ENGINEERING BY DESIGN:
A METHODOLOGY FOR DESIGNING
CREATIVE ENGINEERING ACTIVITIES

By

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1996
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by

Matthew William Ohland
This dissertation, all that I have, and all that I am are dedicated to my wife, Emily.
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ENGINEERING BY DESIGN:
A METHODOLOGY FOR DESIGNING ENGINEERING DESIGN ACTIVITIES

By

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Chairperson: Dr. Marc I. Hoit
Major Department: Civil Engineering

There has been a great effort in recent years to effect a significant change in engineering education. This reform movement has had many objectives and proponents. Herein it has been postulated and shown that properly formulated design activities can fulfill a great many of the reform objectives. Furthermore, it was hypothesized that it was possible to design a methodology for creating such activities in order to facilitate their implementation. The crux of the Engineering By Design methodology is a framework for collaboration of engineers and educators which combine
their various areas of expertise to create lessons which are both technically accurate and educationally sound.

This design methodology was first developed by analyzing the process used to design an activity for use in the Civil Engineering component of University of Florida's Introduction to Engineering class. After the methodology was formally established, the methodology was used in collaboration with a University of Florida professor to design an activity to teach the concept of tributary area. To evaluate the methodology, a post-test was administered and feedback from the students was obtained. The post-test scores were very high (average 18 out of 21), which indicated excellent mastery but lacked sufficient range to conduct any correlational studies. Quantitative analysis of student feedback was conducted, indicating positive results.

A second application of the methodology was conducted to design a lesson to teach descriptive statistics to a high school physics class. Constraints on this design caused the lesson generated using Engineering By Design to be very similar to the lesson used to teach the control group. As a result, the post-test indicated only a slight increase in the performance of the experimental group.
CHAPTER 1
INTRODUCTION

The Reform of Engineering Education

Previous Reform Movements

There is currently a widely recognized need for reform of the engineering education system of the United States. The current reform movement is the most recent of a number of periodic evaluations of the state of engineering education. Previous evaluations included those by the Society for the Promotion of Engineering Education (SPEE)\(^1\) chaired by Wickenden (1930) and Hammond (1940 and 1944), by the American Society for Engineering Education (ASEE) chaired by Grintner (1955), and by the National Research Council (NRC)\(^2\) chaired by Haddad (1985).

\(^1\)Founded in 1893, the Society for the Promotion of Engineering Education changed its name to the American Society for Engineering Education in 1946.

\(^2\)The National Research Council is the operating agency of the National Academy of Sciences (NAS), the National Academy of Engineering (NAE), and the Institute of Medicine.
In a recent NRC publication, the following themes were identified as unchanging throughout the various reports listed above (NRC, 1993, p. 1):

1. the need for strong grounding in the fundamentals of mathematics and the physical and engineering sciences;
2. the importance of design and lab experimentation;
3. a call for more attention to the development of communication and social skills in young engineers;
4. the need for integration of social and economic studies and liberal arts into the curriculum;
5. the vital importance of good teaching and attention to curriculum development; and
6. the need to prepare students for career-long learning.

Although these themes are common to the five reports, the priority assigned to each varies according to the economic, political, and social conditions of the time.

Proponents of the Current Reform Movement

The current reform has many proponents. The National Science Foundation (NSF) has given multi-million dollar grants to support the formation of engineering education coalitions (NSF, 1990), the NRC established project RISE
(Regional Initiatives in Science Education) ("Educational Reform for K-12," 1995) and issued the working paper mentioned above (NRC, 1993), and the ASEE issued the report "Engineering Education for a Changing World" (ASEE, 1994). Support for the current reform also comes from the private sector which, in addition to its representation in the above groups, has offered statements and programs of its own (Black, 1994 and McMasters, 1991).

Altogether, there are many more reports and initiatives in support of engineering education reform than can be mentioned here. Tobias (1992), noting the proliferation of reports just addressing American undergraduate mathematics and science [pre-engineering], estimates that 300 such reports have been issued since 1983. Tobias goes on to note the lack of impact of these reports despite the staggering cost in dollars and time. Though Tobias' focus is on introductory courses in undergraduate science, her observations shed insight on the reform of engineering education as a whole.

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3Project RISE receives funding from NSF and the Howard Hughes Medical Institute.
This forces us to question the possibility of reform. Is the current reform movement simply to be placed on a shelf as a testimony to the organizational inertia of academia? What distinguishes the current effort is the apparent paradigm shift of the National Science Foundation (Pister, 1993). Just as the NSF was the driving force in creating the research-driven university climate which Boyer (1990) referred to as the "scholarship of discovery," the NSF is also leading the engineering education community into a new era which also encourages and financially supports research in teaching and learning.

Another necessary proponent of any major change is the Accreditation Board of Engineering and Technology (ABET). Academic institutions have traditionally been concerned that proposed changes might threaten a school’s accreditation. Recently, however, ABET has become more concerned with quality than specific content and "bean counting" (Harris et al., 1994, p. 71). This paradigm shift in ABET will permit universities and colleges to be more flexible in their approach to engineering education without the threat of losing accreditation.
Context of the Current Reform

Not surprisingly, many of the goals of the current reform movement are echoes of earlier reports reverberating off today's political, economic, and social conditions. It is pertinent to analyze these driving forces in order to understand the movement's true objectives.

The driving forces behind this reform are many—the demands of industry [the employer of 70% of engineering graduates (Farrington et al., 1994)], concerns of a shortfall of engineers, and existing weaknesses in the preparation of students for study in engineering (the student pipeline) are among them.

The demands of industry

The engineering curriculum model in the United States after World War II was heavy on mathematics and science and lighter on design (Hubbard, 1993). The United States and other countries using that model would discover that the lack of hands-on training would prevent new engineers from becoming effective designers without additional training (Farrington et al., 1994). In Japan, this problem was
solved through hands-on assignments in the first two years of employment. In Germany, institutions were established which require all faculty to have certain minimum levels of industry experience. In the United States, it is the current reform movement that seeks to address the problem.

Advances in computer and telecommunications technology continue to make the economy a global one. Trade agreements and tariff reductions also knock down international economic barriers. The political environment in the post-Cold War era is also a harbinger of new levels of international cooperation.

This globalization has introduced new economic constraints which have had a dramatic effect on the engineering profession. Downsizing has formed smaller core engineering groups, with other engineers forced into the roles of subcontractor and consultant. Future engineers will not only need to adapt from one project to another, but may need to face transitions from company to company or industry to industry (Otala, 1993 and Leake, 1993). Much of an engineer's education will become obsolete after a time. Some have described this process as a sort of educational decay, with a half-life of 5 to 10 years (Healy, 1994).
Such a profession requires that engineers have a lifelong commitment to learning, which will be at their expense. These conditions demand that engineers understand the process of engineering and possess diverse fundamental skills. These will be more vital than specialized skills, since engineers will frequently work outside of their field of specialty.

Traditionally, there has been a misalignment of the direction industry suggests for academia and the direction academia charts for itself ("The More Things Change," 1993). Industry representatives generally prefer more practical knowledge so that new hires can "hit the ground running." Sources in academia generally criticize this approach, citing that the more broadly trained engineer will ultimately serve the company better. In this age when technology and particular practices is evolving so quickly, the needs of industry are approaching what has traditionally been the suggestion of academia.

If the formal education of engineers becomes more general in nature, there will be a concomitant increase in the specialization of continuing education. This increase in demand for continuing education can be answered partly by
universities through distance learning and other methods. Commercial interests will assume the rest of this training responsibility.

A shift toward a curriculum focused on skills and the ability to learn new knowledge is inevitable. Especially with the onset of the information age, the amount of knowledge grows exponentially. A curriculum which attempts to expand to include new content cannot hope to keep up. We must, therefore, teach engineering students to learn, and focus on the skills to apply new knowledge rather than the knowledge itself (Monteith, 1994). Pister points out that there is a trade-off in higher education: excessive focus on increasing students’ knowledge takes time away from teaching students how to use their knowledge in practice (1993).

This increasingly global market for engineering services and products also prefers engineers with an understanding of other cultures and languages. The need for cultural understanding and the diversity of career paths calls for a strengthening of the liberal arts training engineering students receive (Morrow, 1994), a suggestion which has always received considerable resistance (Florman, 1993 and Kranzberg, 1993). A growing number of American
engineering students are conducting a portion of their studies abroad, as well (Ercolano, 1995).

Altogether, industry representatives seem to agree on certain deficits in engineering graduates: the ability to work on a team, the ability to communicate effectively, and an awareness of workplace expectations (Katz, 1993).

Concern of a shortfall of engineers

There is considerable difference of opinion as to the level of this concern. Many sources indicate a serious shortfall of engineers will occur within a decade. Heckel (1996) indicates a 25% downturn in freshman enrollments since 1980 and a 9% decline from Fall 1992 to Fall 1994. Bakos and Hritz (1991) claim that the shortage is at all degree levels, and is caused by changes in demographics and student interest level. Lohmann (1991) anticipates a shortfall of engineering graduates not because of demographics or interest but because of inadequate preparation in the public school system. Other reports agree with the issue of quality raised by Lohmann ("New Report," 1990).
On the other hand, there are other reliable sources which forecast no shortage of engineers at all. The Bureau of Labor Statistics (Kutscher, 1994) indicates an increase in engineering employment which will maintain a constant percentage of total employment base. LeBuffe and Ellis (1993) indicate that during the decade following the early 1980's engineering enrollment followed demographic trends. Van Valkenburg (1991) indicates that there is great exaggeration regarding any potential shortage, citing an American Council on Education study which indicated that more students anticipated study in engineering than in any other discipline. Van Valkenburg also seems to suggest that any oversupply of engineers will be absorbed by the workforce, because engineering graduates are excellent candidates for "crossover," finding employment in alternate fields.

Since there seems to be consensus that having an adequate supply of engineers is vital to the national economy and it has been suggested that generating an oversupply of engineers is an acceptable outcome, it seems appropriate to look more closely at the factors which impact student enrollment in engineering. Student enrollment is
controlled by two major factors: student interest and student preparation. Both of these are necessary. Preparation for study in engineering is discussed in the next section—only interest will be addressed here.

Many critical factors affecting student interest in engineering are beyond the control of academia (though not outside its sphere of influence). Government policies, economic trends, and salary ranges can all influence student career and study choices. There is one significant factor which can be controlled by those in academia—an understanding of the profession itself. A Gallup poll sponsored by the American Consulting Engineers Council indicates that about a third of Americans have no idea what engineers do ("Thirty Percent," 1990).

Past President of the Accreditation Board for Engineering and Technology (ABET) Jerrier Haddad notes (1996, p. 5) that "engineering is an enigma to the lay public." The lack of understanding of the engineering profession causes many problems. If prospective engineering students do not understand what engineering is, they may not pursue it. Worse yet, students who are not interested in engineering may pursue it in error. The latter causes the
student and the educational institution to waste valuable resources to uncover the error. If teachers and high school counselors do not understand the requirements for entrance into engineering study, students who are otherwise excellent candidates for such study will be hindered by poor preparation if they do matriculate. The problem is greater still—even those who are truly not interested in engineering should learn what engineers do, because these others may become lawmakers, voters, investors, etc. who will make decisions which affect the engineering profession. More importantly, many of those not interested in engineering may be relatives of students that someday consider engineering. The advice of relatives is one of the strongest influences on a student’s choice of a career path (Van Valkenburg, 1991).

One of the primary stumbling blocks to the understanding of engineering by the general populous is that although the basic sciences are taught in the K-12 curriculum, engineering is not traditionally present in the curriculum at all.

To establish a foothold for engineering in K-12 schools, engineering educators must play a role.
Engineering professors have traditionally separated themselves from the pre-engineering educational system (Oaxaca, 1991), but this must change if the engineering profession is to have high quality graduates in the future. Partnerships which put engineering educators and practicing engineering in direct contact with students have a significant impact. These provide prospective engineering students with role models and an improved understanding of the profession. Such local partnerships were recommended by the 1994 ASEE report "Engineering Education for a Changing World." Other efforts to improve the image of engineers by providing appropriate role models in the media are being pursued by some ("Engineers to the Rescue," 1992). While programs which reach students directly are important, such programs are not feasible on a large scale, but will be relegated to local engineering firms and educational institutions.

Our efforts will have a greater impact if we work directly with those in the K-12 system who are fewer in number and are less transient than the students—the teachers and the counselors, curriculum coordinators, and other administrators. Collette (1994) estimates 47 million
students in the K-12 system, but less than a tenth that many teachers and administrators.

The benefit of this kind of intervention in the K-12 educational system is two-fold. To be sure, those interested in engineering will learn what it is and what precollege study is appropriate to be prepared for it. There is another important benefit—engineers can help reform the system which threatens the quality of students entering college programs, as feared by Lohmann (1991) and others. This concern and its remediation are discussed more thoroughly in the section which follows.

Weaknesses in the student pipeline

Walter Massey, former Director of the National Science Foundation, has said of the public education system (1992, p. 52), "Somehow, over the past several decades, we have allowed science and mathematics education to erode to the extent that we are jeopardizing our ability to produce skilled scientists and engineers, technical workers, and a scientifically literate public." There seems to be consensus regarding Massey's portrayal of the condition of K-12 education in the United States. Some paint an even
worse picture, where 95% of the American population is scientifically illiterate (Lohmann, 1991). The K-12 system, and sometimes the K-14 system (adding junior colleges), is referred to as the student pipeline. Viewing engineering education as an industry, the pipeline is the supplier of the raw material which engineering schools turn into a finished product, the graduate engineer. As is usually the case, flaws in the raw material can have a significant effect on the both the process and the end product.

These deficiencies in the K-12 pipeline are a call to action for the engineering community. The problem must be approached at all levels. It is critical for the future of the engineering profession that elementary, middle, and high school students have the scientific literacy required in today's society. It is also essential that those students who develop an interest in engineering be well prepared to pursue it.

In response to the perceived drop in quality of mathematics and science education in the student pipeline, new standards have been introduced. The National Research Council recently issued the National Science and Education Standards (NRC, 1995) and the National Council of Teachers
of Mathematics released *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989). These standards indicate specific objectives for each grade level. For these standards to achieve their intended purpose of improving the education in the pipeline, teachers must be adequately prepared to meet the standards. Unfortunately, on the whole, precollege faculty are not up to the task. Numerous studies indicate that many precollege faculty are unlikely to teach mathematics and science well due to both insufficient education and perceived inadequacies (Lohmann, 1991 and Jones, 1992a). Engineers, especially those in academia, must therefore work with in-service and pre-service teachers to help develop both competence and confidence. Partnerships as described earlier as well as appropriate courses at the college level will achieve this aim.

Another weakness in the pipeline is the lack of diversity. Diversity is important in engineering to achieve the best divergent thinking as a profession, apart from any moral considerations. The engineering student population is predominantly comprised of white males with certain thinking/learning preferences. The underrepresentation of
women and minorities in engineering is well documented (Jones, 1992b and Felder et al., 1995).

Less acknowledged, but equally noteworthy in discussing diversity, is the fact that most successful engineering students have similar thinking and learning preferences (Lumsdaine and Lumsdaine, 1995b, Frey, 1990, and Felder, 1993). The students who are successful are those who are likely to prepare for and study engineering the way that is has traditionally been taught. Changes in the educational system will allow a more diverse population of engineering students to be successful.

Fortunately, many of the changes which will benefit groups underrepresented in engineering will benefit all students. Sheila Tobias notes, “the best strategy for increasing the persistence and success in engineering (and all the sciences) of women and historically underrepresented minorities . . . is to improve the teaching-learning environment for all” (Hamlin, 1994, p. 28).

Just as improving the success of groups underrepresented in engineering will improve the environment for all students, approaches which address any of these objectives may address others as well. The objectives will
now be summarized, and the intended approach to address them will be introduced.

**Summary of Reform Objectives**

There are a great many individual objectives in the reform movement. These are described in detail in the previous sections and are summarized in the list that follows.

1. Satisfy the changing needs of the profession
   a. Emphasize team skills and communication
   b. Provide more hands-on design experience
   c. Teach students to learn
   d. Make students strongest in transferrable skills
   e. Strengthen liberal education

2. Increase enrollment
   a. Teach nature of engineering to students/teachers
   b. Help teachers to foster interest in engineering

3. Improve student quality
   a. Remediate in-service teachers to meet standards
   b. Prepare pre-service teachers to meet standards
   c. Inform K-12 personnel of pre-engineering curriculum
   d. Encourage all genders, races, and thinking types

It is proposed here that design activities, when properly devised, can accomplish most of these objectives. In the section which follows, design activities will be discussed as to the success they have had and what changes might be made to them to further enhance their applicability.
Design Activities as a Method of Meeting Reform Objectives

Design is one of the defining elements of the engineering profession. Since World War II, however, design has been primarily relegated to the later years of engineering education, the first two to three years of curriculum comprised mostly of basic mathematics and science. This has placed a burden on prospective engineers that they must endure what was seen as "necessary preparation" prior to engaging in design. Many would-be engineers have lost interest in such pursuits before reaching the part of the curriculum which included design (Ercolano, 1996).

