20	20
Design by Analogy + Word Trees	**51**	10	17	10	11	15	12	**41**	21
Far Field Analogies	6	**25**	27	N/A	N/A	N/A	N/A	N/A	19
Historical Innovators	0	5	3	8	12	7	13	5	7
TIPS	0	27	0	0	5	7	4	3	6
TOTAL # OF CONCEPTS	**96**	**71**	**100**	**90**	**82**	**101**	**79**	**81**	**87.5**

Table 3. Number of Concepts for the Different Teams and CG Methods (Senior-Level Teams)

	Number of Concepts								
CG Technique	Team 1	Team 2	Team 3	Team 4	Team 5	Team 6	Team 7	Team 8	Avg.
6-3-5 + Morphological Analysis	16	3	**43**	**47**	25	**42**	**32**	12	28
Transformational Design +Mind Maps	23	1	10	25	**29**	30	18	20	20
Design by Analogy + Word Trees	**51**	10	17	10	11	15	12	**41**	21
Far Field Analogies	6	**25**	27	N/A	N/A	N/A	N/A	N/A	19
Historical Innovators	0	5	3	8	12	7	13	5	7
TIPS	0	27	0	0	5	7	4	3	6
TOTAL # OF CONCEPTS	**96**	**71**	**100**	**90**	**82**	**101**	**79**	**81**	**87.5**

Table 4. Number of Concepts for the Different Teams and CG Methods (Freshman-Level Teams)

projects.

Table 4 shows the results of the number of concepts per technique and the average number of concepts generated by the freshman invention teams. While it is clear that the smaller freshman teams (two members compared to an average of 5-6 members for the senior teams) generated a lower average (39 concepts), the results are encouraging and impressive. As with the senior teams, the number of concepts generated by the freshman teams per technique varied across the teams. It is also clear that the freshman teams tended to concentrate on fewer techniques. This result might be explained by the quantity of domain knowledge and experience by the team members. Senior-level teams with greater domain knowledge may have been more willing to generate more concepts to fully wield this knowledge compared to the freshmen. It is also likely that the senior-level teams had a different level of motivation to develop more concepts since their results were funded by external sponsors, whereas the freshman projects were self-generated projects to develop inventive products.

STUDENT INVENTION	HISTORICAL INNOVATOR
Pill Dispensing Machine	Thomas Adams: Gumball Machine
Silent Wrapper Opening Device	Hiram Percy Maxim: Maxim Silencer
Multi-Purpose Laundry Device	Sarah Boone: Ironing Board
Multi-Functional Drafting Tool	Karl Elsener: Swiss Army Knife
Self- Guiding Ball Rebounding Device	Copernicus: Revolution and Rotation
2-in-1 Stable Tongue Scraper & Toothbrush	Christopher Columbus: Go Perpendicular
Tangle-Free Headphones Device	Zvi Yemini: Water-Powered Hose Winding Reel

Figure 14. Examples of Student Inventions and Corresponding Historical Innovators

In evaluating the historical innovators as a tool to inspire inventive thinking, we review the design teams' choice to integrate this as a meaningful tool during ideation. It was exciting to see that the students generated new resources to add to the repository of historical innovators for concept generation. Indeed some of the design teams were influenced by the current historical innovators and other design teams sought out other innovators whose principles more closely resonated with their design. For example, in the freshman teams, two of the teams were inspired by the provided resources on Copernicus and Christopher Columbus. The rest of the teams incorporated different innovators. We note that the students also chose to include diverse innovators as inspiration, as shown in Figure 14.

In addition to the exciting results related to the quantity of generated concepts, the design teams at USAFA and UT were surveyed regarding the self-assessment of creativity. Both control (used only the 6-3-5 / C-Sketch CG method) and experimental (used a suite of CG Methods) groups were surveyed using the instrument shown in Fig. 15. The students rated themselves for each of the 18 descriptors given, using the Likert scale provided (1 through 6). This assessment was conducted before the CG process and again after completion of all concept generation.

Eighty-six (86) student surveys were recorded representing over 1500 data points (recall each survey used has 18 questions. The control group (20 seniors) experienced an 8.2 percent increase while the experimental groups experienced between 12.0-13.6 percent increase (48 seniors) and 17.2 percent increase (18 freshman) as they progressed through the CG process. Focusing on the senior design teams, the USAFA experimental senior-level team members experienced an average of 13.6 percent increase and the UT senior-level team members experienced an average of a 12.0 percent increase. Using Gaussian statistical analysis, a probability is calculated to determine if a statistically valid difference exists between the control group and experimental groups. This analysis provides a statistical answer to the question "how confident are we that the increase in creativity ratings for the control and experimental groups (8.2 percent vs. 12.0-13.6 percent) are really different." This question is relevant because these numbers are actually averages, with corresponding standard deviations, across a large student base. In this case based on a statistical t-Test with unequal sample sizes and unequal variance, the 8.2 percent increase versus the 12.0 percent and 13.6 percent increases in creativity measures are in fact statistically different, respectively. The statistical comparisons correspond to a p-value of 0.02 and 0.05, respectively. Thus, using the CG suite not only resulted in a large number of useful and innovative concepts, but actually improved the students' self-perception of their own creativity, which could possibly lead to lasting impact on their effectiveness as designers and engineers.

