Abstract – The design process takes an initial idea or problem and converts it to a final product or solution. Some state that creative thinking occurs when the initial idea is novel and becomes a valued product for a specific application. A definition of systems thinking states it as a means for working through the design process. It helps define a phenomenon holistically—by its contents, objectives, interactions, relationships, and environment—and uses analysis and synthesis to form new conclusions.

This paper describes the basic theories behind systems thinking and creative thinking and relates them to the design process. The paper emphasizes the application of system and creative thinking in the freshman design course at the University of Tennessee at Chattanooga (UTC). This course emphasizes the use of systems and creative thinking in its instruction and application of the design process.

Index Terms – Creative Process, Creative Thinking, Creativity in Design, Systems Thinking

INTRODUCTION

The design process is a systematic decision-making process that aids in evaluating and generating characteristics and solutions for an entity or process to meet specified constraints and achieve specified objectives. Creative thinking is integral to progressing successfully through the design process. Creative thinking occurs when something novel is developed that becomes a valued product in a specific domain. Creative thinking often occurs when a difficulty, problem, or deficiency is sensed or an element is tested or proven. Systems thinking, a process of defining a phenomenon holistically—by its contents, objectives, interactions, relationships, and environment—is also integral to the design process. It uses analysis and synthesis to form new conclusions.

This paper investigates the relationship between systems thinking and creative thinking, their relationship to engineering and the design process, and their relationship to student learning and holistic thinking. It also describes techniques introduced to freshman students to help them improve their creative and systems thinking skills. Of interest is the ability of students to understand these techniques and to apply them to the course project. This paper also comments on teaching strategies that have worked well in introducing creative and systems concepts and which have not.

DESIGN AT UTC

The elements of design are emphasized throughout the engineering curriculum of the University of Tennessee at Chattanooga (UTC), beginning with the freshman year. At least ten credit hours are devoted to teaching (to all engineering majors) design concepts in an applied, interdisciplinary setting. At the freshman level the students are introduced to the foundations of design. At the sophomore level the students use design concepts to design and build small structural and mechanical projects (trusses and instruments for measuring force and displacement). The students also emphasize testing of the devices. At the junior and senior level the students use design concepts to solve real-life and open-ended interdisciplinary industry-based problems provided by industrial sponsors. The student project teams work with the industry sponsors (in the industrial setting) and a faculty advisor to develop, test, and most often prototype a solution. In addition, students apply design concepts in a three credit hour discipline-based capstone course during their senior year. The structure of the design curriculum is shown in Figure 1.0.

FIGURE 1
THE DESIGN CURRICULUM SEQUENCE AT UTC

The goal of the design curriculum is to graduate students who understand and can apply the steps of the design process to various interdisciplinary and discipline-based applications. The first step toward meeting this goal is to introduce the steps of the design process in UTC’s 3 credit hour freshman
level course Introduction to Engineering Design. Then the main focus is the reinforcement of this process and steps during the remaining three years of the curriculum. The design process emphasized at UTC is shown in Figure 2.

The freshman design course uses short lectures and hands-on design exercises to emphasize the body of the design process—problem definition, conceptual design, alternative selection, and preliminary design (see the shaded portions of Figure 2). Concurrent with the design methodology is a graphics design laboratory on sketching and CAD. A major outcome of the course is a small team design project, with application of basic engineering science, engineering graphics, and written and oral presentation.

**SYSTEMS THINKING**

Systems analysis is fundamentally different than traditional forms of analysis. It begins with analysis—separating a study into individual pieces—but emphasizes synthesis—looking at the relationships between parts to form new conclusions. Systems analysis is most often used when confronting complex problems with a variety of variables that cannot readily be quantified and whose structures are not well defined. It uses ad hoc models to represent variables (the environment, components, and alternatives) associated with specific evaluation questions [1].

One model often used illustrates a process or entity as an architecture that involves operational, functional, technical, and physical descriptions (see Figure 3). The operational description introduces the entity and concisely defines how it meets its stated goal. The functional description is a decomposition of the main function of the entity into its subfunctions, taking care to define the required inputs and outputs of each subfunction and the behavior of each function. The technical description defines the arrangement, interaction, and interdependence of the elements of the entity so that a set of requirements is met. The physical architecture clarifies the physical resources that support and constitute the entity, as well as their relationships [10].

