# Engineering Design as a Learning Process

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## Introduction

Design of products, processes, and systems is the task that distinguishes the engineering profession. Either directly or indirectly most engineers are involved in the design process. Despite its central role in the engineering profession and its recognized importance[1,2], most engineering students complete their undergraduate degrees with only a cursory glimpse at real engineering design. Their experience is often disconnected and incomplete as the curriculum tends to focus on skills requiring convergent thought processes.

There are several arguments made in defense of the current engineering curriculum, where engineering science and analysis predominate. Possibly the most common is that these subjects are easier to present, amenable to large class sizes, and accommodate the teaching strategies that are popular and economical in university settings. Engineering design education requires small class sizes, one-on-one faculty-student interaction, active learning strategies, and teamwork; lectures and exams do not suffice. Proper engineering design education requires faculty that understand design and recognize its significance to engineering. Further, faculty must have the time and dedication required to integrate design throughout the entire curriculum. Design cannot be made to fit neatly in a one-semester course at the end of an undergraduate education.

There are also those that believe that design processes are particular to various industries and therefore it would be overstepping boundaries to presume to teach such processes at the academic level. While this may be true that at lower levels of abstraction where specific knowledge and details are important, at higher levels of abstraction it can be shown that the basic processes are quite similar across disciplines and domains.

Others claim that engineering design processes are ad hoc and rely on creativity and experience and thus should be addressed later during the student's professional career where experts in individual fields or industries can serve as mentors. However, engineering design can be shown to be a systematic, cognitive process rather than an ad hoc endeavor. Although creativity and experience do play roles in the process, these do not preclude the possibility that engineering design can be effectively taught. There are many recognized means of promoting creative abilities[3-6] that are available for classroom instruction. Contrary to what some educators may believe, students arrive with a base of experience from which their design abilities may successfully grow. A student has already spent a lifetime interacting with a world surrounded by design artifacts. If asked, most students can explain, at least on a conceptual level, how many complicated components or systems work or behave.

Efforts to integrate design throughout a curriculum may be enhanced if the design process is better understood. Understanding may be promoted if engineering design is seen as a learning process, in context with Bloom's Taxonomy, a widely used and accepted taxonomy of the cognitive domain. Examination of an engineering design domain in terms of Bloom's Taxonomy may produce a framework for analyzing the process and its inner workings. Presenting design in the context of Bloom's Taxonomy may also enable students to recognize that they already possess much of the prerequisite skill and knowledge to be successful designers. Once the students gain such confidence it is possible that they can begin to focus on acquiring the tools required to perform engineering design. In essence the students are afforded the opportunity to put their ideas and experiences into new products or processes.

## The Engineering Design Process

Since the late 1950's and Sputnik engineering design has taken a back seat to scientific and analytical research. During the 1980s Germany and Japan began to awaken to the importance of research in the area of engineering design. Slowly, the United States has begun to recognize its importance also. However, as a research field, there is still much to be learned. Many theories and processes have been proposed, but the fundamental principles and a design taxonomy are still elusive. Until these are established, the best that can be done is to examine what is proposed and determine its suitability with respect to individual experience and understanding.

Several authors have proposed engineering design processes[7-11]. Each of the proposed design methods provides a rational, systematic approach to engineering design. There are two common features associated with design methods. First, design methods formalize design procedures in an effort to avoid the oversights and errors that can occur when informal methods are used. Second, design methods require that the designer's thoughts be expressed explicitly. This is extremely beneficial when design teams are used or in complex design environments.

As one begins to study these processes it becomes obvious that there are more similarities than differences. Although individual steps may be labeled differently and some propose different groupings of tasks, they all represent a very similar process, the essence of which is captured by Cross[7]. There is agreement among researchers that the process is iterative, with vague transitions between tasks, and task overlap or concurrency. All design problems have common features: there is always a design goal, there are always design constraints that provide guidelines under which the design goal may be achieved, and there are criteria that help engineers recognize when a design solution is successful.

## Bloom's Cognitive Taxonomy

During the 1950s Benjamin Bloom and a group of university educators delineated a simple, user-friendly model of human thought consisting of six levels of increasing complexity[12]. Similar to the previously discussed design process, the hierarchy represented by Bloom's Taxonomy is not rigid and transitions between levels are not always discrete. The learning process represented is cumulative and is highly iterative in that an individual my find it necessary to retreat to lower levels to fill in details as more is learned at higher levels. Thus, the learner must be able to naturally move between levels during the learning process. However, it is necessary that an individual have some mastery at lower cognitive levels within a domain before it is possible to move to higher levels.