5. Conclusions

Invention, innovation and design are arguably at the core of the engineering education universe. This paper undertakes a study of innovation processes in engineering education through the development and assessment of a suite of concept generation techniques for engineering students. Building on a previous study, we advance the suite of techniques through the evolution and diversification of a technique known as historical innovators. This technique now includes principles from historical innovators demographically diverse in gender, race, engineering experiences and era. Design teams using this evolved technique created inventions that were founded by the principles of individuals with which the teams identified and were inspired.

The suite CG method was then used by multiple teams of senior-level engineering design students and freshman multi-disciplinary students at both USAFA and UT. One purpose of this suite is to facilitate the creation of a large number of innovative solutions to various design problems. In addition, the CG methods are intended to increase the creativity of the students who use them. These CG methods include three methods that are well known (6-3-5 / C-Sketch, Mind Mapping and TIPS), two methods that have recently been reported in the engineering design and cognitive science literature (WordNet based Design by Analogy and Transformational Design Methodology), and two methods that have recently been reported in the engineering education literature (Historical Innovators and Far-Field Analogies).

Assessment consisted of quantifying the number of concepts generated using the individual CG methods and also evaluating the increase in creativity of the students using these methods compared to those who did not use the suite of CG methods. The number of concepts per team, generated from the suite of CG methods, averaged 88 from across all methods and eight senior-level design teams (five to six members per team). This result equates to 14.7 concepts per CG method. The control group used only the 6-3-5 method and generated approximately seven concepts per team. Additionally, the increase in creativity for the group using the suite of CG methods is statistically distinct for the group that did not use the CG methods, advancing from an 8.2 percent increase to between 12.0 percent and 13.6 percent increase. These results, in addition to the pure quantity of generated concepts, are extremely encouraging for the future of engineering education to enhance creativity of students and focus on creating the next generation of inventors, innovators and entrepreneurs.

INSTRUCTIONS For each of the 18 adjectives listed below, rate yourself (fill in blue cells) using the (1-6) scale shown (green cells)				
#	I am …	Rating		
1	Capable		SCALE	
2	Clever		1	Strongly Disagree
3	Confident		2	Disagree
4	Egotistical		3	Slightly Disagree
5	Humorous		4	Slightly Agree
6	Individualistic		5	Agree
7	Informal		6	Strongly Agree
8	Insightful			
9	Intelligent			
10	Interests Wide			
11	Inventive			
12	Original			
13	Reflective			
14	Resourceful			
15	Self-confident			
16	Sexy			
17	Snobbish			
18	Unconventional			

Figure 15. Creativity Measurement Instrument

6. Future Research

This paper illuminates the rationale and processes in the development, evaluation, reflection, and evolution of tools to support and inspire engineering students in the design process, specifically during concept generation. In this most recent research, our focus is on the evolution of the historical innovators technique. For our future research, we will explore the effectiveness of students using the Thinkmap Visual Thesaurus (Thinkmap Visual Thesaurus, 2011). The Thinkmap Visual Thesaurus will be introduced as a complement to the WordNet technique for ideation. WordNet is intriguing to use because it produces troponyms and hypernyms of key functions and customer needs by representing verbs for design that are non-obvious and lead to exciting new ideas. The Thinkmap Visual Thesaurus provides related verbs, nouns and antonyms. A rationale to research the inclusion of the Thinkmap Visual Thesaurus is that we will identify if and how expanding the semantic tools generates more and novel concepts. Secondly, we will understand more about the importance of user interface with the tools. The WordNet tool generates meaningful, but static display trees of the verbs. The Thinkmap Visual Thesaurus is highly interactive and creates word maps with meanings and branch to related words that blossom and move. We anticipate grasping key insights about semantic inquiry in design by analogy by using these two tools as complements.

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Senior Design Teams:		
USAFA:	*Control (USAFA)*	*Experimental (USAFA)*
Mean (Creativity Rating, % Increase)	8.2	13.6
Variance	38.44	56.25
Observations	20	20
Hypotehsized Mean Difference	0	
Degrees of Freedom	36.70	
t Stat	2.48	
P(T<=t)	1.79E-02	
P(T>t)	0.98	
UT:	*Control (USAFA)*	*Experimental (UT)*
Mean (Creativity Rating, % Increase)	8.2	12.0
Variance	38.44	43.56
Observations	20	28
Hypotehsized Mean Difference	0	
Degrees of Freedom	42.58	
t Stat	2.04	
P(T<=t)	4.79E-02	
P(T>t)	0.95	

Table 5. Results of Creativity Assessment Process (Senior Design Teams)

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