Traditional Laboratory Exercises

It has long been recognized that experiments are an excellent method by which students can achieve hands-on experience; this is the foundation for laboratory activities included as part of a course or as an entire course in the high school and college curriculum. Unfortunately, such activities have traditionally had little to do with design.
Most laboratories are intended to be as near a reproduction of the “correct” answer as is possible.

While reality sometimes finds a foothold in the laboratory (e.g. error analysis), much of the work in laboratories has traditionally been closed-end, with one “correct” answer. Laboratories done in teams can provide the opportunity for the development of teamwork skills. However, the teamwork usually ends when students leave the laboratory—partners usually take turns in writing the laboratory report.

Therefore, while traditional laboratories fulfill the objective of providing hands-on experience and team skills for students, they do little to address the other objectives. If properly designed, a laboratory exercise can teach students investigative skills to learn on their own. Frequently, however, because lab time is limited, students are generally given a step-by-step process to follow.

Capstone Design Courses

Many schools, in order to satisfy the ABET requirement for design content, have “capstone” design projects. These
design projects, which culminate the curriculum for an engineering bachelor's degree, are common (Miller and Olds, 1994 and Harris and Jacobs, 1995). If used in absence of design practice in the earlier part of the curriculum, such design projects perpetuate the approach to design discussed earlier by Ercolano (1996), wherein students are not permitted to experience design until their formal education is finished. This results in students who are not experienced in design, and discourages some students who might make excellent designers, but lose interest in the curriculum in which design is not well integrated.

**Design for Freshmen and Sophomores**

In the late 1960's, some faculty realized the shortcomings of traditional laboratories and introduced project-based courses into the curriculum (Durfee, 1994). More importantly, there has been a recent trend to insert design activities into the first two years of the engineering curriculum (Mahendran, 1995, Durfee, 1994, Dally and Zhang, 1993 and Dym, 1994). Such early design experiences have been found to be the most successful in
meeting a great many of the objectives of the reform movement (Peterson, 1993).

**Design in the K-12 Pipeline**

There has also been a great deal of interest in recent years to expand the use of design projects in the K-12 system. Such efforts generally fall into two categories: those that interact directly with students and those that seek to expand the talents and perspective of K-12 faculty. Both of these types of programs are important. There is no better way to support a student’s interest than for the student to be encouraged by an engineer. As mentioned earlier, however, the number of students in the school system is an order of magnitude larger than the number of teachers. This fact points to the effectiveness of teacher-oriented programs.

**Student intervention**

One approach to bringing projects to K-12 students is through pre-prepared curriculum kits such as those developed by Snell in conjunction with the Southern Illinois
University at Edwardsville engineering school (Meade, 1992) and by Turner (1996) sponsored by the Florida Department of Education. Crawford et al. (1994) extended that approach to develop an engineering design curriculum for grades K-5. In the higher grades, more advanced projects are possible. Conrad and Mills (1994) introduced "Stiquito" to students in the middle grades. The design and programming of the robot insect allows students to learn and employ concepts from electrical, mechanical, chemical, computer, and industrial engineering.

Other programs bring engineers into the classroom as mentors, focused on conducting hands-on exercises to teach a concept. Examples at the elementary level include the Emeritus Scientists, Mathematicians and Engineers and A World in Motion (Meade, 1992). In the middle grades, Pols et al. (1994) used aeronautics activities as a vehicle for exposing students to engineering. At the high school level, even more aggressive programs exist which include a short lecture followed by demonstration and laboratory time. Such a structure was used by Ayorinde and Gibson (1995) to present a primer in composites engineering to high school students in an engineering preparatory program. Such
programs are very successful because just as teachers are intimidated by mathematics and science, most engineers are intimidated by a classroom full of young people. Around the country, various companies (Chen, 1990), educational institutions (Meade, 1992), and even governmental organizations (Otts, 1991) sponsor such programs.

Design competitions have also been effective in introducing students to engineering. Titcomb et al. (1994) used design problems appropriate for a high school physics course to establish a design competition which had the participation of nearly half the high schools in Vermont. The Junior Engineering Technical Society (JETS) offers a year-long comprehensive high school program, with design competitions playing a key role (JETS, 1994).

An excellent blend of these various methods is the summer institute. Special programs such as the Hands-On Institute of Science and Technology (HOIST), held at the University of Florida summer 1995, can provide a more

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4HOIST was held at the University of Florida from July 9-15, 1995. It was coordinated by Marc Hoit and Matthew Ohland of the Civil Engineering department, and funded by a combination of student fees and a grant from the American Society of Civil Engineers. A report of the implementation of the institute is in progress.
intensive introduction to engineering and design. HOIST participants engaged in active design projects, saw demonstrations, met engineering mentors, and went on a field trip to a power plant, a prestressed concrete manufacturer, and engaged in social activities designed to further develop camaraderie and teamwork skills, such as a very challenging scavenger hunt.

**Faculty intervention**

As discussed before, it is more effective to work with teachers because each teacher will interact with a much greater number of students. One method of accomplishing this is to prepare K-12 teachers in institutes such as the Bell Atlantic/AAAS Institute for Middle School Science and Technology Teachers (Jones, 1992a) and the SouthEastern Consortium for Minorities in Engineering (SECME) summer institute (Ohland et al., 1996). Courses in such institutes can fulfill continuing education requirements for the teacher and even provide graduate credit for teachers pursuing master's degrees. The SECME summer institutes for teachers have trained more than 2,100 teachers since their inception in 1977. Intervention at the faculty level has
been very successful for SECME—those teachers have seen more than 40,000 SECME students graduate. Those SECME students have SAT composite scores more than 200 points higher than the African-American average (Leake, 1994).

Because of the effectiveness of such training programs for teachers, several such programs have been initiated in recent years. Washington State University (WSU) established the six week Teacher Institute for Science and Mathematics Education Through Engineering Experience, which gives 20-30 middle school, high school, and community college educators contact with approximately 15 WSU faculty members ("Engineering for K-12 Teachers," 1994). Conrad (1994) introduced engineering and technology to Arkansas teachers in a three-week workshop. The Stevens Institute of Technology Center for Improved Engineering and Science Education has broadcast teacher training teleconferences (Chao, 1992). VISION, a three-week institute for teachers in Howard County, Indiana, is a partnership of Indiana University, Purdue University at Kokomo, area schools, and six area businesses (Schwartz, 1996). These programs, and many others around the country, recognize the importance of intervention at the faculty level.
Integration into state curricula

The most aggressive approach is to integrate design directly into the curriculum. Since curriculum is generally established by a state’s board of education, this is still difficult to do on a nationwide basis. Since there are only 50 states, however, the number of entities to work with to institute this kind of change is significantly smaller than even the number of schools in the K-12 system. New York State is the leader in this sort of curriculum development. Since 1986, middle school teachers have been prepared through in-service training to offer a course called "Introduction to Technology," which all students are required to take (Hacker, 1993). This movement, which began in the middle grades, has led to a "Principles of Engineering" elective course which is taught at the high school level.

Typical Design Project Objectives

It is important to note that design projects are employed in all these approaches to improving the engineering educational system. It is the multidisciplinary
nature of design that makes this possible. Properly posed
design projects are capable of meeting many of the
objectives of the reform movement. Encouraging creative
behavior is a common theme in design projects (Ko and Hayes,
is among the most transferrable of skills. Others also
include documenting the design process and making a
presentation of the results (Fentiman and Demel, 1994, and
Starkey et al., 1994). This adds written and presentation
skills to the interpersonal communication which already
accompanies such design projects. Still others choose to
include social context in their projects, showing young
engineers how they can be a service to the community.
Clearly, a great number of objectives are possible in
properly planned design activities.

Essentially, because the design projects are themselves
designed, it is possible to include a wide variety of
objectives. This is testament to the interdisciplinary
nature of the design process. Since such a wide variety of
objectives is possible, it is appropriate to consider what
set objectives has been most effective and what additional
objectives might make design projects even more effective.
Dissertation Structure

A comprehensive set of objectives was therefore established. This set of objectives has been used to create Engineering By Design, a process for developing design projects. This process is of course a creative one, so such a methodology begins with a process similar to standard creative problem solving techniques. Various approaches to problem solving and their applicability to the task at hand will therefore be discussed in Chapter 2.

To create design activities which are educationally complete, a modern understanding of teaching and learning must be merged with standard problem solving approaches to create a more advanced process. Teaching methods and learning styles are discussed in Chapter 3.

The Engineering By Design methodology was developed through the creation of a prototype project for the Civil Engineering section of Introduction to Engineering, a one-credit graded course at the University of Florida. The prototype design activity and the development of the methodology are discussed in Chapter 4. The full set of objectives is introduced. These objectives can be applied
to the process of creating any design project. Many of these objectives directly address the objectives of the current reform movement. Other objectives are added which enhance the ability to implement, sustain, and disseminate the activities.

Assessment of the *Engineering By Design* methodology is accomplished in two ways. The first is by measuring the success activities made using it, qualitatively and quantitatively. The second is by reviewing the feedback of those who have used the methodology. The assessment of *Engineering By Design* is included in Chapter 5. Also included in Chapter 5 are the field observations by the author of the success of various design projects.

Lastly, conclusions and recommendations are included in Chapter 6. Conclusions are based on both the formal assessment and the observations discussed in Chapter 6.
CHAPTER 2
CREATIVE PROBLEM SOLVING

Introduction

"No single technological advance will be the key to a safe and comfortable long-term future for civilization. Rather, the key, if any exists, will lie in getting large numbers of human minds to operate creatively and from a broad, open-minded perspective, to cope with new challenges." This quote (Lumsdaine and Lumsdaine, 1995a, xv) by Paul MacCready, inventor of the various "Gossamer" low-energy aircraft, highlights the importance most flexible skill we can impart to engineering students—the ability to think creatively.

The key to creative problem solving is recognizing that real problems have more than one solution. While we seek the optimum, we will never know that we have achieved it. A new approach or a new understanding of the fundamentals underlying the problem may lead to great improvements in the
solution. Since assessing how people solve problems is itself an open-ended problem, there are a multitude of approaches to describe the process. This, of course, confounds the process of formulating a methodology for problem solving, forcing the methodology to remain broad and flexible (Greeno, 1980).

The Stages of Problem Solving

There are a number of stages in the process of creative problem solving. Different authors have different names and attributes for these stages, but the general pattern enjoys wide agreement in principle. The discussion will follow the stages delineated by Lumsdaine and Lumsdaine (1995a), but the terminology and perspective characteristic of other researchers will be introduced throughout. The four stages of Lumsdaine and Lumsdaine are enumerated below:

1. Problem Definition
2. Idea Generation
3. Idea Evaluation and Selection
4. Solution Implementation

These four stages alone are not sufficient to complete the Engineering by Design methodology, due to the unconventional nature of the problem the methodology seeks to solve—that of
the design of a creative activity itself. For now, only the conventional stages will be discussed. Each stage will be considered as it applies to the activity designer and to the activity participants. The additional stages which are included in *Engineering by Design* (which will only be completed by the activity designer) will be covered in chapter 4.

**Problem Definition**

"The uncreative mind can spot wrong answers, but it takes a very creative mind to spot wrong questions." This quote by Anthony Jay cited by Fabian (1990) is directed at the importance of a well posed problem. Real problems rarely are clearly defined. In creating the methodology, this means that the activity designer must be sure to be aware of all goals of the activity on a conscious level, so that the design of the activity is a well-posed problem. In the designed activity, however, it is the activity participants who must define the problem—this is a skill which they must practice to develop.
Problem definition is the most critical step in the problem solving process. The less defined a problem is, the more solutions it will have. Definition, therefore, is the process which reduces the scope of a problem, and thus the time necessary to achieve an acceptable solution. Although most problem solvers recognize problem definition as the first step in the process, the actual approach those individuals use is frequently quite different (Kepner and Tregoe, 1965).

Kahney (1986) breaks down the data which go into the definition of a problem into four categories. There is information about

- the initial state;
- the goal state;
- operators (specific actions permitted in the solution);
- and operator restrictions (constraints on the actions).

Kahney goes on to clarify these groupings through comparison to the "Towers of Hanoi" problem, shown below in its initial state, with three differently sized rings stacked on peg "a" as shown. The largest ring is on the bottom, the smallest is on top, and the medium-sized ring is in the middle.

The goal state is to achieve the same configuration, but with the rings on peg "b" instead.
In such a simple problem, there is only one operator, which might be called "move," which allows the rings to be moved. This operator has three restrictions: only one ring may be moved at a time, a larger ring may not be placed on top of a smaller ring, and rings may only be placed on one of the three pegs.

With clear information given in each of Kahney's categories, this problem is well defined. Most problems assigned in engineering education and in the K-12 pipeline are similar in that regard. Problems in those arenas are typically closed-ended, having a single correct answer (Felder, 1988). If a problem is to yield a single correct answer, it must be well defined.
In the problem of creating a design activity, the initial state will contain information regarding the current knowledge, skills, or attitudes of the participants. The goal state will indicate which of these the design activity is intended to change.

Lumsdaine and Lumsdaine (1995a) anthropomorphize the problem solving process by assigning personae to various stages. The description of the initial state is left to the detective, including the process of distinction, which is characteristic of Kepner and Tregoe (1965). Distinction is used to set the problem apart from what is not the problem. This step not only reduces scope, but informs the direction the following stages should take.

If a problem is complex or unstructured enough, Lumsdaine and Lumsdaine have the “explorer” take over the problem definition stage. The explorer looks at the context of the problem more than the problem itself. The explorer analogy is also used by von Oech (1986). In von Oech and Lumsdaine and Lumsdaine, this mind-set clearly overlaps the boundaries of problem definition and idea generation. This overlap can be a wasteful one. If the “exploring” is not limited to the problem itself, but instead, as von Oech and
Lumsdaine and Lumsdaine seem to suggest, probes for a solution as well, there is the inherent risk of focusing on possible solutions before the problem has been adequately defined. Premature attempts at a solution have been shown to lead to wasted resources. Kepner and Tregoe give a number of examples of this wasting of resources through industrial case studies (1965).

Part of the explorer's role lies in problem definition, however. Van Gundy (1984) describes the stage of problem definition as the process of establishing limits or boundaries for a situation, constructing walls which allow us to view a problem as finite. VanGundy advocates the "redefinition" of a problem, a process by which a problem solver takes the time to look beyond the established boundaries of a problem. This redefinition is the only viable role of the explorer within the problem definition stage.

Earlier work by Parnes (1967), creator of what is called the Creative Problem Solving approach, breaks this stage into two stages, one of Fact Finding, and a second of Problem Finding. Lumsdaine and Lumsdaine have wisely collapsed these two, which overlap significantly.
Idea Generation

"What you see is what you get. Change your eyes." This quote by Sam Keen cited by Fabian (1990) reveals the core of the idea generation phase of problem solving. It is by looking at the same things in new ways that new ideas are achieved. Volumes of research have been written on just this stage of the problem solving process. The study of idea generation includes research on cognition itself, as Piaget's theories of child development focus substantially on how a child's develops new perspectives of a problem (Brown and Desforges, 1979).

This stage of the problem solving process is the most creative one, where it is ideas that are being created. Lumsdaine and Lumsdaine (1995a) assign this stage the "artist" persona, seeking the image of a free spirited creator not afraid to be avant-garde. Defining a problem certainly uses thinking skills, but need not be creative, per se. The next stage of idea evaluation and selection certainly does not use creative thinking. The key in evaluation and selection is critical thinking, which will be
discussed in detail in the next section. Critical thinking is inappropriate in this stage, because it may prevent the generation of ideas, thus limiting the range of possible solutions. Critical thinking is just one of the barriers to creative thinking. The body of research into idea generation has outlined a great many barriers. Authors of methods to encourage creative thinking offer various ways of overcoming these barriers.

The Barriers to Creative Thinking

Lumsdaine and Lumsdaine refer to these as mental barriers or mental blocks (Lumsdaine and Lumsdaine, 1995a). Von Oech describes them as mental locks (von Oech, 1983). To Fabian (1990), they are mind-sets—those barriers which prevent us from producing new ideas. Such barriers will be introduced throughout this section. In the following section, a large number of approaches to generating ideas will be presented. Reference will be made to how those approaches attempt to break various barriers.

As earlier, the discussion follows Lumsdaine and Lumsdaine. Von Oech's list (1983) contains a greater number
of listed barriers, some of them having been grouped together by Lumsdaine and Lumsdaine. Those which are unique to von Oech are shown in quotes.