The least complex level encompasses knowledge, which is simply the ability to recall information, facts, or theories. There is no implication that the individual understands what is recalled. This level assumes that there is stability within a subject field and depends on authority external to the learner. Knowledge is basic and necessary for all other cognitive activities.

The next level, comprehension, encompasses the largest class of intellectual abilities. The individual has the ability to understand the material and demonstrate its use after being shown how, but is unable to relate the knowledge to other ideas or apply it to new problems. Thus, comprehension is the lowest level of understanding. At the comprehension level the individual is able to perform such tasks as choosing proper theories, equations or tools, but is not ready to successfully employ them.

The third level is the application stage, where the individual can apply knowledge, rules, concepts, methods, and theories to new situations without being shown how and has the ability to generalize knowledge. Individuals are capable of putting simple equations and tools to work. Most of what individuals learn is intended for application.

Analysis is the fourth level of the taxonomy and requires that the individual be able to decompose a problem or information into its parts, determine relationships between the parts and their relationship to the whole, or classify and organize the parts. At this level the person is able to identify both content and structure, as well as differentiate nonessential information from that which supports the main conclusion or purpose. Also at this stage the individual is able to perform complicated computational processes and employ complex tools. Each of these first four levels requires convergent thought processes where the individual is concerned primarily with the external world, gathering and understanding knowledge, and applying it to problems. These encompass the primary skills and activities that formal education concentrates on developing.

The fifth level, synthesis, requires competency in the tasks included in the four previous levels. At this level the individual is able to create new ideas, structures, or patterns, and thus uses divergent thinking. The result is the conception of something new or substantially different than what previously existed. The learner's focus is on the internal world. Prior to this level of cognition the learner examined what is, at the synthesis level the learner examines what could be.

The sixth level is the evaluation stage in which the individual qualitatively or quantitatively judges the value of information, ideas, methods, or processes with respect to specified criteria. Evaluation ranks  highest since it contains elements of all of the previous levels. However, evaluation may occur relative to tasks at the lower cognitive levels. The activity helps the individual bring together their thoughts and acts as a mental filter regarding what information may be saved in long-term memory.

## The Link: Bloom, Engineering Design and Creativity

Table 1 presents a summary of the cognitive processes required at each level of Bloom and the corresponding engineering design activities. As one reads across the table it becomes clearer how the design process maps to Bloom's Taxonomy. Once the mapping becomes evident it is possible to conclude that design is a cognitive process that can be addressed in a systematic, disciplined manner.

Many are quick to point out that creativity plays a major role in the synthesis (or design alternatives) level. Psychologists have discovered that there are phases to the creative process as well[13]. The first stage consists of acquiring the knowledge and gaining understanding of the phenomenon in a domain. These are the same tasks described as part of the lower levels on Bloom's Taxonomy. Once one becomes immersed in a domain, an incubation period is typically required to allow the brain to search for related information and form generalizations based on its previous experience and abstractions. In the creative cycle incubation is followed by insight, commonly referred to as the eureka experience where inspiration surfaces from the unconscious mind. This can be directly linked to the synthesis level of Bloom's Taxonomy. Unfortunately, insight is not easily set to a schedule and may happen at any time. An argument may be made though that the more connections that the brain has made, i.e. the more learning that has occurred, the easier and faster it will be for the mind to unveil a new idea[14]. Once a new idea is discovered, it is necessary to determine its merit, in other words evaluation of the idea is made. If the individual decides the idea is worth pursuing, elaboration on the original concept may ensue. This final step directly maps to the design improvement stage of the engineering design process where refinements and enhancements are realized that improve the design solution. The efforts to improve or elaborate on a design solution often require revisiting previous levels of cognition, defined by Bloom, as the engineer iterates through the design process. Thus, Bloom's Taxonomy clearly demonstrates how the lower levels of the learning process foster creativity.

## Integrating Design into an Engineering Curriculum

Traditional engineering curricula emphasize the first four levels of Bloom's Taxonomy. As has been shown these levels are important to engineering design, but design requires higher level cognitive processing found at the fifth level of the taxonomy, synthesis. Engineering educators do an exceptional job in instructing students through the analysis level of cognition. However, to graduate engineers competent in engineering design, learning must proceed through all six levels of Bloom's Taxonomy. The following paragraphs suggest classroom strategies that may be implemented to assist students to operate at the higher cognitive levels while reinforcing their capabilities at the lower levels.