Systems thinking is a generalization of systems analysis used to evaluate a variety of systems. There appears to be no formal accepted definition of systems thinking. However, many advocates of “systems” and “systems theory,” and “systems analysis” agree that the aim of systems thinking is to spell out in detail what the whole system is, including its environment, its objectives, and how the objectives are supported by the activities of its parts [2]. Others promote that the whole system is not just the sum of the parts or subsystems; it is a system composed of interrelated subsystems [3]. These interactions should be studied with respect to their dynamic as well as static relationships. Thus, the subsystems of an entity should not be studied separately with the idea of putting the parts together into a whole. The starting point has to be with the total system and should consider feedback loops and dynamic interaction. Thus, systems thinking can be defined as the process of defining a phenomenon holistically—by its contents, objectives and its interaction with the contents, objectives, relationships, and resources of the environment in which it operates or is applied. It separates a system of study into individual pieces and looks at the relationships to form new conclusions.

The majority of applications of systems thinking have occurred in the area of process analysis and improvement initiatives in industry—specifically the initiatives that improve process quality. Managers and consultants to industry have begun to recognize the value of transforming from classical department-based organizations to process-based organizations [4]. The process-based initiatives include benchmarking, concurrent engineering, continuous improvement (CI), ISO 9000, mistake-proofing, quality...
functioning, theory of constraints (TOC), Toyota Production System (TPS), and total quality management (TQM). These are systems thinking based initiatives. For example, TOC is based on a number of principles that mention systems and systems thinking—(1) systems thinking is preferable to analytical thinking, (2) an optimal system solution deteriorated over a system’s environment changes, (3) the system optimum is not the sum of the parts, and (4) knowing what to change requires an understanding of the system’s current reality and its goal, and the difference between the two [5].

**CREATIVE THINKING**

The American Heritage College Dictionary [6] characterizes creativity as being “original and expressive; imaginative.” Some interpret this as ideas coming from one’s unique perspective. Others interpret creativity as looking at or seeing the same things as others, but thinking differently to make new connections [7]. Still, others dictate that creativity is a product of the unconscious mind—something that occurs when least expected. Also, there are those that believe creativity is unexplainable—it eludes human understanding [8].

No matter which definition one identifies with, creativity is used to look at problems and systems from a different viewpoint, often to generate solutions with regards to satisfying constraints and design objectives, and often driven by a desire to be original [11]. Creative thinking occurs through (1) divergent thinking that allows the evolution of information generation and (2) transformation thinking that allows the production of new patterns through gathered knowledge and experiences [12]. The creative outcomes are achieved following a specific unconscious or conscious process: exploration, incubation, intimation, and illumination [8].

Exploration involves immersion in the problem, searching for new ideas, gathering a broad range of information, and clarifying and defining the problem. Being receptive and open to listening is crucial here [9]. Incubation involves the passive activity of taking time to digest the data gathered. The problem is simmering in your unconsciousness where the ideas are free to recombine with other ideas in original patterns that you may not recognize in the conscious state [9]. Many of our best ideas come when we are relaxed, doing some mundane task. Intimation is the step in the process where an idea is purposefully pursued. The problem is plucked from the unconscious and attention is devoted to it to seek a solution. Progress is being made and that progress feels to be on the “right track.” The last step in the process is illumination. This is the conscious recognition of an idea and the transformation of the idea into action.

We can interpret the above stages as

1. Information gathering and stating of the problem
2. Idea generation
3. Solution generation
4. Solution description

Interestingly, the first stage is similar to the problem definition and conceptual design steps of the design process shown in Figure 2. The second and third stages are similar to the design process’s alternative selection step. And the fourth stage—solution description—provides a similar output as the preliminary design step. In addition, problem solving involves back and forth movement between creative thinking (divergent) and critical thinking—convergent thinking that applies accepted principles [11]. This connection illustrates that the creative process strongly supports and is imbedded in the activities required of the design process.

Design projects provide a range of opportunities to act creatively and provide creative solutions. These opportunities are defined and range from controlled to open opportunities. The most simple and closed of these is selection design. This is the act of selecting already available standard components and assembling them in a straightforward manner to achieve the design objective. The designer is able to select new known components and combine them to do something that has previously been done. A more complex application of creativity is configuration design. This involves taking standard components and arranging them to improve performance or physical features. An even more complex application of creativity is parametric design whose challenge is to take a design that already exists and vary the performance, physical, and operational parameters to achieve new design objectives. This application provides more design freedom than the previous two applications. The last application is most thought of as the application of creativity—original design. This category refers to the design of objects and process that are a fundamental departure from the existing [8].

There are a number of techniques that help individuals and teams address and capture their creative thoughts. One popular team exercise is Brainstorming. A Brainstorming session involves generating, in a supportive and noncritical atmosphere, as many ideas for solving a problem as possible. Brainwriting is a variation of Brainstorming that preserves the anonymity of the idea generators. Team members record their ideas on slips of paper that are circulated among the team so new ideas can be added. Brainstorming can be enhanced with Mindmapping—a powerful graphic technique that uses words, images, numbers, logic, rhythm, color and spatial awareness to illustrate ideas and relationships. An example of a Mindmap is shown in Figure 4.
The Introduction to Engineering Design course (IED) at UTC emphasizes the integration of design, systems thinking, and creative thinking. The means for introducing these concepts is a semester long project. Tables I and II summarize the class discussions and assignments that introduce these concepts.