**False assumptions**

"I’m not Creative." This attitude will be especially prevalent in those with low self-esteem with respect to their intelligence. However, because highly intelligent minds can think of solutions quickly, a better solution may be achieved by a person with a slower mind, who must wait and take in more data before proposing a solution. This additional information may lead to an improved solution (De Bono, 1986). In fact, there are a number ways that a highly intelligent can be trapped into poor thinking. De Bono lists nine of these, which Lumsdaine and Lumsdaine (1995a) annotate to show that creativity is dependent on using the whole brain.

"Play is Frivolous." The best example of this is given by von Oech (1983) in the Moebius strip. The Moebius strip is a strip formed in a loop with a half-twist introduced before connecting the ends. This was merely a topological fascination for many years, because the resulting shape has
only one side. Fifty years ago, however, conveyor belt designers decided to use that to their advantage, achieving equal wear, since all the surface of the belt is used. The Moebius strip shows promise for application in other technologies as well. It is key to notice that while the Moebius strip was merely an amusement for many years, it sparked innovation years after its introduction.

Play is also a regular source of learning. In the animal kingdom, play is the process by which animals learn the skills they need to survive. Children learn many things through play. Therefore, if adults are unwilling to play, they are cut off from certain opportunities for learning.

"That's not my Area." This barrier listed by von Oech (1983) belongs in this category. The assumption being made is "because this is outside of my field of expertise, I have nothing to offer." Because it is precisely the gathering of a variety of experience and expertise which promotes divergent thinking, this assumption is false.

There is only one right answer

French philosopher Emile Chartier once said, "Nothing is more dangerous than an idea when it is the only one you
have."

The need for different perspectives in idea generation has already been discussed. Unfortunately, multiple choice testing, closed end problems, and other artifacts of our formal schooling teach us that there is only one correct answer to a problem. To knock down this barrier to creativity, we must introduce an entirely new approach than the one that is commonly used.

**Looking at a problem in isolation**

Avoiding this barrier is the remainder of the job of the "explorer" persona introduced earlier. Here the explorer can introduce new directions for ideas based on the context of the problem. The common analogy for this barrier is "not being able to see the forest for the trees." The key to encourage multidisciplinary approaches to problems. This is a substantial argument in support of partnerships of engineers and educators—as discussed earlier, each brings different contextual information to the partnership.

**Following the rules**

Innovative ideas come from the unconventional—if participants in the idea generation stage remain bound to
the conventional way of doing things, new ideas are constrained. We cannot, however, completely abandon order, or chaos will result. Some rules will remain, which will be discussed later. Exactly what rules are appropriate will depend on the method of idea generation and whether it is done individually or in groups. Lumsdaine and Lumsdaine (1995a) seem to have covered von Oech's "That's not Logical" barrier (1983) in this category.

**Negative thinking**

This barrier is particularly serious, in that it affects not only the negative thinker, but also influences all those around him or her. Counted here are attitudes which are negative in many (if not all) contexts—negativism, sarcasm, debasing remarks, and others. Criticism is also included here. As stated earlier, critical thinking and discrimination are important in the next stage, but are not conducive to idea generation.

**Fear of failure**

Lumsdaine and Lumsdaine (1995a) also characterize this barrier as one of "risk-avoidance." In nature, genetic
mutation, or errors in the process of transmitting genetic information, can introduce adaptations and improvements to a species. The human race, however, has been conditioned to avoid failure. The grading system used throughout the educational process is itself a constant reminder that those who make the fewest errors are more rewarded (Von Oech, 1983).

At some level, error is recognized as a part of life and a necessary process in learning, hence "to err is human" and "trial and error." If error were not anticipated, "trial and error" would instead be referred to as "trial and success." The role of failure in technological progress is well documented, from Edison's many attempts to find a suitable filament for the light bulb to the metallurgical revolution following the Ashtabula Bridge disaster caused by the brittle failure of cast iron.

Discomfort with ambiguity

While many would prefer that solutions always be "black and white," the problem definition itself and the best solutions are often in the gray areas. Students are notoriously uncomfortable with ambiguity, because they are
rarely exposed to it. Well-defined, closed-end problems leave no ambiguity.

The reason we are taught to avoid ambiguity is that it can lead to miscommunication. On an exam, this means losing points. In giving directions, it can result in the follower becoming lost. Ambiguity, because it introduces multiple meanings, is also able to lead to new perspectives and idea generation.

Paradoxes are a common form of ambiguity. Many of the greatest advances in physics have been characterized by paradox. The inventors of the jet engine believed that they had found a way to violate the second law of thermodynamics, but continued their work anyway. Zeno's paradox encourages us to develop a more complete understanding of geometry. Many researchers study the order of chaos. Entertaining ambiguity is useful in order to proceed to a higher level of understanding.

The Use of Groups in Idea Generation

It has been discussed that idea generation is dependent on finding new ways to look at the same information.
Because of individual differences in experience and thinking preferences, the best way to gain new perspectives is by conducting creative problem solving, especially the idea generation stage, in groups. Further, it is best if the members of a group have different perspectives and knowledge, i.e. the group is heterogeneous. This has the potential to yield greater results than those of an individual, who will find it more difficult to stray from his or her preferred perspectives. Heterogeneity will be discussed further in relation to learning styles in the later part of chapter 3.

This potential, however, is not always realized. Osborn (1963) first published his landmark work *Applied Imagination* in 1953. Although Osborn details an entire approach to creative problem solving, the idea generation stage is where his greatest contribution lies. As the inventor of verbal brainstorming, which will be discussed in greater detail later, Osborn claimed that group brainstorming was an effective method of group problem solving.

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5Various individual differences will be discussed in much greater detail in the next chapter.
Osborn used many examples from industry to support his work, but made other assertions which were less well supported. Fortunately, Osborn’s work was fascinating enough to spark research which verified claims (Parnes and Meadow, 1959). Other research, however, has rejected the claim that idea generation by groups outproduces the same individuals working alone (Taylor et al., 1958, Bouchard, 1969 and 1972, Bouchard and Hare, 1970, and Bouchard et al., 1974).

More recent research has attempted to pinpoint the source of the discrepancy which causes the success of group idea generation to be inconsistent (Diehl and Stroebe, 1987, Harkins, 1987, Williams et al., 1981, Harkins and Jackson, 1985, and Kerr and Bruun, 1983). The conclusion is that additional barriers to creativity are introduced when idea generation is done in groups—these barriers follow.

**Barriers Specific to Group Idea Generation**

Diehl and Stroebe (1987) define three potential group effects. These are evaluation apprehension, social loafing, and production blocking.
Evaluation apprehension

Evaluation apprehension is the fear of having one's ideas judged either by others in the group or by an external observer. Von Oech includes this concern as "Don't be Foolish." The pressure to conform and avoid standing out are strong, and are often important, such as when driving in traffic or singing in a choir. In idea generation, however, conformity can lead to "groupthink," where participants are more concerned with approval than generating original ideas.

Research investigating evaluation apprehension has shown some ambiguity. Colaros and Anderson (1969) found an inverse relationship between imposed evaluation apprehension and productivity, as would be expected. Maginn and Harris (1980), however, discovered that the presence of "judge" observers did not significantly affect productivity. The only thing which is clear from the results of these two studies is that "evaluation apprehension" is difficult to guarantee, and even more difficult to quantify.

Social loafing

In social work contexts, both social loafing (Harkins, 1987 and Williams et al., 1981) and social facilitation
(Schauer, 1985 and Harkins, 1987) effects have been identified. Which will occur seems dependent upon the relationship of the group members and the environment in which they are working (Harkins and Jackson, 1985 and Kerr and Bruun, 1983).

Social loafing was minimized when group members were co-workers, and competition was more of a factor. This seems surprising at first, since we would like to think that facilitation would occur simply because co-workers were all "playing on the same team," or cooperating, rather than competing. It is already becoming clear that the most important factor in overcoming the barriers to group idea generation will be the establishment of a supportive and cooperative environment.

**Production blocking**

Production blocking occurs when a group member gets an idea, but is unable to voice it immediately. While waiting for a chance to contribute the idea, the owner of the idea may simply forget it, or may use the intervening time to become critical of their unvoiced idea, violating the deferred judgement principle. Since group idea generation
techniques generally allot equal time for contributions by each member, this particular barrier is much greater in larger groups.

Overcoming the Barriers to Creative Thinking

There are two main ways to overcome the barriers to creative thinking—by using a technique which eliminates the barrier by design, or by imposing rules on top of the technique which seek to specifically remove the barriers. There are many techniques throughout the literature. A discussion of these follows.

Techniques of Idea Generation

A great number of idea generation techniques have been suggested—many more than can be described here. Van Gundy (1984) is an excellent compendium of techniques, detailing some 30 individual techniques and 31 group techniques. The division of the techniques into two groups seems to imply that the individual techniques cannot be used by groups, whereas many of them can. This, however, does not diminish the usefulness of Van Gundy's work, which is an excellent
survey of methods which have been used at each stage of the creative problem solving process.

Here, the discussion will focus on group techniques, which will be used by the partnerships developing activities through Engineering By Design, and should be incorporated into design activities, to teach team skills. Since today’s students are not skilled in teamwork, as discussed earlier, means they will need to become comfortable with the concept. Short creative thinking warm-up exercises, as found in Lumsdaine and Lumsdaine (1995a) and others, are good tools to get students in a cooperative frame of mind as well as stimulate creativity.

**Verbal brainstorming**

This is the classical method invented by Osborn (1963). The objective is for members of the group to verbalize their ideas, which are intended to then stimulate the ideas of others in the group. Osborn speculates that groups of five should work best, but research to establish an optimum number of members is inconclusive, as discussed earlier.

Osborn’s two primary principles which define verbal brainstorming are “deferment of judgement” and “quantity
breeds quality." Parnes and Meadow (1959) found that deferred judgement is a key factor in the generation of ideas, as Osborn contends. Groups brainstorming using a deferred judgement procedure produced 70% more "good" ideas (in the same time period) than individuals attempting to generate ideas without deferment. Removing the group effect, individuals producing ideas on their own were also found to have significant gains using deferred judgement.

Osborn's assertion that quantity inevitably produces quality is perhaps the more difficult tenet to accept. We are taught the "quality not quantity" approach at an early age. There is support for Osborn's claim with respect to idea generation (Chamberlain, 1944). Another argument for quantity leading to quantity is one of probability—the more ideas which are presented, the more ideas there should be of an acceptable caliber. Osborn reports a study which compared the number of good ideas generated in the first half of a brainstorming session to the output of the second half of the same session. The latter half had 78% greater production of good ideas than the first half.

In order to stimulate new directions during brainstorming, Osborn identified nine types of thought-starter

**Table 1** Nine Categories of Thought-Starter Questions

<table>
<thead>
<tr>
<th>Question</th>
<th>Sub-questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Put to other uses?</td>
<td>New ways to use object as is?</td>
</tr>
<tr>
<td></td>
<td>Other uses if modified?</td>
</tr>
<tr>
<td>Adapt?</td>
<td>What else is like this?</td>
</tr>
<tr>
<td></td>
<td>What other ideas does this suggest?</td>
</tr>
<tr>
<td></td>
<td>Any idea in the past that could be copied or adapted?</td>
</tr>
<tr>
<td>Modify?</td>
<td>Change meaning, color, motion, sound, odor, taste, form, shape?</td>
</tr>
<tr>
<td></td>
<td>Other changes? New twist?</td>
</tr>
<tr>
<td>Magnify?</td>
<td>What to add? Greater frequency? Stronger?</td>
</tr>
<tr>
<td></td>
<td>Larger? Higher? Longer? Thicker?</td>
</tr>
<tr>
<td></td>
<td>Extra value? Plus ingredient? Multiply?</td>
</tr>
<tr>
<td></td>
<td>Exaggerate?</td>
</tr>
<tr>
<td>Minify?</td>
<td>What to subtract? Eliminate? Smaller?</td>
</tr>
<tr>
<td></td>
<td>Lighter? Slower? Split up?</td>
</tr>
<tr>
<td></td>
<td>Less frequent? Condense? Miniaturize?</td>
</tr>
<tr>
<td></td>
<td>Streamline? Understate?</td>
</tr>
<tr>
<td>Substitute?</td>
<td>Who else instead? What else instead?</td>
</tr>
<tr>
<td></td>
<td>Other place? Other time? Other ingredient?</td>
</tr>
<tr>
<td></td>
<td>Other material? Other process?</td>
</tr>
<tr>
<td></td>
<td>Other power source? Other approach?</td>
</tr>
<tr>
<td></td>
<td>Other tone of voice?</td>
</tr>
<tr>
<td>Rearrange?</td>
<td>Other layout? Other sequence? Change pace?</td>
</tr>
<tr>
<td></td>
<td>Other pattern? Change schedule?</td>
</tr>
<tr>
<td></td>
<td>Transpose cause and effect?</td>
</tr>
<tr>
<td>Reverse?</td>
<td>Opposites? Turn it backward?</td>
</tr>
<tr>
<td></td>
<td>Turn it upside down? Turn it inside out?</td>
</tr>
<tr>
<td></td>
<td>Mirror-reverse it?</td>
</tr>
<tr>
<td></td>
<td>Transpose positive and negative?</td>
</tr>
</tbody>
</table>
Other guidelines for Osborn’s verbal brainstorming also include encouraging wild ideas, which can spark divergent thinking, and building from the ideas of others. The latter, known as “hitchhiking,” is given priority in sessions where group members generally take turns in presenting their ideas.

The classical verbal brainstorming, essentially as Osborn introduced it, is the most common method used today. Fabian (1990) refers to it as the “bread-and-butter” process. Fabian also points out that, although the principles are basically simple, they are not always followed in practice, which has led to varying degrees of success.

**Brainwriting**

In order to overcome additional barriers such as production blocking and evaluation apprehension, some have adopted a written method for brainstorming, called brainwriting. In this approach, ideas are written down in cells on a piece of paper. Each row on the paper has three cells. When a group member fills a row, they give up their paper for another one. In this manner, ideas are
transferred among group members via the paper. This technique has advantages—participants can write down their ideas at their own pace, and the effects of more vocal or dominating people are minimized. For these reasons, this method is gaining popularity in the United States (Fabian, 1990). Although this technique helps more introverted group members participate fully, it should only be used until a group has developed a rapport. The reason I suggest this is as follows: speaking and hearing stimulate greater cognitive activity than writing and reading.\textsuperscript{6} This effect may be mitigated somewhat by achieving visual stimulation by encouraging brainwriting participants to draw pictures in the cells.

**Electronic brainstorming**

In further attempts to eliminate creative barriers, brainstorming has recently been computerized (Gallupe et al., 1991 and Gallupe et al., 1992). In this process, members each sit at their own computers, but their ideas are automatically sent to other group members. Gallupe et al.

\textsuperscript{6}Research to support this claim is discussed in the following chapter.
(1991), found this method significantly reduced all three barriers specific to group idea generation. While this is an intriguing approach in a corporate setting, there is little opportunity to exploit electronic brainstorming in the classroom.

**Force-fitting**

Force-fitting, relating to apparently unrelated concepts, is a technique often incorporated into other techniques (Fabian, 1990). It necessarily introduces novelty, and can be spontaneously be used if an idea generation session becomes "stuck." Lumsdaine and Lumsdaine (1995a) use this term very loosely, using it to refer to a variety of methods for stimulating a group when it is "stuck." De Bono (1970) refers to this method as "Random Stimulation."

**Morphological analysis**

As its name would suggest, this technique focuses on the form of the problem. Once the problem is stated, two or three major dimensions are identified. Each dimension is subdivided into categories. Ideas are then generated for
each combination of the subdivisions of the various dimensions. Felder (1988) gives the example of devising a mode of transportation. One dimension would be the medium in or on which transportation occurs. Another dimension would be the power source. This would lead to combinations such as a cable-powered device to travel through air (such as a ski lift) and an internal combustion powered device to travel through water (a diesel submarine, for example). Other combinations may spark new paths for development where there is no existing method.

Idea Evaluation and Selection

In this stage, the process focuses on critical thinking. The wild and crazy, impractical nature of idea generation is absent here, and is replaced by the pragmatic, utilitarian, and practical. There will still be new ideas created in this stage, as practical concerns introduce constraints which call for the adaptation of previous ideas. Idea evaluation and selection as a part of the problem process are important, but are generally overemphasized in
engineering education, as indicated by Lumsdaine and Lumsdaine's choice of "engineer" as the persona characterizing this stage. Von Oech (1986) uses the "judge" persona, to whom Lumsdaine and Lumsdaine (1995a) ascribe the completion of this stage.