### Organize Content So It Requires More Complex Tasks

There is often confusion regarding complexity and difficulty when considering activities and performance according to Bloom's Taxonomy. This confusion often leads educators to incorrect conclusions regarding student abilities to perform competent design. There is evidence that all individuals are capable of working at the higher levels, although some will require more time to get there. Educators often mistake difficulty for complexity and thus fail to enable their students to progress up the taxonomy. Difficulty refers to tasks within a specific level. As an example, an engineering professor may require that students be able to solve a two-dimensional dynamics problem using Newton's second law. Once a student has mastered that, the professor presents a three-dimensional problem that may also be solved using the same process. However, the three dimensional problem requires many more calculations and much more book-keeping. The student is operating at the same level on Bloom's Taxonomy using the same skill set, however, the problem became more difficult. Suppose the professor proposed a different problem that was still based on using Newton's law that required the student to design a means to deliver tennis balls to a tennis player at various speeds and heights. This problem is more complex and may require more time to solve, but it is not by definition more difficult. It does, however, require the student to continue to move upward on Bloom's Taxonomy. Table 2 provides an example of increasing complexity and difficulty in an assignment. If the educator desires to promote higher order thinking, it is important to focus student effort on increasing complexity in preference to difficulty.

When using this strategy it is important that students have gained proficiency in the lower level activities. Given the appropriate encouragement and foundation, students will naturally proceed to the higher-level activities. Evidence shows that humans are born with the capacity to do just this[14]. It is also critical to give students who learn more slowly adequate time to progress through the lower cognitive levels into more complex processing. If educators fail here, many potentially good designers may never achieve their capabilities because they have given up on themselves without understanding why.

Questions that may help students think at higher levels of complexity include:

- Can you think of some applications where this theory can be used?
- What designs have you seen where this theory should be used?
- How is this material different?
- How will you predict whether your design is good?
- Where can we go from here?
- Have we left out anything important?
- Can we trust our results?
- How can you test this theory?

Notice that several of these questions encourage students to move to the evaluation stage at the top of Bloom's Taxonomy. Performing evaluation requires students to complete the learning cycle. Students often defer evaluation to their instructors and consider a grade to be the end of the process. Although teacher assessment of student work is important, self-assessment can plan an equally critical role in preparing students to be life-long learners. At some point the students will become professionals who need to be able to evaluate their work. Preparing students to do so provides them with a powerful design skill and encourages them to complete the learning cycle.

Some content areas do not require processing at high levels. In fact there is a large class of problems that do not required divergent thinking. For example, creativity is not needed to solve for the strain at a point on a cantilever beam subjected to a bending moment. These types of problems play an important role in helping students gain proficiency at lower levels of cognition.

However, since students will prefer to solve problems at the lowest level of complexity possible, faculty should be careful to propose problems at the proper level of complexity.

Open-ended problems encourage students to draw from their own experience and naturally progress up the levels of Bloom's Taxonomy. These problems typically require that students use every level of Bloom and may even be constructed to explicitly require this. For example, a student may be asked to design a widget of some sort and be provided very little as far as requirements or information goes. The student will need to examine what is known, seek what is not known, apply experience and knowledge in a new way, analyze the design environment of similar problem solutions, develop a new solution, and lastly evaluate it against some criteria that was possibly developed as part of the process. Students need to be shown how to approach such solutions and then required to practice the process. Bloom's Taxonomy can serve as an excellent model for tackling open-ended problems.

Encourage Students to Design

Creating a fun learning environment can stimulate students to progress to higher levels of thought. Research shows that if students like what they are learning they are more likely to maintain interest and move up the learning hierarchy[14].

There are many creative techniques that students can employ and faculty should introduce and encourage their use. Brainstorming and variations on this technique[15] can be used to encourage students to think outside the box. Once the brainstorming session is complete, students can participate in evaluation of concepts, thus completing the sixth level on Bloom's Taxonomy.

Hands-on activities often provide good learning experiences. Small design projects that require students to develop a design solution in a given time using a limited number of common materials and tools offers many opportunities to promote higher order learning and divergent thinking. Such projects can be implemented into a class period. Students my be encouraged to work in design teams to promote the exchange of ideas and experiences, interaction, and communication. These projects have been used successfully with students as young as elementary school[15]. Successful implementation requires the educator to be alert to opportunities for follow-up questions and discussions that provoke thought and reflection. These are often situation-specific. Probing questions need to be used to enable students to effectively generalize the experience beyond its original scope so that it can be used as a springboard to future learning.