### TABLE I

<table>
<thead>
<tr>
<th>Topic</th>
<th>Lecture Emphasis</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to Engineering</td>
<td>Defining the engineering design process and the entities involved.</td>
<td>Select a small tool or appliance in need of improvement; determine client and client needs; create a goal statement, design objectives and constraints; present in a report.</td>
</tr>
<tr>
<td>Problem Formulation</td>
<td>Defining client/customer needs</td>
<td>List device attributes; clarify objectives; define functions; create objective tree; create 3 levels of functional block diagrams; present in reports.</td>
</tr>
<tr>
<td>Developing Design Criteria</td>
<td>Identifying and distinguishing between attributes, functions, objectives, constraints, and implementations of a device.</td>
<td>Create a report on device research and findings.</td>
</tr>
<tr>
<td>Technical Writing</td>
<td>Formatting for readability; eliminating vagueness, sexist language, wordiness; ensuring parallel construction</td>
<td>Create a report on device research and findings.</td>
</tr>
<tr>
<td>Ethics and Professional Context</td>
<td>Recognizing ethical situations</td>
<td>Complete survey on “Professionalism Indicators”</td>
</tr>
<tr>
<td>Oral Presentations</td>
<td>Types of oral presentations; planning and organizing; creating and using slides; delivery</td>
<td>Present research and findings on device.</td>
</tr>
<tr>
<td>Group</td>
<td>The triad of teaming</td>
<td>Take Personality Style</td>
</tr>
</tbody>
</table>

### TABLE II

<table>
<thead>
<tr>
<th>Topic</th>
<th>Lecture Emphasis</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept Generation and Creativity</td>
<td>Defining concept generation and creativity; Model of the creative process; Blocks to creativity; techniques for aiding idea generation</td>
<td>Decide which device to improve; brainstorm 10 possible solutions; create a morphological chart of solution components.</td>
</tr>
<tr>
<td>Decision-Making</td>
<td>Identifying the need for decision-making tools; introduce pair-wise comparison, evaluation scales and metrics, comparison evaluation using scales and weights</td>
<td>Select 3 to 5 solutions you believe best; compare using comparison techniques; select best; substantiate reason.</td>
</tr>
<tr>
<td>Prototype Testing</td>
<td>Understanding the need for test procedures; creating usable test procedures; documenting procedures</td>
<td>Determine how to complete a puzzle; write instructions for another team to put puzzle together; write test procedures for new functions of your device.</td>
</tr>
<tr>
<td>Documenting Design</td>
<td>Creating a usable package</td>
<td>Create team report.</td>
</tr>
</tbody>
</table>

The Design Project

The goal of the project in IED is to design a better device for a specific customer. The device of emphasis is a small tool or appliance costing the student less than $25.00. The project begins the second design session meeting and is completed the last week of class when the students demonstrate their prototype. The project has two parts—the individual component and the team component. The individual component emphasizes identification of the problem and understanding of the device. The team component emphasizes idea generation, decision-making, and design test. The project process is shown in Figure 5.
Design Project – Individual Component

At the beginning of the semester each student selects and purchases a small tool, appliance or tool he or she or someone they know has observed as operationally or functionally deficient. No two students can purchase the same type device. Initially the students learn all they can about this device, its users, and its other clients to identify the problem. For example, the first assignment requires the students to state the deficiency as a problem statement, so they must interview the users or clients of the device and thoroughly understand the device needs and the users’ concerns. They then look at the device’s physical, functional, and operational features and define device attributes. They can learn about the device on the product website, on the website www.howstuffworks.com, or by tearing down the device and researching each component. From these attributes the students break out design objectives, device functions, constraints, standards or codes, and device descriptions. This is a rather large first assignment but the students are provided two weeks to complete the research and write the supporting report.

Later class instruction introduces the students to objective trees, input/output functional block diagrams, and function node trees to help them clarify and document their understanding of their device and its functional relationships. Objectives trees, functional block diagrams, and function node trees are systems thinking tools designed to help the students focus on understanding the device from an environment focus. The students submit their trees and diagrams to the instructor for feedback and improve for adding to a revised first report to fully document their understanding of their device and the users’ dilemma.

Design Project – Team Component

Midway through the semester the instructor places the students in 3 to 5 member project teams. The members are selected to optimize the variation in device and problem statements. This is done so the project teams can witness the variation in problem statements and applications. The students are required to share and discuss their devices and problem statements in detail with the other team members and then to decide which device problem to solve. Before initiating this action, the students are introduced to concepts of group dynamics, personality styles, and team problem solving.