As was true in the case of idea generation, methods for selecting the best choice abound. Van Gundy (1984) details 16 methods from advantage/disadvantage counting to weighting systems. In the case of idea selection for creating engineering design activities, little effort is expected. In the event that more than one approach is viable and might be selected, there is great opportunity for the combination of multiple approaches within an educational context. In the corporate community, of course, elimination of all but a single path may be necessary, since each idea will have development costs associated with it. But common to the corporate objective and the educational objective is that further testing is usually possible to determine the feasibility of various ideas. A simple advantage/disadvantage discussion, as would commonly be used, will suffice in this context.
Solution Implementation

This is, of course, the most time consuming part of the process. Lumsdaine and Lumsdaine (1995a) assign the role of "producer" to this stage. The image of a movie producer certainly does not fit, since financial backing is not enough to achieve successful implementation of an idea. If we consider the term "producer" from a more general perspective, as a person who creates the end product, it is then acceptable. More apt, it seems, is the von Oech (1986) persona, the warrior. Solution implementation requires a tenacity and a passion, even a relentlessness, to achieve the objective.

In the case of the students themselves, the solution reached as a result of problem solving has traditionally not been implemented. This is at times cost prohibitive. However, it is vital that students complete the process at least some of the time, for a number of reasons. Without completing the process, students will not see "the big picture" of problem solving through to its conclusion. Students will usually have the most to learn during the
implementation stage—they will discover which assumptions they made were not valid, run into unanticipated difficulties, and have to improvise and improve their design. The eliminating of implementation from the design process leaves students with the understanding that all designs which can be put on paper are viable designs, a dangerous fallacy. We must strive to disabuse students of this notion.

We must instead consider the cost of implementation as a significant factor in designing the creative design activity itself. Approaches to reducing implementation cost will be included in the discussion of the prototype design activity in chapter 4.

Lumsdaine and Lumsdaine (1995a) and von Oech (1986) include evaluation within this last stage. In Engineering By Design, evaluation of the implemented solution is treated separately. As crucial as program assessment is, it must receive adequate attention. It is integrated throughout the process of creative problem solving, not constrained to attention during the final stage.
Summary of Approach Chosen for Methodology

Recognizing that objective definition may be much more nebulous than under traditional circumstances, the problem definition stage was broken down into multiple stages. For example, one potential objective is "to keep students occupied after school has formally ended, preferably with some educational pursuit." Seeking simplicity, especially in working with in-service teachers who are likely not as trained in problem solving techniques as engineers, classical brainstorming was chosen during the idea generation phase. Blocking and other barriers are not expected to be significant, since groups are expected to be small, comprised of 1-2 teachers/professors and 1-2 engineers.

Advantage/disadvantage listing are expected to be sufficient in the idea selection stage. Solution implementation is expected to be feasible by the nature of the design objectives. Evaluation and assessment receive special attention in an added stage.

There is one more stage which is added to Engineering By Design: a stage which is intended to ensure that the
activity is educationally complete, tapping higher level thinking skills and reaching students with all learning styles. The foundation for this stage will be laid in chapter 3.
CHAPTER 3
LEARNING AND TEACHING

To achieve the desired end of creating educationally sound activities for teaching engineering, appropriate teaching methods must be understood and applied, and are studied here. K-12 teachers who graduate from education programs receive training in educational psychology, which includes the study of how students learn and of how teachers teach, called pedagogy. Few college professors receive this sort of training. James Stice (1987a, p. 95-96) describes how he became a professor and learned to teach:

I found that I enjoyed it hugely and decided to make college teaching my career. ... If you gave [the students] a problem that was a little different from what they had seen before, they were stumped. How could I [teach a deeper understanding] to a class of thirty students? I lacked the resources at the time. So, I lectured and did what I could to help those who came to see me after class.

Twenty-three years passed, and I learned some things about the craft of teaching. Larry Grayson introduced me to the idea of using instructional objectives, Dwight Schott showed me the wisdom of teaching and testing at higher levels of Bloom’s Taxonomy (Bloom, 1956)...)
As in Stice's case, most professors who are good at teaching have become so by virtue of trial-and-error, having little or no training or study in what he calls "the craft of teaching." This situation is compounded by the current academic incentive and reward system, under which research interests must take priority over teaching, and faculty who are outstanding teachers but merely adequate researchers are never granted tenure or are relegated to an inferior position (Felder, 1994).

Application of the Engineering By Design methodology is intended to influence the current situation in two ways. The first is for engineering professors to become aware of the issues of educational psychology. The methodology clearly does not provide training in those areas, but can at least increase awareness and point the way for those interested in improving student learning.

A second is in establishing a framework to support the partnership of engineers with teachers. As stated earlier, each party brings different knowledge to this partnership. Teachers stand to gain insight into the engineering design process and the application of scientific knowledge. Engineering educators, on the other hand, stand to benefit
from learning how the teacher approaches the educational process.

Here, educational psychology will be divided into four areas—development, learning, pedagogy, and individual differences. An overview of each area will be given and the impact on the Engineering By Design methodology will be discussed. The discussion primarily follows the structure of Slavin (1988).

**Development**

Prior to this century, continuous theories of development purported that children think as adults do, but lack the observation and practice which will allow them to reach the same conclusions. In this century, Piaget introduced the concept of development through stages, or discontinuous development. Since that time, stage theories have been generally accepted, and such theories have been developed in three realms of development: cognitive, social (and personal), and moral.
Cognitive Development

The best known theorist of cognitive development is Jean Piaget, a biologist who applied biological principles to the psychological studies which he began by analyzing the behavior of his own children (Slavin, 1988). Piaget's four stages are sensorimotor, preoperational, concrete operational, and formal operational. Here, the sensorimotor stage will be taken for granted, as that stage lasts from birth to two years, and students in the K-12 system have moved into the preoperational stage.

The preoperational stage

This stage lasts from age 2 to 7, and is characterized by a child's development of the ability to use symbols to represent objects. This includes at the early part of the stage the ability to understand the difference between an image (in a photograph, mirror, etc.) and the actual object, and in the later stages includes the mastery of using the alphabet and numbers.

Thinking at this stage is strongly influenced by egocentrism, and a child will normally assume that all
things exist to serve some purpose for them (Piaget and Inhelder, 1956). Egocentrism precludes the possibility of solving many problems, because it introduces such a large constraint (e.g. that any solution must involve the child) (Owen et al., 1981). In this stage, a child’s thinking is generally centered, or focused on a single characteristic at a time. For example, when comparing two objects for size, a child may focus only on the height, and assume the taller one is larger, regardless of the width of the shorter object.

In this stage, certain problem solving concepts are lacking. They do not understand conservation, demonstrated by pouring the same quantity of liquid from one container to one of a different shape. Children who do not grasp the principle of conservation are likely to think the amount of liquid has changed. The concept of reversibility is also absent. Reversibility is necessary to change the direction of a process to return to the original position. A child who does not understand reversibility will likely think that two halves of a sandwich are more sandwich than the whole. The logical processes with which we make conclusions based on such principles as reversibility and conservation are
called operations, hence the definition of this stage as pre-operational. A pre-operational child does not relate the previous experience of seeing the sandwich as a whole to the new experience of seeing it cut in four pieces (Phillips, 1975).

The fact that children move from this stage into the next, concrete operational, during the elementary years (at ~7 years of age) has significant implications. The SouthEastern Consortium for Minorities in Engineering (SECME) received a $260,000 grant in 1994 from the Carnegie Corporation to develop a K-5 model of their successful program which previously served only grades 6-12 (Leake, 1994). Since the younger students in that group are pre-operational, they require a very different approach. Those students, given the same information as those in the next stage, are likely to draw conclusions which have severe logical flaws (Piaget, 1962).

These same developmental considerations have affected the implementation of the Emerging Engineers after school curriculum materials designed by Dorothy Turner of the Alachua County School District (Turner, 1996). Mrs. Turner and I have found in field-testing the curriculum that the
younger elementary school children are overwhelmed by parts of the activities which children even a year or two older are able to grasp. As a result, the youngest are typically relegated to carrying out work (using only motor skills) as directed by their older peers. This does not imply that the activities are wasted on the younger children. Those children are still learning social skills, cooperation, teamwork, etc., while participating in a technical activity. They are not, as are the older children, engaged in the more advanced process of problem solving.

The concrete operational stage

This stage is characterized by a child's development of the concepts of conservation and reversibility. In this stage, children are able to decenter their thinking, focusing on multiple parameters. Children can separate themselves from their surroundings, overcoming the egocentrism characteristic of the preoperational stage (Slavin, 1988). Because of these advances, children develop an increased ability to think logically (Phillips, 1975). This stage of development lasts from approximately age 7 to age 11.
One key to problem solving, the ability to infer, is developed during this stage as well. Pre-operational children will describe things only as they appear, whereas in this stage, children will use other information to draw their conclusions (Flavell, 1986). Other important skills which appear during this stage include inversion (negative/positive concepts), reciprocity (if Tom is taller than Sally, then Sally is shorter than Tom), and inclusion (the ability to compare part to whole) (Slavin, 1988). Knowing that these concepts are developing in children in this age range (through the end of elementary school) alerts us to target their development in the younger children in the range and their advancement in older children in the range.

Flavell (1985) describes this stage as one in which children take a very practical-minded approach to solving problems. This follows Piaget’s conclusion that abstract thinking skills are weak during this stage. This stage is therefore a crucial one for the use of hands-on activities. Children at this stage will have difficulty making any progress toward understanding any concept for which a physical model is not produced.
The formal operational stage

This stage lasts from approximately 11 years of age to adulthood. Here is where abstract thinking is fully developed. Individuals in this stage can approach problem solving systematically, analyzing one factor at a time (Inhelder and Piaget, 1958). In this stage, form is distinct from content, and conclusions may be drawn by analogy. Slavin (1988) indicates that formal operational ability permits individuals to consider hypothetical or potential situations.

Slavin’s wording identifies an important issue—if children cannot discern potential situations, can they be taught such concepts as potential energy (and its conversion to other forms)? What about changes of states of matter? What it does tell us is this: if we are to teach such subjects to children before the formal operations stage, we must use concrete examples which demonstrate the process. Dry ice, for example is a solid, but there is visible evidence of the sublimation process. Such examples will be the hallmark of successful teaching prior to the formal operational stage.
Comments on Piaget’s theory

While Piaget’s theory is clearly still at the forefront of the study of human development, other researchers have sought to clarify and question his theory. Gardner (1982) and Price (1982) demonstrated that it may be possible to teach some principles (such as conservation) to children prior to the concrete operational stage. Other researchers (Donaldson, 1978, Black, 1981, Gelman, 1979, and Nagy and Griffiths, 1982) showed that there are early signs of some Piagetian principles, even though the principles may not be fully developed.

Other parts of Piaget’s theory have been challenged (Miller, 1983 and Nagy and Griffiths, 1982), but there are still clear lessons to be learned. Most important are the significant differences of which we must be aware when working with children of different ages. Elementary school children, for example, cannot simply be taught with an oversimplified version of a middle or high school lesson. Instead, the entire educational approach must address their cognitive level. On the other hand, since by middle school most students will have entered the formal operational stage, we can expect quite a lot from them. A well posed
design activity has the ability to stimulate a great deal of learning even at that age, because the tools needed for problem solution are fully developed. All the middle school student lacks is experience and knowledge, which vary greatly anyway. Therefore, if a design project begins by giving formal operational students the opportunity to observe phenomena themselves, they should be able to draw valid conclusions in order to proceed.

**Personal and Social Development**

Education, especially higher education, is primarily thought of as the champion of cognitive development. Social development is also of tantamount importance throughout the education process. Such skills as teamwork and interpersonal communication depend heavily on social development. Issues of underrepresentation of women, minorities, and even people of certain thinking types all have roots which extend into the realm of social development.

As was the case in cognitive development, the prominent theory here is a stage theory. Personal and social development consists of the development of an individual's
relationship to self, other people, and society. Sigmund Freud may be best known in this field, but Erikson, trained as a psychoanalyst by Freud, identified eight stages in this realm of development. Table 2 lists Erikson’s eight stages and the psychological crisis which must be resolved at each stage (Slavin, 1988, p.38).

### Table 2 Erikson’s Stages of Personal and Social Development

<table>
<thead>
<tr>
<th>Stage</th>
<th>Approximate Age range</th>
<th>Psychological Crisis</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Birth-18 mo.</td>
<td>Trust vs. Mistrust</td>
</tr>
<tr>
<td>II</td>
<td>18 mo.-3 yr.</td>
<td>Autonomy vs. Doubt</td>
</tr>
<tr>
<td>III</td>
<td>3-6 yr.</td>
<td>Initiative vs. Guilt</td>
</tr>
<tr>
<td>IV</td>
<td>6-12 yr.</td>
<td>Industry vs. Inferiority</td>
</tr>
<tr>
<td>V</td>
<td>12-18 yr.</td>
<td>Identity vs. Role confusion</td>
</tr>
<tr>
<td>VI</td>
<td>Young Adulthood</td>
<td>Intimacy vs. Isolation</td>
</tr>
<tr>
<td>VII</td>
<td>Middle Adulthood</td>
<td>Generativity vs. Self-absorption</td>
</tr>
<tr>
<td>VIII</td>
<td>Late Adulthood</td>
<td>Integrity vs. Despair</td>
</tr>
</tbody>
</table>

When cognitive stages were discussed, the one occurring prior to elementary school was not discussed. Here, even the first two must be discussed, because the way in which each individual resolves each crisis affects their approach to problems later in the educational process. Stages VI on, however, will not be covered. It should be recognized that
those later stages may have implications regarding continuing education, which is not the focus here.

**Trust vs. mistrust**

In this stage, the child should learn to trust (Erikson, 1968). This trust is generally founded in a maternal figure. If a child’s mother does not meet the child’s needs of love, stability, and security, the child is likely to develop a mistrust in the world. In education, this will lead to a variety of attitudes, e.g.: skepticism, cynicism, and negativism.

**Autonomy vs. doubt**

During this stage, children seek independence and autonomy. Supportive parents will help a child develop a sense of autonomy within bounds. If a child is not encouraged to do this, or worse, restricted so that he or she cannot do this, the self-confidence of the child suffers. Children who do not successfully resolve the crisis of this stage are hindered in the development of their self-esteem and leadership skills.
Initiative vs. guilt

This stage brings with it relentless exploration of relationships and the world. Not surprisingly, the end of this stage closely corresponds to the beginning of Piaget's concrete operational stage of cognitive development. It is likely that the exhaustive exploration of one's surroundings that permits the cognitive transition to take place. Erikson characterizes the child's attitude in this stage as "I am what I can imagine I will be" (Erikson, 1980). What Erikson indicates that failure to resolve this crisis properly causes children to feel guilty about natural impulses (Slavin, 1988).

The term "guilt" seems inadequate to describe this result. The more natural negative consequence is timidity—reluctance to explore, fear of the new, distaste for change. These outcomes lead directly to significant barriers to thinking, and can have wide ranging effects in the educational process. On Erikson's time scale, children will enter the K-12 educational system before this stage ends, and so the early years of elementary school are a venue for fostering the more positive outcomes. Discovery learning (Bruner, 1966), which aims at the development of
Piagetian principles and concepts, is also well supported by Erikson’s theory.

Considering the importance of nurturing the exploration phase of development, this clearly supports the implementation of such programs as Head Start (Department of Health and Human Services, 1996), founded in 1965 by the Federal government, which can provide a discovery environment for children who are otherwise at an economic disadvantage.

**Industry vs. inferiority**

A time of tremendous learning, this stage finds children learning much by trial-and-error, since their logical processes are not yet developed. It is at this stage that the use of failure as a tool for learning must be emphasized. Otherwise, children may focus on the failure, which will stunt their continued learning. Since this stage is from 6 to 12 years of age, elementary school is the time to ensure this message is taught clearly to students.

Activities at this level should allow children to explore false paths as rigorously as true ones, and provide only the most basic problem structure. It is important,
when evaluation is performed, that unsuccessful attempts are praised for their merit as learning tools. Since children in this stage generally enter this stage believing that they can and will succeed (Entwistle and Hayduk, 1981), the most critical challenge is to provide for multiple paths to success and multiple measures by which success is measured (Cohen, 1984).

Enhancing children's understanding that there are multiple paths to success will also strengthen their creative thinking skills, since they will be encouraged to seek alternative solutions.

Identity vs. role confusion

It is the nature of this stage of development which makes many afraid of working with middle school students. With the variety of physiological changes that occur from 12 years to 18 years comes a redefinition of the identity established through the earlier stages. At the beginning, the independence that an adolescent seeks causes them to experiment socially, at times adopting severe and anti-social behavior. There is also a characteristic heightening of the importance of the relationship to peers. Under such
conditions, parental influence diminishes, and peer influence, both positive and negative, can have a significant impact on development.

This stage continues to the end of high school, when the final part of identity is established as students choose career paths. If students do not establish a strong sense of identity through this stage, they will suffer from what Erikson terms "role confusion." The increased role of the peer group in this stage indicates that group activities are vital as well. Cooperative learning strategies, discussed later in this chapter, will help focus adolescents toward success as part of a team.