Product dissection, or reverse engineering, can be an effective means to help students progress through the lower levels of Bloom and prepare them for synthesis[16]. As the name implies, the students trace through Bloom's Taxonomy in reverse. The actual dissection process is usually initiated by asking the students to reflect on a given product, considering alternative uses or designs. The student is then directed to take a product apart, or in other words decompose it into its component parts. Students are typically given some instructions to assist them in the decomposition and to help them to recognize important concepts. During the dissection students may be asked to compare or categorize components, deduce their function, or examine interactions among components. These activities are included in the analysis level of Bloom's Taxonomy. Students may develop application-level capabilities if they are asked to discover other products or components that perform similar tasks; or calculate given performance parameters. Many times dissection activities include sketching or describing components, surmising design objectives or requirements, or speculating about the processes used to fabricate components. These tasks may are classified as the comprehension level activities. In product dissection students can be guided to recognize materials, name and classify components, understand relationships between components, and hypothesize about manufacturing and assembly processes. Depending on the nature and scope of these tasks, students will need to function at various levels from knowledge to analysis on Bloom's Taxonomy. Students can also be asked to develop synthesis skills as part of the dissection activity. This may be accomplished by asking students to redesign a component or come up with another design solution entirely. Students may also be asked evaluate the product, its functions, and the method by which they are delivered. Evaluation plays a key role in enabling students to complete the learning process.

Some questions that faculty may consider during a dissection exercise include

- What are some things you wondered about while you were taking the product apart?
- Why do you think the designer used *x*?
- In what other ways could the designer have met the design requirements?
- Did the designer leave out anything important?
- How is this product similar to or different from a *similar product or competing product*?
- Are there other ways this product could be used?
- How would you modify the design?

Recognize Students Come With Experience

It has been argued that it is not possible to teach design to lower division students because they do not know enough to accomplish any real design effort. However, students have been interacting with products and processes over the course of their life and can in most cases at least conceptually describe how systems work. Thus, in many cases they are capable of progressing through the lower levels of Bloom's Taxonomy with some guidance and can be encouraged to think at the synthesis and evaluation levels based on their understanding of their world. It is important to explain to students that they can do this and show them how. Such emphasis should begin with entering freshmen and continue as a thread through the curriculum. It seems illogical to spend four years emphasizing the first four levels of Bloom's Taxonomy and expect that by some magical transformation students will be able to leap to the higher levels during a one-semester capstone design course at the end of their academic career. If previous courses have failed to emphasize the fundamentals and nature of design, it is impractical to expect students to be prepared to successfully execute a design solution. It is critical to encourage higher order thinking throughout the entire undergraduate curriculum[13]. Practice promotes consistent effectiveness. Graduating well-rounded engineers requires nothing less. Engineering design takes practice and involves carefully executing principles and systematic techniques. If these processes are not understood, work will be sloppy and lack discipline.

In the same vein, although a cursory overview of supporting topics may be required, educators should not spend a disproportionate amount of time regurgitating familiar topics. It is also important to remove topics of lesser importance to gain enough time on the syllabus to practice the skills required at the higher levels. Educators who are interested in encouraging higher-level thinking should avoid dwelling on trivial information and should not force students into memorization for its own sake. Students will often find such tasks mundane and meaningless.

Tapping into what students already know can be done. The following questions provide some guidance.

- Based on your experience what is the best choice?
- How is this design like *something student is familiar with*?
- Have you ever seen this happen?
- Have you ever seen this done differently?
- Based on your experience what might happen next?
- What could have caused this?

## Conclusions

Experience teaches most educators that engineering students like to learn by example. It is a common experience to find students frantically searching for a similar problem to use. In many cases this can be attributed to a teacher's failure to communicate how and why certain processes are used to solve problems. Failure to understand solution or design processes may very well be a residual effect of failing to encourage students to work through the higher levels of learning.

There are natural links between the engineering design process and Bloom's Taxonomy that when made provide understanding of the design process and a means to communicate about the process. Making the connection between Bloom's Taxonomy and Engineering Design enables one to place engineering design into a familiar context – the way in which humans learn. Bloom's Taxonomy describes the cognitive levels an individual evolves through as the learning occurs.

Making students aware of their learning process helps them to attach meaning to the activities and tasks required to become good designers. Educators can use Bloom's Taxonomy to develop and organize exercises to encourage students to move up the taxonomy and think at higher levels of complexity in any course. The result of higher order thinking is the ability to create new ideas and products. If students are challenged to achieve this level of thought throughout their coursework their design education will not longer be incomplete and disjoint. They will enter industry as confident designers ready to learn the specifics and details appropriate to their fields with a firm grasp of what to do with them.

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