The students are then introduced to concept generation and creative thinking practices. Brainstorming and Mind-mapping are discussed and practiced. The qualities of a creative thinker are discussed and the realization that all can be creative thinkers is emphasized. Also emphasized is the necessity to be open to other’s ideas and not to criticize those ideas, especially in the brainstorming process. The students then generate at least 10 possible solutions for their selected device and problem statement. Students are also introduced to the concepts of morphological charts. Morphological charts are another systems thinking tool that helps students break the possible solutions into components and recombine them to develop additional possible solutions. Morphological charts also provide a framework for students to try combining the known into unknown recreations—an aspect of being creative.

Once the 10 possible solutions are generated, the students are asked to select 3 to 5 they believe to be the “best” solutions based on ability to create a prototype and to meet the customer criteria. This is a “we think” selection with no basis in decision theory. Then the students are introduced to several concepts of decision-making including pair-wise and weighted comparisons. They select the best of the 3 to 5 solutions using these tools and the customer criteria outlined in their objective trees. The decision on how to weight the criteria is sometimes based on the clients’ needs; other times based on a vote of opinion of the team members.

Each team is required to develop a prototype of the solution. The students are provided no resources to create the prototype. They must depend on their personal knowledge and material they desire to invest in to complete the project. This limits the students in some ways, but requires them to be creative.

The teams must develop procedures to test each new function of their improved device to determine whether it
meets the customer criteria. We discuss the value of test procedures, how to create test procedures, and how to record data. Design of experiments is not mentioned; however, the concepts of repeatability and reproducibility are. The test procedures, collected data, and analysis are included in the team final report.

The team final report results from a compilation of the device individual report from the first half of the semester and the team exercises of the second half of the semester. Each of the team exercises are reviewed by the instructor and comments are provided prior to the submission date of the report so the students can revise and improve their work. The students must present their report in writing as well as orally. The oral presentation includes a demonstration of the prototype.

**DISCUSSION**

As is for any type of work expected of students, the results and the feedback from the students experiencing the IED project and the emphasis on design, and systems and creative thinking vary. The students have much difficulty defining their devices with respect to functions. The systems practice of using input/output functional diagrams takes a level of thinking they are not used to. They have some difficulty defining the main function but even more difficulty determining subfunctions and their relationships. The students, however, have much less difficulty defining the operation of their device as a process of steps (linear thinking).

The students perform well at defining the customer, client, and designer objectives for their device. This appears to be a result of an emphasis on defining objectives as “being” statements with a specific phrase structure (to (action word) + (object) + (qualifying phrase)). Harder to define, however, are constraints that emerge from the objectives. Even though constraints are described as limiting factors to the design space and boundaries to the system environment, the students have difficulty stating the constraints so they can be measured.

The students react interestingly to the creative element in the project. They, as it often is, enjoy creating a prototype of the solution to improve their device. However, they want to start the prototype work before working through the creative process. The students tend to want to go from a shortened “statement of problem and data gathering” stage to the “solution description” stage. The course structure and assignments, however, force the students to stay in the first stage and provide an opportunity to experience stage 2—idea generation—only after providing time for incubation. Some teams take advantage of the creative process, especially the idea generation stage. Others, however, find it difficult to step outside of the “expectations box.” They want to find the “right” answer instead of wanting to experiment with new ideas.

Some students and teams experiment with non-linear thinking techniques such as mindmapping and brainstorming. The course does not force the students to use these techniques though the instructor requests students to record how they generate ideas and experience “group think.” The course final does ask students to define a device using mindmapping to illustrate their understanding of mindmapping and how it can be applied. Most students attempt the exercise but illustrate a linear thinking pattern. However, more students are beginning to show spatial and visual representation and a tendency toward new connections (see Figure 6).

![FIGURE 6
STUDENT GENERATED MINDMAP](image)

**CONCLUSION**

The freshman design course at UTC takes the freshman student away from the traditional student and instructor expectations of the typical analytic engineering course. The emphasis on systems and creative thinking in the context of the design process is new to the students. The emphasis of the instructor to grade on thinking processes instead of results is also foreign to the engineering students. Some students are resistant to the experience, but many others openly enjoy the opportunity to create unique solutions.

As the course has evolved, it has produced better results from the student as the instructor has begun to relate each class topic to its role in the design process or systems or creative thinking. The “why” for each activity or exercise needs to be emphasized since the three concepts being introduced are rather abstract.

Evaluation of the effects of the course on the student products during the sophomore, junior, and senior years is presently occurring. There seems to be some changes to how students are thinking about defining a problem and evaluating alternatives appearing in a requisite sophomore course. This will be assessed more thoroughly over the next 2 years as students progress through the design sequence.
REFERENCES