**Moral Development**

Although at first this seems irrelevant, especially in an educational system so shaped by secular humanism, there is much of moral development which affects the educational process. Moral development will not only find impact in ethics, which should be integral with the engineering process, but also in the nature of "rules" and how they are interpreted. Morals also have bearing on social
interaction, and are thus an issue for developing cooperation, especially in a pluralistic society. In addition to his work in cognitive development, Piaget (1964) studied this facet of development. Piaget’s theory of the moral reasoning was extended by Kohlberg (1963, 1969).

Piaget’s theory accounts for only two stages of moral development, formed by watching children play marbles. The children’s reasoning concerning the rules of the game yielded insight into their moral development. The first stage, called heteronomous morality, begins at approximately the point at which children make the transition from preoperational to concrete operational thinking. Prior to this stage, the children’s concept of rules was not fully formed. The youngest children did not know what rules were, and those up to approximately age 6 did not grasp the purpose or nature of rules. Piaget therefore assumes that morality is not possible prior to that stage, since the concept of rules is not even understood. A brief discussion of the two stages follows.

The first stage, heteronomous morality, is dominated by moral reasoning which is imposed by consequence. Rules are seen as inflexible, and are enforced by an external
authority. The second stage, autonomous morality, arises when the egocentrism of younger children gives way to the concern for others. Here, fairness is expected, and rules are can be flexible but should be agreed upon. In the second stage, intent becomes as important or more important than the action itself.

Further conclusions regarding the impact of moral development on the educational process will be made on the basis of Kohlberg's theory, summarized in table 3.

<table>
<thead>
<tr>
<th>Level/Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preconventional Level</td>
<td>Rules are set down by others</td>
</tr>
<tr>
<td>Stage 1</td>
<td>Punishment and obedience orientation</td>
</tr>
<tr>
<td>Stage 2</td>
<td>Instrumental relativist orientation</td>
</tr>
<tr>
<td>Conventional Level</td>
<td>Individual adopts rules and will sometimes subordinate own needs to those of the group</td>
</tr>
<tr>
<td>Stage 3</td>
<td>&quot;Good Boy-Good Girl&quot; orientation</td>
</tr>
<tr>
<td>Stage 4</td>
<td>&quot;Law and Order&quot; orientation</td>
</tr>
<tr>
<td>Postconventional Level</td>
<td>People define own values in terms of ethical principles they have chosen to follow</td>
</tr>
<tr>
<td>Stage 5</td>
<td>Social contract orientation</td>
</tr>
<tr>
<td>Stage 6</td>
<td>Universal ethical principle orientation</td>
</tr>
</tbody>
</table>
Note that Piaget’s two stages are encompassed by Kohlberg’s three levels of two stages each. Whereas Piaget studied the moral implications of children at play, Kohlberg analyzed their responses to moral dilemmas, hypothetical situations which force an individual to make moral decisions.

**Preconventional level**

Stage 1 of this level is similar to Piaget’s heteronomous stage, and is characterized by obedience to avoid punishment. In stage 2, however, children grow to include the consideration of the interests of others, although their own interests will normally still take precedence. According to Kohlberg (1969), this stage can last until age nine.

During the early years of elementary school, therefore, we must assume that students will not consider the benefit of their classmates in their decisions. The result of this is that activities which involve younger elementary school children should have clear consequences and rewards.

In the later elementary years, in stage 2, we can make more significant progress in the development of teamwork
skills. One example of the application of this would be in the sharing of equipment during an activity. Clear rules as to how the equipment is to be shared should be established ahead of time.

**Conventional level**

Stage 3 is the first of the conventional level, which is very similar to Piaget’s autonomous state. Acceptance is important in this cooperative stage, and is gained by finding those things that please others. Hogan and Emler (1978) describe this stage as focusing on the "Golden Rule." Since students in this stage are able to assume the perspective of others, they can modify their behavior for the benefit of their team, their class, the teacher, and others. This stage is not surprisingly concomitant with the onset of the adolescent strengthening of peer relationships described by Erikson. The combination of this stage of moral development and the simultaneous stage of social development make this the most critical time to develop teamwork skills.

Stage 4 heralds the replacement of the “rules of the pack,” which govern peer acceptance, by the rules of
society, or laws. During this stage, it is assumed that breaking the law is always wrong. The effects of peer pressure are strong until the social stage of young adulthood and, as a result, this stage may not begin until that time. As educators, we must encourage this stage to develop, and strive for ushering the next level of moral reasoning. According to Slavin (1988), fewer than 25% of the population will advance beyond stage 4.

Postconventional level

This level, the most advanced, recognizes that laws can be changed and are subject to a higher set of ethical principles established by the individual. After his original work (1969) Kohlberg later concluded that there is little separation of stage 5 and stage 6 (Slavin, 1988). This stage is necessary for influencing and evaluating the existing laws. This level of moral reasoning will be necessary to evaluate some moral dilemmas presented in engineering issues. To prepare students for such tasks, we must ensure that they advance to the postconventional level. This can be done by discussing laws and their purpose, as well as through the examination of moral dilemmas.
Overall Effect of Developmental Stages

The presence of some stages will limit the nature of the activities which are appropriate for students. In other cases, we must keep in mind the developmental level of the students to make sure we expect them to strive, but not to make objectives so far ahead as to cause frustration. With respect to Erikson’s stages of social development, understanding the crises that can be anticipated throughout a student’s development not only helps us as educators to direct that development, but also to understand certain behaviors exhibited by students.

Learning

Learning, as opposed to development, depends on experience. Learning and development are clearly intertwined, but the distinction is intended to separate those parts of a child’s growth which we can affect (learning) from those which we cannot (development), which result from the physiological maturation of the human brain. A child is constantly experiencing many things: the
temperature in the room, the clothing choice of the student next to them, the noise made when they tap their feet on the tile floor, and even the voice of the teacher. These pieces of experience going on all around a student are known as *stimuli*. Of the many stimuli we are bombarded with at any one time, we only consciously notice a small portion. For example, predictable, repetitive noises, such as an air conditioner or a clock, which can easily be heard, become relegated to the subconscious.

How stimuli are internalized is the subject of various learning theories. Learning has been viewed from two primary perspectives, behavior and cognition, leading to two branches of learning theory.

**Behavioral Learning Theory**

The focus of behavioral learning theories is the way in which positive or negative consequences can be used respectively to encourage and discourage certain behaviors. Because such behaviors are readily observed, such as the completion of homework, research in this field frequently focuses on the behavior of animals.


**Conditioning**

Pavlov’s classical conditioning theory is well known (Pavlov, 1960). An unrelated stimulus (such as the ringing of a bell) can be associated with a positive consequence (the presentation of food) for a dog. As a result, the dog can be conditioned to salivate when the bell is rung, regardless of the presentation of food. While Pavlov’s work stimulated new directions in learning research, it has little application here, because if the researcher continues to ring the bell without the presentation of food, the conditioning will be lost.

Thorndike (1932) similarly proposed the Law of Effect, stating that actions rewarded by positive consequences are reinforced and actions resulting in negative consequences are discouraged.

Whereas Pavlov and Thorndike examined situations where there was a clearly desirable stimulus involved, Skinner established an environment where there was no clear positive consequence, much like a child growing up in its environment. Skinner placed rats in a box with all stimuli controlled by the experimenter. A bar which could be pressed by the rat was present in the box. Although the rat
cannot anticipate any pleasant consequence from pressing the bar, the rat does it anyway, as a child will explore his or her surroundings. Upon pressing the bar, the rat receives a food pellet. This consequence reinforces the rats behavior, making the rat more likely to press the bar. Experiments involving what is now known as the "Skinner box" and those which followed have led to the development of the classification of various learning principles which follow.

**Consequences**

Consequences are the results of behavior. Positive and negative consequences are referred to as *reinforcers* and *punishers* respectively.

**Reinforcers.** It is the effect of a consequence that defines that consequence as a reinforcer—it must encourage the original behavior to recur. As a result, a particular consequence which is observed to function as a reinforcer may not continue to function as a reinforcer indefinitely. For example, while a hug from a teacher may be an excellent reinforcer in elementary school, it is not generally effective in the adolescent years. It is also the case that
reinforcers which work for one individual will not necessarily work for another individual. While playing in the tub may be a reinforcer for some children, but not particularly useful in reinforcing the behavior of a cat.

Reinforcers can be either primary or secondary. Primary reinforcers are those which satisfy basic needs, such as food, water, love, and security. Secondary reinforcers are consequences which are assessed an importance because of a relationship which has been established to a primary reinforcer. For example, praise is a secondary reinforcer, because it can enhance a child's security.

Reinforcers can also be categorized as positive or negative. Positive reinforcers are most common—pleasant consequences to encourage good behavior. Negative reinforcers are, on the other hand, exemptions from unwanted responsibilities.

**Punishers.** Consequences intended to discourage a specified behavior are considered punishers. These are not the same as negative reinforcers, which reinforce good behavior by allowing children to avoid something seen as
negative. Just as with reinforcers, it is success in stopping the unwanted behavior which proves a consequence to qualify as a punisher. If a selected consequence gives an adolescent perceived status among his or her peers, the consequence will serve as a positive reinforcer of the unwanted behavior, rather than as a punisher.

Although punishers have been shown to be effective (Hall et al., 1971), it is generally agreed that punishers should only be used when attempts at reinforcing the corresponding appropriate behavior have failed (Slavin, 1988).

**Immediacy of consequences**

The time relationship of behavior and consequences is obviously very critical. If the food pellet were delivered to the rat in Skinner's experiment even a single minute after pressing the bar, the rat might be doing something else (like walking around) at the time, and the latter behavior would be reinforced instead. It is clear that to be most effective, consequences should follow behavior immediately or as quickly as possible (Leach and Graves, 1973).
One way in which this affects design activities was discussed earlier—when students design a solution to a problem, it is very important for them to proceed to implementing the solution, in order to experience the consequences of their design. If implementation is not possible, then some form of feedback should substitute for it. This may take the form of having student teams give presentations of their designs with evaluation by the teacher.

**Shaping**

Shaping is the process of reinforcing the behaviors which are intermediate steps toward an established goal. This is common even in higher education—first students are taught and tested in drawing free-body diagrams, then internal forces can be analyzed. If an instructor moved directly into analyzing internal forces without verifying (through homework and/or testing) student understanding of free-body diagrams, misconceptions would persist and hinder student progress. The key in shaping desired behaviors is that the final goal is broken down into steps which stretch the skills of the students, but do not cause the students to
be overwhelmed. Shaping, therefore, requires knowledge of the current level of the students.

**Extinction**

Of course, any learned behavior will diminish and eventually become extinct if reinforcement for it is completely withdrawn (Williams, 1959, Wolf et al., 1965, and Zimmerman and Zimmerman, 1962). This is good news in the case of negative behaviors which have previously reinforced, such as behaviors learned with previous teachers and habits formed in the K-12 system which are no longer adequate in higher education. Ideally, for all positive behaviors and learned skills, new reinforcers naturally occur. The same, of course, occurs with skills, which dull if not exercised.

**Discrimination**

To achieve a desired goal, the students must know what it is. For grades to serve as an effective reinforcer, students must know what is expected to receive a good grade. This allows the student to discriminate between the actions which will or will not contribute to their grade.
Generalization

A shortcut to learning new concepts is generalization from previous learning. Generalizations might not occur naturally, however, and should be identified wherever possible. In creating an activity, the designer should seek something from the students’ own experience in which to ground the activity. This will permit the generalization of the knowledge the students already possess.

Modeling

Modeling is the process by which students learn by watching others. Bandura (1969, 1977) proposes that humans learn much by example rather than by consequences. There are many applications of this principle. If a teacher is enthusiastic about introducing a design project, students will be more enthusiastic about doing it.

This principle is effective to the point that students will imitate other students whose behaviors are reinforced. Thus reinforcing any student in a group is beneficial to the group as a whole. This principle is known as vicarious learning (Broden et al., 1970). A critical application of this principle is when students ask questions. If the
behavior of asking questions is reinforced, all the students will be more likely to ask questions.

**Self-regulation**

Students are also able to reinforce their own behavior (Meichenbaum and Goodman, 1971, Meichenbaum, 1977, Wilson, 1984, Kendall, 1981, Bornstein, 1985, Drabman et al., 1973, Rosenbaum and Drabman, 1982, and Broden et al., 1971). This is best done by providing the students with a list of intermediary objectives (or by having them develop their own list) to use as a checklist to monitor progress.

**Other applications of behavioral learning theory**

The lessons of how to reinforce good behavior are of obvious importance when we work with younger children, but it has generally been assumed in higher education that our students are self-motivated. Increasingly, this is not the case. As a higher percentage of the population seeks college instruction, many students drift into higher education simply because it is expected. The most common reinforcer in higher education is the use of grades. Grades are a secondary reinforcer, because they have no intrinsic
value—their value must be taught. Grades can also be a punisher, because a student who does not achieve certain grades may have to take courses again or not be able to pursue desired courses or even a major. Grades also generally do not satisfy the immediacy of consequences principle, either. Periodic (but not necessarily predictable) quizzes or other assessment can help. Returning assignments quickly is also important.

The other principles find similar application in higher education, especially in today's climate, in which such a large percentage of the population matriculate in college. Self-regulation is the best objective for higher education, but students must be taught that process if they have not learned it in the K-12 system.

**Cognitive Learning Theory**

There has been a great revolution in the study of cognitive learning since World War I (Slavin, 1988). Concepts such as short term and long term memory are commonly understood to the extent that they are important here. Therefore, this section will only discuss those
principles which can be affected through activity design. This will include barriers and facilitators to learning which have been studied by cognitive researchers, especially those which encourage long-term retention of learned information.

Interference

This is a common barrier to establishing information in long-term memory (Postman and Underwood, 1973). Peterson and Peterson (1959) showed that people permitted to absorb information without being disturbed were more likely to retain it than people who were given more information during an equivalent amount of time. This indicates that simply pausing while information is mentally rehearsed and passed from short-term to long-term memory is of educational benefit. Other ways to encourage the transfer of information from short-term to long-term memory is through repetition, including applying new information to a novel situation.

Retroactive inhibition is the process of confusing new information with information previously learned. For example, many students in high school physics have no
problem learning and applying the right hand rule until the left hand rule of other phenomena is introduced later. When the right hand rule is the only choice, students are able to apply it. After the new information is introduced (the left hand rule) and the students must choose which rule to apply, retroactive inhibition causes them to lose the ability to apply the original rule (until they master both concepts together). The key characteristic here is the loss of previous information or skills.

Proactive inhibition is characterized by the interference of learning new information because of previously learned information. If the response in the above case was that students continued to use the right hand rule in all cases, the case would be one of proactive inhibition, because the previous information was retained, but prevented the learning of new information (the left hand rule). Inhibition can be minimized by varying the presentation technique when presenting different material (Andre, 1973 and Andre et al., 1976).

Retroactive and proactive facilitation can also occur. Slavin (1988) uses the example of learning foreign languages. An American student who studies Latin might
better understand English through the process. This would be an example of retroactive facilitation. If, on the other hand, a student found that the study of one romance language (Italian, say) facilitated the study of a second romance language (e.g. Spanish), this would be an example of proactive facilitation.

**Primacy and recency**

Another useful piece of information is that if a number of concepts are learned, those at the beginning and the end are retained best (Stigler, 1978, Rundus and Atkinson, 1970, and Greene, 1986). This has profound implications for the structure of a planned activity or lesson.

**Mnemonics**

There are many techniques to improve the process of transferring information from short-term to long-term memory. Such techniques are called mnemonics (Higbee, 1979). Among the best are those that rely on imagery (Anderson and Hidde, 1971). For example, when I present the *Truss Bridge Laboratory* (the prototype design activity discussed in the next chapter) to adult groups, I ask them
to recall the meaning of truss they already know.\textsuperscript{7} By doing this, I have given them a mental image which gives insight to the function of a truss in the engineering sense of the word—to support or gird up. This technique would not be effective in teaching Introduction to Engineering, however, as the majority of freshmen will not be familiar with the former meaning.

\textbf{Practice}

Earlier it was discussed that allowing time for mental rehearsal helped students transfer information from short-term to long-term memory. Not surprisingly, overt practice has an even greater effect. The kind of intensive practice involved in cramming for a test is known as \textit{massed practice}. This example immediately identifies the greatest failing of the method—although initial mastery is facilitated by this approach, long-term retention is best achieved through \textit{distributed practice}. In distributed practice, concepts are practiced a little each day over a period of time. This,\textsuperscript{7}

\textsuperscript{7}"A device consisting of a pad usually supported by a belt for maintaining a hernia in a reduced state." Random House Webster's Electronic Dictionary, College Edition, version 1.5, 1994.
obviously, is the intent of homework. Another interesting point is that students benefit from continued practice after mastery has already been achieved. This is known as overlearning (Krueger, 1929), a principle which has led to approaches such as drilling of basic facts.

**Organization**


Instructors at all levels generally recognize the benefit of organizing their lessons. Less understood, however, is that students benefit immensely from having that organizational layout shown to them. Hierarchical outlines are very effective in this regard. When hierarchy is not well suited to the material being covered, even an agenda is helpful. This coordinates well with the principle of self-regulation discussed within behavioral learning theory—if
students are informed at the outset of the objectives of a lesson, the path they should take to succeed is clearer. 

**Common elements of cognitive principles**

There are many other approaches to improve learning. Questions can encourage students to fill in gaps or anticipate what might happen (Felder, 1988, Rickards, 1979, Berliner, 1968, and Rothkopf, 1965). Questions presented prior to instruction can narrow students' thinking, however (Hamilton, 1985 and Hamaker, 1986). Also important is that questions not imitate the instructional material, but manipulate it so as to force students to think about it (Andre and Sola, 1976 and Andre and Womak, 1978). Having students assess important issues through outlining (Anderson and Armbruster, 1984 and Van Patten et al., 1986) or summarization (Doctorow et al., 1978 and Brown et al., 1983) are also effective.

The key to the principles mentioned here and others (Slavin, 1988) is that a higher level of processing of 

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*The same principle applies to research subjects, as will be addressed in chapter 5; knowing the expected outcome of the research can influence their behavior.*
information seems to root that information in the long-term memory. Specific identification of higher levels of processing will follow in the next section. Different students will respond to different approaches. This makes it important to understand and to be able to use the many approaches detailed above. A deeper understanding of the differences among children will also be helpful. These differences will be discussed in greater detail in the next section as well.

**Pedagogy**

Pedagogy is the study of teaching. There are two main issues here—deciding what to teach and how to teach it. The process of selecting what to teach begins with society’s needs and ends in the classroom. How to teach begins with educational research and can include formal training in educational methods. The discussion here will begin with how educational aims, statements of what to teach, are developed.
Educational Aims

In formulating what we are to teach, we must eventually develop specific instructional objectives and standards by which mastery is to be measured. Because they are so important, instructional objectives are the first order of instruction discussed by Slavin (1988) and others. The process does not simply begin with instructional objectives, however. Formulating more general goals is an important step, and is included by Kubiszyn and Borich (1993). Especially since the goal stage is incorporated into the Engineering By Design methodology in chapter 4, the early stages of the “what to teach” process will be discussed further here.

Goals

Goals are the most general specifications of desired educational outcome. “To learn archery” is a goal, but in no way describes the teaching method or the mastery level students are expected to achieve. This is what sets goals apart from instructional objectives. Because they are not specific, goals have a number of interesting properties—they
do not change rapidly; they are usually established at a high level, such as by society, by the school board, by the American Society of Engineering Education (ASEE), by the Accreditation Board of Engineering and Technology (ABET), etc.; and they provide a great deal of flexibility. More examples of goals are given in the design of the methodology in chapter 4.

General educational program objectives

These objectives are more specific than goals, but not as specific as instructional objectives. They have more focus than goals, and are measurable, but are still broad with respect to outcomes and time scale. In the public school system, these are generally established by the school administration in response to school board goals. In higher education, these are set at the college or departmental level.

Instructional objectives

Paramount in teaching is the establishment of instructional objectives. Objectives identify what is to be taught. The may specify factual information, skills,
concepts, behavior, and anything else that might be taught. Implicit in the design of instructional objectives is that their outcomes be measurable. Because they are so specific, they may be directed toward individuals or groups within a class. Instructional objectives are therefore developed by the teacher, but must still be in line with the educational program objectives and the goals which have already been established.

An example using all three levels of educational aims

The Hands-On Institute of Science and Technology (HOIST) was a one-week residential summer institute attended by 33 high school students. Examples of all three levels of educational aims are included below as appropriate to that summer institute.

Goals:
1. To broaden awareness of engineering.
2. To foster problem solving skills.

Educational program objectives:
1. By the end of the institute, students will be able to name and describe at least 7 engineering disciplines.
2. Students will work cooperatively in teams of three or four to design and build at least 5 projects.
3. Students will be permitted at least two hours of social time each day to develop relationships with their peers.
Instructional objectives
1. Given a list of constraints, student teams will design and construct a container to protect an egg from breaking when dropped.
2. Student teams will have one day to select and procure their own materials for their design.
3. Student teams will analyze unsuccessful container designs to determine at least one reason for the container’s failure.

Note how the ability to measure the objectives increases in the later stages. A clear understanding of the instructional objectives is essential to appropriate assessment.

Bloom’s Taxonomy of Educational Objectives

It was discussed earlier that the more students process information, the more likely they are to retain it. One way of increasing a student’s level of processing is through repetition. Another is through the use of higher level thinking skills. Bloom et al. (1956), divided educational objectives into six categories of thinking skills, in ascending order of complexity. The six categories are shown below. Many authors simply list these in order (e.g. Slavin, 1988 and Howard et al., 1996), which tends to trivialize the importance and abundance of the lower levels.
The figure above is a more accurate representation of the overall nature of educational objectives. Although those at the top indicate higher level thinking skills, those at the bottom are needed in great quantity to provide support those at the top. Kubiszyn and Borich (1993) provide action verbs at each level to help clarify objectives. Their lists are included in each section.

Knowledge

At the knowledge level, memorization is required. This can include remembering a process as well as facts. Although this is the most basic skill in the hierarchy, it is also the most fundamental. Language itself is rooted in knowledge, because the letters of the alphabet and even the words assigned to objects are arbitrary. Kubiszyn and
Borich (1993) list the following action verbs: define, describe, identify, label, list, match, name, outline, recall, recite, select, and state.

**Comprehension**

Comprehension is distinguished by the ability to understand what has been committed to memory. For example, at the knowledge level, a student could identify one picture as a cat and another picture as a dog. At the comprehension level, however, the same student could explain the differences—thereby supporting his or her decision. Action verbs describing comprehension are: convert, defend, discriminate, distinguish, explain, extend, estimate, generalize, infer, interpret, paraphrase, predict, summarize and translate.

**Application**

Application requires using previously acquired knowledge to solve a problem. The essence of application is novelty, which forces the student to select which principles from their existing knowledge are related to the task at hand. Sample action verbs include: change, compute,
demonstrate, develop, employ, modify, operate, organize, prepare, produce, relate, solve, transfer, and use. Note that at this level, the action can be, and frequently is, non-verbal.  

Analysis

Analysis requires an understanding the underlying structure of a system. This can be achieved through organizing information or by breaking it down, to understand how all the information is related. Comparing and contrasting fit here if the comparison does not result in a value judgement. Appropriate action verbs are: break down, deduce, diagram, differentiate, distinguish, illustrate, infer, outline, point out, relate, separate out, and subdivide.

Synthesis

The synthesis level requires novelty of the student. Design is at this level, which makes the use of design

9"Verbal," in this case, indicates written or spoken. This definition is also used later when discussing learning styles.
activities educationally attractive. Synthesis will obviously rely heavily on the previous levels of thinking skills, since the new product will be a synthesis of what the student has already learned. Sample synthesis verbs are: categorize, compile, compose, create, design, devise, formulate, rewrite, and summarize.

**Evaluation**

Evaluation is the highest level of educational objective identified by Bloom and his colleagues. Some have disagreed to the ordering of these objectives, especially with respect to the last two, but the success associated with the application of Bloom’s principles reduces the concerns of ordering to more an issue of semantics. Inherent in evaluation is the need for a standard or criterion to serve as a basis for judgement. The criteria themselves may be defined by the student. Evaluation objectives are described by: appraise, compare, contrast, conclude, criticize, defend, justify, interpret, support, and validate.
Taxonomy of Affective Objectives

Krathwohl et al. (1964), also designed a taxonomy of objectives related to attitudes and values, or affective objectives. These are also relevant, because we frequently want to impart attitudes (toward learning, toward engineering, toward teamwork, etc.) through education. The five objectives are arranged in a hierarchy, as with the previous cognitive objectives.

Receiving (or Attending) simply indicates awareness at the lowest level, and willingness to listen at a higher level. Once a student is actively participating, either by request or by choice, that level is termed responding. At the highest level of responding, the student will clearly be engaged by and pleased with the activity. The next level is valuing, which proceeds through acceptance, preference, and commitment stages (Kubiszyn and Borich, 1993). Organization requires students to balance different values which conflict, such as wanting to encourage development, but prevent forestland destruction. The last level, characterization by value, requires a consistent set of values which is internalized such that all the student’s...
acts are directed by that value complex. Presumably, this level is similar to the highest level of moral reasoning postulated by Kohlberg (1969), in that not all individuals reach this level.

Effective Instruction

Slavin (1988) developed the QAIT model of effective instruction based on earlier work by Carroll (1963). Whereas Carroll’s model focused on all factors which account for the effectiveness of instruction, Slavin constrains the discussion to those which are in the purview of the instructor. The QAIT model recognizes four spheres of effective instruction where the instructor may have influence: Quality of instruction, Appropriate level of instruction, Incentive, and Time.

Quality of instruction is a measure of curriculum design as well as presentation. Appropriateness requires considering the developmental levels of students discussed earlier, but also depends on whether or not students possess the skills prerequisite to the lesson. Incentive is an affective concept, and so is regulated through the
principles of behavioral theory and measured against the affective objectives. Time is both a measure of time scheduled to teach and of time spent actually spent teaching. The next section will discuss how individual differences among students affect instruction.

**Individual Differences**

The impact of individual differences on instructional effectiveness is extreme. None of the four elements in the QAIT model is unaffected by the diverse aptitudes, attitudes, knowledge, skills, and learning styles of the students. Some of these can be influenced by an instructor. Aptitudes and learning styles cannot be modified in the short term, and so are parameters rather than variables in the learning process.

**Aptitude**

In higher education, differences in aptitude are somewhat constrained, since the United States does not yet have government-mandated higher education, as is the case
with the K-12 system. Although there is benefit to a heterogeneous ability level, which will be discussed more extensively when cooperative learning techniques are described, if ability differences are too great, it becomes too difficult to serve the needs of the students throughout the range.

**Between-Class Grouping**

A solution to differences in aptitude is to group classes on the basis of ability. In the K-12 system, this has led to groupings with varying terminology; "low-track," "middle-track," "high-track," "advanced," "honors," "remedial," "special education," and "gifted" are all such groupings, though the last two are beyond the normal variation of ability and are called exceptionalities. The other methods are all forms of what is known as tracking. Tracking methods are widely used and supported (Wilson and Schmits, 1978), although research shows that mild gains in achievement for "high-track" classes are offset by much larger losses in achievement by those assigned to "low-track" groups (Slavin, 1988).
In higher education, heterogeneity of ability is reduced through the choices students make during registration. Students can skip over certain prerequisite courses on the basis of prior experience, or take accelerated courses if they wish. College advising also plays a role in placing students in the classes appropriate to their abilities.

**Within-Class Grouping**

Ability grouping within a class to reduce heterogeneity (when desired) is also possible (Slavin and Karweit 1982 and 1985 and Goodlad, 1983). Research findings to support this approach are strong, because such groups can be changed as necessary (Weinstein, 1976), are focused on particular skills rather than gross ability measures, and do not have the same stigmatic effect, because students still identify with the class as a whole (Cohen and Anthony, 1982). When such grouping is used, research shows that defining two ability groups (and no more) is most effective (Slavin and Karweit, 1984, Spence, 1958, Dewar, 1964 and Walden and Vowles, 1960).
Learning Styles

There has been a great quantity of research on learning styles, thinking preferences, and personality types in the last century. As a result of trying to characterize such a complex system as human individuality, there is much overlap of these various characterizations. Redundancy even seems to be present to a degree within some of these typologies. The most common of these will be discussed here, with final and particular attention to those of Felder and Silverman (1988), which have achieved common usage in recent research in engineering education because of Felder’s engineering focus. All of these methods follow two basic principles—some number of bipolar descriptor pairs can be identified and all individuals will lie somewhere in the continuum between each bipolar pair.

These are included here rather than with the discussion on learning, because teaching styles closely parallel learning styles. Another factor which influenced the placement of this discussion is that the focus here is on the teaching methods needed to address the various learning types.
The Myers-Briggs Type Indicator (MBTI)

The MBTI was designed to assess and apply the psychological types identified by Jung (1923). First designed in 1942 (Myers and Myers, 1980), the MBTI was introduced formally in 1962 (Myers, 1962), and was well received as a valuable instrument for educational purposes. Extensive research on the MBTI (Conary, 1966, Myers and Davis, 1965, Ross, 1963 and 1966, Stricker and Ross, 1963, and Stricker et al., 1965) encouraged its use over the Gray-Wheelwright measure, developed concomitantly and also based on Jung’s types (Gray and Wheelwright, 1944, Grant, 1965).

The MBTI became further institutionalized through the efforts of McCaulley (1976, 1977, 1978), and gained recognition in engineering education in 1980, when a consortium of engineering schools sponsored by the ASEE Educational Research and Methods (ERM) division collected baseline MBTI data on entering students and tracked them (McCaulley et al., 1983). The ASEE-ERM study found that certain types—those more skilled in communication and teamwork—were not retained as well as other types. This finding indicates not only that the curriculum might be made more receptive to students preferring communication, but
also has implications for the remaining students, who especially need training in those areas.

Due to the strong influence of Myers-Briggs terminology on other typology research, the four bipolar attribute pairs identified by the MBTI are described in the table which follows (McCaulley and Natter, 1974). Each row indicates a bipolar attribute pair.

<table>
<thead>
<tr>
<th>Extroversion - person’s interest flows mainly to the outer world of actions, objects, and persons.</th>
<th>Introversion - person’s interest flows mainly to the inner world of concepts and ideas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensing - the person prefers to perceive the immediate, real solid facts of experience.</td>
<td>Intuition - the person prefers to perceive the possibilities, meanings, and relationships of experience.</td>
</tr>
<tr>
<td>Thinking - the person prefers to make decisions objectively and impersonally, analyzing facts and ordering them in terms of cause and effect.</td>
<td>Feeling - the person prefers to make decisions subjectively and personally, weighing values and the importance of choices for oneself and other people.</td>
</tr>
<tr>
<td>Judging - the person prefers to live in a planned, orderly way, aiming to regulate and control events.</td>
<td>Perceiving - the person prefers to live in a spontaneous way, aiming to understand and adapt events.</td>
</tr>
</tbody>
</table>

The Myers-Briggs typology has also reached considerable public notice in the Keirsey Temperament Sorter, a short
form of the MBTI. This 70-question test is included in a national best seller which has sold over 1.5 million copies as of 1984 (Keirsey and Bates, 1984). Keirsey has adapted the Jung-Myers typology to his clinical practice since 1955. As a result, Keirsey supports conclusions regarding the resulting 16 personality types with 40 years of clinical study of differences in temperament and character in mating, parenting, teaching, and leading. Since the test is self-scoring, it has even been adapted for use on the Internet ("Keirsey," 1996).

The Herrmann Brain Dominance Instrument (HBDI)

Whereas the MBTI is a measure of personality types, it is clear that the preferences measured by the MBTI influence students' approach to learning. Herrmann's work expands on the split-brain research which earned Dr. Roger W. Sperry a Nobel prize in 1981. While the work of Sperry and associates focused on left-brain/right-brain differences, Herrmann added the concept of brain dominance, discovering that individuals can have preferences in either mode.

Herrmann continued his work to develop a four-quadrant model of dominance, driven by the physiological structure of
the brain itself (Lumsdaine and Lumsdaine, 1995a). The hemispherical division of the brain into "left" and "right" accounts for the cerebrum, about 80% of the brain. The cerebrum controls vision, hearing, body sensation, intentional motor control, reasoning, conscious thinking and decision making, language and nonverbal visualization, imagination, and idea synthesis.

Each cerebral hemisphere surrounds one half of the limbic system, which controls hunger, thirst, sleeping, waking, body temperature, chemical balances, heart rate, blood pressure, hormones, and emotions. The limbic system is vital to the process of moving information into short- and long-term memory. By recognizing the contribution of the limbic system, which is also laterally divided, the four quadrant model was introduced.

The four quadrants were labeled alphabetically, and the preferences associated with the quadrants are as follows (Lumsdaine and Lumsdaine, 1995a, p. 80): A - logical, factual, critical, technical, analytical, and quantitative; B - conservative, structured, sequential, organized, detailed, and planned; C - interpersonal, kinesthetic, emotional, spiritual, sensory, and feeling; D - visual,
holistic, intuitive, innovative, conceptual, and imaginative.

The HBDI is useful for a number of purposes—by analyzing the brain dominance characteristics of successful individuals in different time periods, trends in national policy can be studied. Also, recognizing that the most effective teams will be those which have preferences in all areas present, the HBDI can assess to what extent a team achieves that end. Lumsdaine and Lumsdaine (1995a) detail a number of activities which are appropriate for practicing thinking skills in each of the four quadrants.

The Kolb Cycle and the 4MAT System

The Kolb cycle (Kolb, 1984) begins with a bipolar model of learning style, with two bipolar attributes. With only four possible combinations, a quadrant system is formed. The quadrants are not arbitrarily ordered, as is the case with Herrmann’s—instead, the Kolb quadrants are ordered as a cycle. The Kolb cycle is shown in the following figure.

The two bipolar attribute pairs are as shown—active/reflective and concrete/abstract. Kolb proposed that all learning passes through this cycle to
become internalized, beginning with the exploration of context in quadrant 1, proceeding to the integration of observation and existing knowledge in quadrant 2, on to practice and testing quadrant 3, and to speculating applications and improvements in quadrant 4.

McCarthy (1990) developed the 4MAT system of learning styles which seems primarily based on the Kolb learning cycle, although McCarthy credits other educational theorists as well. Through the 4MAT system, each quadrant is broken down into two parts with clear objectives for the educational process. The questions depicted in the
quadrants of the Kolb cycle are taken from 4MAT (McCarthy, 1990, p. 35). Whereas Lumsdaine and Lumsdaine (1995a) use the Herrmann model as the focus of whole brain teaching through creative problem solving, the Kolb model and the 4MAT system are also used in such a manner. Using McCarthy’s objectives, Harb and colleagues (1993) provide lists of appropriate activities characterizing each of the quadrants.

Stice, in reviewing the effectiveness of teaching through the Kolb cycle (1987b), indicates that retention increases as more of the quadrants are used, in apparent correspondence with Dale’s cone of learning (Dale, 1969, p. 107). This cone of learning, as developed and revised by Hyland, is used by Felder and Brent (1995, p. E4) in the Effective Teaching Workshop (Felder et al., 1992). Just as using higher level thinking skills will help commit information to long-term memory (Bloom et al., 1956), the higher a student’s level of active engagement while learning, the more the student will retain.

The essence of the cone of learning concept is that retention has been assessed for different levels of activity in a hierarchy from passive to active. Below, the most
critical information from the cone of learning is summarized. We tend to remember:

- 10% of what we read
- 20% of what we hear
- 30% of what we see
- 50% of what we hear and see
- 70% of what we say
- 90% of what we both say and do

This is an excellent supporting argument for active learning methods discussed later in this chapter.

**Felder's learning styles**

Through the *Effective Teaching Workshop*, Felder and Brent (1995) continue to spread the message of a set of learning styles and parallel teaching styles first proposed by Felder and Silverman (1988). Felder and Silverman characterize five elements of learning style: perception, input, organization, processing, and understanding. The corresponding five elements of teaching style are content, presentation, organization, student participation, and perspective. The bipolar pairs of learning and teaching style which bound the continua represented by those elements are shown in the table (Felder and Silverman, 1988, p.675).
Table 5 Felder and Silverman’s Learning and Teaching Styles

<table>
<thead>
<tr>
<th>Preferred Learning Style bipolar pair/element</th>
<th>Corresponding Teaching Style bipolar pair/element</th>
</tr>
</thead>
<tbody>
<tr>
<td>sensory perception</td>
<td>concrete content</td>
</tr>
<tr>
<td>intuitive</td>
<td>abstract</td>
</tr>
<tr>
<td>visual input</td>
<td>visual presentation</td>
</tr>
<tr>
<td>auditory</td>
<td>verbal</td>
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<tr>
<td>inductive organization</td>
<td>inductive organization</td>
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<tr>
<td>deductive organization</td>
<td>deductive organization</td>
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<tr>
<td>active processing</td>
<td>active student participation</td>
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<tr>
<td>reflective</td>
<td>passive</td>
</tr>
<tr>
<td>sequential understanding</td>
<td>sequential perspective</td>
</tr>
<tr>
<td>global</td>
<td>global</td>
</tr>
</tbody>
</table>

Felder and Silverman’s model is largely a synthesis of a number of other researchers’ approaches, with special attention to applications within engineering education. The sensory/intuitive pair corresponds to the same pair within the Jung/Myers-Briggs. To reach students with each of those learning styles, the corresponding teaching styles are concrete and abstract. These teaching style terms match one of the bipolar pairs in the Kolb model, and Felder and Silverman (1988, p. 676) acknowledge that the Kolb concrete/
abstract dimension is closely related to sensing and intuition.

They go on to define visual/auditory learners (1988) which was later redefined as visual/verbal (Felder and Brent, 1995), matching the corresponding teaching styles. The issue here is one of processing—that some students prefer to process picture-based input and others prefer verbal (spoken or written words) input. Information can also be organized inductively or deductively. The difference here is whether observation precedes general principle (induction) or phenomena are deduced from a general principle. Material which is already understood is organized most efficiently in a deductive manner. Unfortunately, this approach does not support learning as well as inductive methods (Felder and Silverman, 1988).

The active/reflective dimension is quite similar to the extravert/introvert defined by Jung and modeled by the MBTI. This dimension is concerned with how students process the information which they perceive, and therefore is independent of the sensing/intuition characteristic. Active learners process new information by doing something with it, through experimentation or relating to others. Reflective
processing is characterized by reconciling and reviewing the material internally.

At first, it appears that if "active" is a learning style, then the active methods suggested by Dale (1969) are likely only effective with those individuals. This highlights the difference between the learning style and the teaching style. The learning style pair, as stated earlier, refers to a preferred processing method, not to appropriate teaching methods. Even students who are inclined to reflect more on what they are doing will learn better through active teaching methods, so the engineering classroom must be a blend of the time-efficient passive and the more learning-effective active teaching approaches.

The final dimension of the Felder and Silverman model represents understanding and perspective. Sequential learners essentially learn information in order, mastering complex material in stages. Global learners, on the other hand, may appear to be lagging behind the sequentials and then make leaps of understanding, possibly unable to display any understanding at all prior to making the leap (Silverman, 1987).
Comprehensive models of learning style

Dunn et al. (1989) denounce the bipolar models in favor of what they refers to as a "comprehensive model," which serves as the basis of the Learning Style Inventory (Dunn et al., 1985) and similar models (Hill, 1971, Keefe et al., 1986). Dunn and her colleagues begin by approaching the problem from a holistic perspective, identifying four broad categories of effects on learning, each with subcategories. These are: "a. Immediate environment (sound, heat, light, and design); b. Own emotionality (motivation, responsibility, persistence, and structure); c. Sociological needs (self, pairs, teams, peers, adults and/or varied); and d. Physical needs (perceptual preferences, time of day, food intake, and mobility)" (Price et al., 1977).

However, when measures are defined based on the attributes encompassed by the Learning Style Inventory model, they generally take on the same form as the bipolar attributes of the other models, e.g. sound—quiet/sound preferred; light—bright/low; temperature—cool/warm; design—informal/formal. In effect, therefore, what Dunn refers to as a comprehensive model is primarily a bipolar model which considers a much large number of attributes.
Even those attributes which are measured more continuously, such as time of day preference—morning/late morning/afternoon/evening, are essentially shining light on the gray areas of the bipolar "morning person" and "night owl." As a result, the Learning Style Inventory model can be reduced to an 18 attribute bipolar model.

Clearly, the Learning Style Inventory model is significantly more complex than those of Felder and others. As stated earlier, Felder's learning styles yield 32 ($2^5$) individual combinations. In contrast, the model of Dunn et al., yields 262,144 ($2^{18}$) such combinations. Since in the educational system of the United States there are 47 million students, presumably all unique, the Learning Style Inventory gains almost four orders of magnitude on the target value. The purpose of such a model, of course, is to reduce the complexity of the original problem enough to make it manageable, while still retaining enough of its core to make the solution meaningful, and the model of Dunn et al., seems excessive.

The research of Dunn et al., serves a better purpose, however, in that it identifies trends of certain attributes over time and also identified certain gender differences in
the measured attributes. In addition, it identifies certain important parameters for classroom design. It seems appropriate that the Learning Style Inventory (and similar models) be used only in such studies. The educational process is overly complicated by attempts to vary the room temperature or lighting conditions to optimize student learning.

Why and How to Teach to All Learning Types

As discussed in chapter 2, different approaches are necessary to identify the best solutions in problem solving. In fact, some problems may require a variety of perspectives to find any solution at all. Westcott and Ranzoni (1963) studied groups of college students and correlated many factors with their approaches to problem solving. While aptitude and academic achievement were not adequate predictors of problem solving style, personality differences had a significant effect. This is confirmation that students with different learning styles are the harbingers of new approaches to the problems that "traditional" engineers seek to solve.
Felder and Silverman (1988) note the benefits that students with various learning styles can offer the engineering profession. However, it has been shown that certain of the styles are favored by traditional teaching methods, and simple but critical changes in teaching style can provide students with all learning styles an improved education. Outside of laboratory work, the engineering curriculum is most commonly lecture and reading oriented. Such a format favors intuitive learners, since they are more comfortable with symbols, bearing in mind that words themselves are comprised of symbols, as are equations, obviously.

Engineering students are more commonly of the sensing preference (McCaulley, 1976), and yet other research (Godleski, 1984) demonstrates the inevitable outcome of the curriculum bias—that intuitors consistently received higher grades. Characteristics of sensing individuals which are essential to the engineering function include (Felder and Silverman, 1988): "an awareness of surroundings, attentiveness to details, experimental thoroughness, and practicality." To address the needs of both sensors and intuitors, both concrete examples and abstract concepts must
be included in the engineering curriculum and in the design activities which are the focus here.

Visual learners remember pictorial representations of all kinds—graphs and diagrams as well as demonstrations and pictures. Visual learners are in the vast majority from college age on (Felder and Brent, 1995), yet teaching is generally dominated by the written and spoken word. Here, as per Dale (1969), it is clear that the use of both modes of presentation together improves learning. As discussed before, it is natural to want to present information deductively since we have learned it and have organized in our minds in such a manner. The best pattern for teaching, however, is to present material first inductively, from the observation of phenomena, then to formulate the overarching principle, and finally proceed to deduce other results from that principle.

The primary way to satisfy the needs of reflective processors is to allow time for thought—especially when asking questions, as discussed earlier. Active teaching methods will benefit both groups, as was introduced earlier. Experimentation and group work will benefit the active learners particularly, while demonstrations will offer
reflective students the opportunity to mull over their observations.

The needs of sequential learners are generally well addressed in teaching. Global learners, however, are generally neglected (Silverman, 1987). Global learners will benefit most from an introduction to the "big picture" and through speculative exercises. Group activities will benefit both types of learners, but interdisciplinary problems will benefit global students particularly (Felder and Silverman, 1988).

The Non-Constant Nature of Preferences

An individual's preferences in interaction, thinking, and learning may change over time. This is logical due to the various developmental stages which occur. For example, a student who, in elementary school prefers learning with peers/is extroverted (and has other similar traits) may become more withdrawn/introverted/etc. when in the midst of the adolescent identity crisis.

Also of interest is that such preferences can be modified somewhat by teaching methods and subject areas
studied. Lumsdaine and Lumsdaine (1995a) found that students in computer science drifted away from Herrmann’s quadrant “C” thinking. Lumsdaine and Lumsdaine also noted, but were not surprised, that the department was devoid of female students.

It is therefore assumed that learning and thinking preferences can be conditioned. As a result, teaching methods which encourage a variety of styles should increase students ability to function in all modes of learning and thinking, thereby producing whole-brain thinkers and facilitating the process of life-long learning.

Cooperative Learning

One teaching method is at the heart of the creative design process, especially in keeping with the teamwork-oriented objectives of engineering educational reform. That method is cooperative learning. There is a plethora of research on the subject of cooperative learning, and although there is some dissent, the bulk of that research indicates a significant positive impact of the method (Slavin, 1991).
Cooperative learning must not be confused with what is known as "Cooperative Education" or "Co-op" programs, referring to education gained through on the job experience. Rather, cooperative learning refers to education which relies on students working as a team to assure that all members achieve academic goals. In these teams, approaches may include such diverse objectives as problem solving, experimentation, practice, or discussion.

Two key concepts are essential to the cooperative approach. Individual accountability must be assured, in order that the performance of the group not mask the lack of learning of any of its members. This is of particular concern in a profession, such as engineering, where licensing, and possibly lives, are at stake. Also paramount is the need for group goals and interdependence. If interdependence is not maintained, the result is likely to be the same as or inferior to that produced by individual work.

In studies which have honored the two fundamental tenets of cooperative learning, consistent positive achievement effects have been observed in all grades, subjects, ability levels, and demographics (Slavin, 1991).
Cooperative learning methods also have significant positive effects on the affective (attitude) domain (Johnson et al., 1991).

There are other hallmarks of proper cooperative learning which distinguish it from what might simply be referred to as "group work"—heterogeneity and social skills development have also been defined (Johnson et al., 1984). Women and minority students will be most effective if they are not outnumbered in their team (Heller and Hollabaugh, 1992). Instructor assigned teams have much more of a positive effect than student chosen teams on student attitudes toward group experience (Feichtner and Davis, 1991).

Cooperative learning techniques for technical subjects have been studied specifically in more recent years (Adams and Hamm, 1990). A longitudinal study was recently completed by Felder and Brent (1994) which studied the process of cooperative education in technical courses in higher education. Felder and Brent cite a body of research in recent years showing the success of cooperative learning in higher education. Rotating various functions within a team is suggested to maintain interdependence, along with
requiring a group product. The Felder and Brent study, which used cooperative learning techniques in five successive semesters of a chemical engineering curriculum, found overwhelming evidence of the success of such methods. Their report highlights their application of methods suggested in Slavin (1991) and others.

In addition to cooperative learning, there are many teaching methods which offer promise for meeting the needs of various types of learners. McKeachie (1986) is an excellent reference for teaching methods in higher education, and his appendix B lists the goals potentially achieved through each method. The various methods used in developing the Engineering By Design methodology will be pointed out as they are implemented.
Engineering researchers are well acquainted with the process of the scientific method, which generally proceeds through a number of steps essentially the same as those for creative problem solving. These two processes are rarely compared, however, because a tremendous amount of research in today's climate is never implemented. As a result, the scientific method is traditionally defined in three major phases (Borg and Gall, 1989): formulation of a hypothesis, deduction of observable consequences, and testing of the hypothesis by collecting data measuring those observable consequences. In some cases, the order of these may be modified—for example, when prior experience has not provided enough data to formulate a hypothesis, data might be collected atheoretically. Those data may suggest a hypothesis to the researcher who collected it, or may simply
be published to suggest paths that other researchers might take.

In this case, I will identify six stages of the scientific method which I will use to describe the two applications of the scientific method in the present work. The six stages are as follows:

1. Statement of Problem
2. Research of Problem
3. Formulate a Hypothesis
4. Deduction of Observable Consequences
5. Testing Observable Consequences
6. Infer Conclusions

The first application of the scientific method in this research is presented here as an example.

The first problem addressed is not the underlying condition of the engineering education system, but it is the wide-ranging set of goals proposed for the reform of that system. Such a wide set of objectives tends to overwhelm administrators and professors and foster studies without yielding improvements. This problem is presented in the early part of chapter 1.

This was followed by research, shown later in the same chapter, to understand the problem and its context. It was then hypothesized that design activities, because of their
interdisciplinary and open-ended nature, could serve to synthesize many of the objectives of the reform movement into a unified approach. The observable consequences chosen in this case are the results of design projects which have been conducted by me and by many other researchers. As a result, the testing of the hypothesis necessitated additional research.

Design projects with wide ranging approaches, objectives, and accomplishments were discovered in that research process. The body of research described throughout the remainder of chapter 1 led to the conclusion that design projects could indeed be used to synthesis a great many of the desired objectives. This conclusion pointed to the continuation of this work in a second application of the scientific method.

The second problem which was recognized was that although design activities have been used effectively for a limited number of the objectives listed in chapter 1, they rarely systematically address the wider set of reform objectives. Research of this second problem uncovered a wide range of problem solving methodologies which are discussed in chapter 2.
Throughout my research of those other strategies, I discovered one element was missing from all of them—an integrated set of educational objectives. Chapter 3, therefore, is focused on the learning and teaching process, an understanding of which is necessary to approach the problem comprehensively.

This led to the formation of a second research hypothesis: that a methodology for designing engineering activities could itself be designed and that such a methodology will aid in the generation of engineering activities which are educationally superior to those generally used for K-12 students as well as students in engineering institutions.

This methodology was formed through the development of a prototype activity, the Truss Bridge Laboratory, which was integrated into the Civil Engineering component of the EGN 1002: Introduction to Engineering class offered at the University of Florida. The entire class handout (which includes the Truss Bridge Laboratory) is included as Appendix A.
The Development of Engineering By Design

The remainder of this chapter will discuss the prototype activity and the Engineering By Design methodology which it was used to develop. The testing of the stated hypothesis is the focus of chapter 5, and conclusions are drawn in the final chapter. The finished methodology is included as Appendix B; the section headings that follow in this chapter are named to match each of the steps of the methodology.

Establish Goals

In modifying the Civil Engineering component of Introduction to Engineering, the goals of the class as a whole had to be considered. This process began with the structuring of the first of the educational aims described in chapter 3, the goals of the course. This gave way to the first stage of the Engineering By Design methodology: Establish Goals. The primary goals of the Introduction to Engineering course and of the Civil Engineering component are for students to:
A. discover differences/commonalities among engineering disciplines
B. be informed/excited about an engineering career
C. experience engineering through visual and hands-on demonstrations and activities
D. be introduced to the team concept and basic communication skills
E. establish basic engineering skills and concepts
F. be recruited and retained in engineering

The Civil Engineering component achieved the first, second, and fifth of these quite well without modification, so the focus of the change would be to more clearly address the third and fourth of these goals. This pointed to the development of a design activity.

Select a Focus

The task had hardly been narrowed at all by the goals; in this situation, as in many others where design activities might be employed, there is a seemingly endless range of options. In this case, any design activity involving Civil Engineering principles would be acceptable. Truss structures were selected as the focus of what would come to be called the Truss Bridge Laboratory. Truss structures would enable us to focus on principles which are distinctly taken from Civil Engineering, and which is also very
physical, demonstrating the concepts of compression, tension, moment, moment of inertia, neutral axis, and failure modes.

**Brainstorm for Ideas**

Ideally, a prolonged effort at generating an idea can be circumvented by the inspiration which can occur during idea incubation (Lumsdaine and Lumsdaine, 1995a). This is what occurred in the case of the Truss Bridge Laboratory. Dr. Hoit entered the office with a bag containing popsicle sticks and small nuts and bolts, suggesting they be used to make trusses.

**Evaluate Ideas**

Regardless of the complexity of the problem being solved, and regardless of the effort (or lack thereof) invested in a brainstorming activity, whenever a solution is presented which is recognized as truly elegant and inspired, consensus in the selection of that idea will likely be achieved. In effect, the process immediately proceeds to the refining of the idea through the idea evaluation.
process. It is recognized that this step is normally a much more significant one, involving compromise and merging of good ideas to make better ideas. Still, a great many concerns were evaluated during this step; in evaluating the idea of making trusses out of popsicle sticks, nuts, and bolts, we discussed such practical issues as:

A. Can clearance holes be drilled without splitting?
B. How strong are popsicle sticks in tension?
C. How much variation is there in popsicle strength?
D. In creating a truss bridge, what span will be necessary to avoid excessive load?
E. Since popsicle sticks are two dimensional, what will hold up the trusses during testing?
F. How will the load be applied?
G. How far should the load be placed from the supports?
H. Should different sizes of members be provided?
I. If so, what sizes, and how will they be cut?
J. How many of each member size should teams receive?
K. How many nut/bolt pairs should each team receive?
L. How can we mass produce the parts kits?

This order is not necessarily representative of the order in which we either conceived of these concerns, but closely represents the order in which they were addressed.

Simple research and calculations were necessary to find the answers to questions A-D. A drill press and a simple jig was used to discover two important facts: a stack of approximately 7 popsicle sticks could be drilled simultaneously with little scrap—if taller stacks were
drilled, even the slightest wobble in the drill bit would consistently cause the bottom popsicle sticks to split longitudinally (this not only answered A, but inadvertently L, since a similar jig is still in use). Rather than attempt to answer B by placing a popsicle in special grips in a low-load tensile tester, it was recognized that the sticks should never fail in tension, since failure at the connections (where the sticks have been drilled) will occur first. Keeping this in mind, D-G were all addressed simultaneously. Simple Warren trusses (a chain of equilateral triangles, illustrated in the laboratory in Appendix A) were tested across various spans (D). The two-dimensional truss was held up by two small heavy boxes, later developed into a special loading frame with plexiglass panels allowing monitoring of deformation (E). The load was applied by wrapping a light gauge wire around two of the joints toward the middle, and hanging from it a 5-gallon pail which was gradually filled with gravel (F).

It quickly became clear that a 12-inch span resulted in loads which were too high (especially if the truss were reinforced in any way), so an 18-inch span was selected. This was also a convenient length; the drilled holes at the
popsicle stick ends were 4" apart, so 5 sticks joined in a line are 20", leaving 1" at each end to rest on the supports. It was found that placing the load at any joints but those nearest the supports would produce acceptable forces to cause failure before the 5-gallon pail would overflow (G).

The remainder of the questions (H-K) were evaluated in more of a brainstorming exercise involving Dr. Hoit and myself. We quickly concluded that simplicity required using as few member sizes as possible (H), and we decided to restrict the number to two. We also decided that the most useful size for the second member would be the length of the legs of the isosceles right triangle of which the full-length popsicle sticks (4") was the hypotenuse, making the holes of the shorter member 2.83" apart, aligned by a new jig (I).

A number of designs were evaluated to determine how many of each member type and the number of nut/bolt pairs it would take to create them. We decided that imposing certain constraints would ensure that students would have to think creatively to optimize their designs (J, K)—one constraint was that we would not provide enough members to simply
reinforce every member in any of the designs we had analyzed. Students would therefore have to selectively reinforce (if at all) and therefore judge which members most needed reinforcement. We also chose the number of bolts to be too few to build a trapezoidal truss three panels high. This would prevent students from simply building large trusses by brute force, but force them to devise more complicated geometries to achieve greater separation of the top and bottom chord (and greater moment capacity, in general).

We also devised a scoring system based on the ultimate load divided by a cost parameter, to challenge students to consider the benefits of designing a small, but sturdy structure rather than building a behemoth which only seeks to carry the maximum load.

**Figure Out the Details**

In order to foster a team effort in producing a group product (as recommended by Felder and Brent), it was decided that the actual design process should dominate the time spent on the activity. As a result, a lesson (described
below) of approximately 20 minutes introduces students to the concepts of moment, moment of inertia, neutral axis, failure modes, and truss design. This lesson is followed by a 45 minute period for design. This is done in instructor-assigned teams of 3-4 people, keeping in mind the grouping rules discussed earlier with cooperative learning (although, unfortunately, we have little information on ability level or the time to assess it). For 10-15 minutes bridges are then tested to failure (with various phenomena pointed out by the instructor), and scored on the strength-to-cost measure mentioned earlier. Prizes have been given out, but "bragging rights" seem to have as much or more value among our students.

The lesson is also key to the exercise, since it must give students enough understanding of the problem so that they do not feel overwhelmed. The presented lesson follows closely the handout material, except that the presentation includes the use of additional visual aids and thoughtful questions. The lesson begins with the big picture (to build a bridge to cross an 18" gorge) to get the globals pointed in the right direction—the big picture includes the application, which helps the sensors.
Quickly, the discussion moves into a demonstration of what goes on inside a beam when it bends, using a foam beam with vertical lines painted on its front face (see Appendix A for an illustration). Students easily note that the lines at the top have been pushed together, and the lines at the bottom have been pulled apart. Students also simply relate these two states respectively to compression and tension, demonstrated during the part of the Introduction to Engineering class which precedes the Truss Bridge Laboratory. The force couple is then drawn on the board, and defined as moment, and the instructor illustrates moment again, this time by applying a couple to the foam beam. Then the question is posed, "If the top is in compression, and the bottom is in tension, what is happening in the middle?" (illustrating the middle of the beam in the vertical direction). If I am not hurried, I will ask students to all have an answer in their minds (or written down) before I ask for a verbal response. I have never taught this lesson when students did not suggest the answer "nothing." I then define the neutral axis as the line where neither tension nor compression exists.
The principle of moment of inertia is then demonstrated by bending a common yardstick in the flat and the upright orientations. Although the same material is used, the upright orientation is much stiffer, and can resist much more moment before breaking. Students are asked to suggest examples of why beams might be used in the flat orientation (greater surface area, diving board, etc.) and in the upright orientation (structural strength, stiffness, balance beam, etc.). The principle of moment of inertia is then discussed in terms of moving material away from the neutral axis, where the material is used inefficiently for moment resistance—drawings of wide-flange steel and concrete girders help students recognize the new concept to objects which are familiar, to anchor the concept in their own experience.

The discussion of using material efficiently quickly leads to the introduction of the truss, which allows force to be distributed over a great number of members. The truss is initially drawn emphasizing the top and bottom chords, where the compressive and tensile forces will be the highest. Simple trusses made from the actual design materials are then shown (for an illustration, see Appendix
A). Examples illustrate the concepts of stability and instability.

Failure modes are then discussed—the yardstick is used to demonstrate buckling, but students easily predict what will happen when the stick is compressed. The geometry change caused by buckling members is illustrated with the help of the foam beam. Students also easily predict that tensile failure will not occur in the middle of a popsicle stick, but at the joints, as is quickly demonstrated with a constructed truss (which has been prepared with a pre-broken joint). Students then relate these two failure modes to the concepts of ductile and brittle failures witnessed earlier in the class (steel and concrete, respectively). Students generally observe quickly that the broken joint causes an immediate failure, but are less able to see that buckling allows the structure to redistribute load (which they readily witness later, as at least one bridge will invariably experience such a buckling failure and redistribution, enduring considerable total deformation prior to failure).

After a brief demonstration of how the trusses will be loaded and a discussion of the objectives and the scoring
system, students begin the design exercise. The instructor (and any assistants) will answer technical questions which pertain to the concepts discussed, but do not answer any questions which suggest or give an opinion of any particular design. After designs are complete, the laboratory activity resumes as described earlier.

Establish Specific Objectives

The following specific objectives apply to the Truss Bridge Laboratory from start to finish:

1. The instructor will present the concepts of compression, tension, moment, moment of inertia, failure modes, and truss stability/instability with extensive visual examples and concrete examples from students’ experience.

2. Students will construct a truss from the provided materials in instructor-assigned teams of 3-4 persons.

3. Student teams will successfully bridge the 18" span established by the loading frame.

4. Student teams will optimize their designs so as to maximize load while minimizing cost.

5. Each student team will place its truss in the loading frame and test it to failure.

6. Students will observe the deformation and failure modes which occur in each team’s truss when loaded.
7. The instructor will describe the deformation and failure of each truss and discuss (in a non-threatening manner) elements of the design which have produced the result.

These seven objectives are very well met during most presentations of the laboratory. Some student teams do not perform well in the process of optimizing (4), but seem curious to understand their failure during the later discussion (7).

**Improve the Activity**

Not surprisingly, a great number of student teams have proved more than adequate to the task of designing creative structures, ensuring that eventually our system of supporting and loading the trusses would be challenged. In the most extreme cases when a student team’s truss designing capabilities exceeded our expectations, the activity itself had to be modified.

One circumstance which required an improvement of the laboratory was that a number of student teams defied the rectilinear nature of the provided parts, and produced arched structures—we have seen a great many approaches which produced this result. One effect of the introduction of
arch designs was that students did not understand the principle of arch thrust, which causes the legs of the arch to spread under loading. As a result, eventually one of the arched designs experienced such a separation of its legs that the truss fell off the outside edges of one of the supports, which were only 1" long (i.e., the legs spread to be more than 20" apart). To avoid the frustration experienced by that team, the instructor now explains the implications of arch thrust, but privately, to student teams which have already begun creating an arched design.

Another way in which students have greatly exceeded our expectations has been in overall strength. Student teams sometimes fill their bucket to capacity (over 80 pounds). As a result, we developed the habit of putting pieces of steel angle in the bottom of the 5-gallon pail when testing designs which have obviously placed an emphasis on overall strength, with less regard to overall cost (this seems to be a fairly common approach, especially among all male teams).

A record of the designs produced by student teams is kept on a scoring sheet. Teams draw their design (providing an excellent channel for the more artistic team members to participate) and record the cost and failure load.
The Truss Bridge Laboratory has had excellent success in meeting the objective of the recruitment and retention of students. The Civil Engineering department at the University of Florida has indicated increases in recruitment since the implementation of the new laboratory. The college of engineering enrollment figures for spring 1995 indicate 100 civil engineering students of out of 819 total engineering students of 3rd year status. This class would have been freshmen before the new laboratory was introduced.

The same figures for spring 1996 (after the implementation of the new laboratory) show 128 of 758 engineering students were in civil engineering. This shows not only an overall increase in enrollment (from 100 to 128), but also an increase in percentage of the engineering enrollment (from 12.2% to 16.9%). Although it is difficult to prove that the revised laboratory was solely responsible for the change, the department chairman agrees with Dr. Hoit and me that the laboratory was the primary cause.

Retention of all students who enrolled in the revised laboratory course was approximately 50% (Hoit and Ohland, 1995). This was true even for the subgroups of women and minorities. This showed a significant improvement over the
lecture version of *Introduction to Engineering* which preceded the laboratory.

The *Truss Bridge Laboratory* has also been featured in engineering outreach activities. The fact that it was designed to be used by other institutions with a minimum of effort has made it an excellent candidate for use with high school groups such as in the Hands-On Institute for Science and Technology, held at the University of Florida July 9-15, 1995, and in teaching in-service teachers in the SouthEastern Consortium for Minorities in Engineering (SECME) 19th annual summer institute, held June 16th-29th, 1995 at the University of Florida. These two residential summer institutes aimed to introduce K-12 students and teachers respectively about engineering and its disciplines. Survey instruments administered at both events indicated that the institute objectives were well met (Ohland et al., 1996).

**The Engineering By Design Methodology**

The process described in each of the sections above led to the identification of the step of the methodology that is
identified by the section titles. The methodology does not simply list these steps, but describes the process of each and gives examples, as appropriate, to help clarify each step’s purpose and application. The methodology itself is included as appendix B.
CHAPTER 5
EVALUATION AND ASSESSMENT

Evaluation of Educational Systems

There are particular constraints placed on the process of designing and evaluating educational systems. There are also effects which are inherent in research involving people. These constraints and effects are described in the following sections, and many of these apply to the research conducted here. The discussion here primarily follows that of Borg and Gall (1989).

Constraints on Educational Research

We are accustomed in research to the presence of two types of variables—those which the experimenter controls, and those which the experimenter cannot or chooses not to control. Differences in terminology abound, and are summarized in the table below. I will use the terms
independent and dependent to refer to variables which are causal and affected, respectively. It is important to note that while some variables can be either independent or dependent (temperature is affected by the number of people in a room, but the temperature in a room can also affect the behavior of the people in it), other variables are strictly independent variables (biological sex, for example, must be independent except in genetics experiments). Such variables which are determined a priori and cannot be manipulated by the researcher are commonly called parameters.

Table 6 Various Terms Used in Classifying Variables

<table>
<thead>
<tr>
<th>Variables which are causal</th>
<th>Variables which are affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent</td>
<td>Dependent</td>
</tr>
<tr>
<td>Manipulated</td>
<td>Responding</td>
</tr>
<tr>
<td>Experimental</td>
<td>Post-test</td>
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<tr>
<td>Treatment</td>
<td>Criterion</td>
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</tbody>
</table>

In most scientific endeavors, researchers are accustomed to having full range of manipulation of the independent variables, up to the limits of the available technology to them. In an experiment to examine thermal expansion, the independent variable is temperature and the dependent variable is the size of a piece of material. A
researcher can vary the temperature greatly, dependent only upon the complexity of the equipment. In educational research, as in any research involving people, there are limits to how different variables can be manipulated, due to the ethical, legal, and practical considerations discussed in the remainder of this section.

**Ethical principles**

In 1981, the American Psychological Association (APA) published a list of 10 ethical principles for the conduct of research involving human participants (Committee on Scientific and Professional Ethics and Conduct, 1981). Those most commonly violated by graduate students are reviewed here (Borg and Gall, 1989):

If the participants are at more than "minimal risk," the investigator must clarify the obligations and responsibilities of the researcher and of the participants in a clear and fair prior agreement. The investigator must receive "informed consent" from each participant.

If deception or concealment is necessary to the research, the investigator must determine if the potential outcome merits the use of such techniques, must evaluate alternate approaches, and must give participants a true explanation as soon as possible.

After the completion of the study, participants should be debriefed as to the nature of the study.
If participants incur unwanted consequences as a result of the research, the investigator is responsible for corrective action if possible.

Information regarding any research participant is considered confidential unless consent is given by the participant. The participant must be informed if their confidentiality is threatened by the nature of the study.

Informed consent is obviously critical—participants must be aware of any risks and breaches of confidentiality and consent to them. In the case of the present work, any carefully considered lesson plan should have an acceptable outcome, so there will never be more than “minimal risk” to the students. The other participants, the instructors testing the methodology, are also at minimal risk. Debriefing is significantly simpler if the consequences to the participant are minimized. In the case of this research, all subjects were aware of the research objectives ahead of time. Especially in the case of the tributary area described later in this chapter, the lesson was so different from what students typically experience that the lesson would appear to lack validity (known as face validity) without prior explanation of the research being conducted. Confidentiality is assured in this experiment through removing the names of students from all published accounts.
In published data tables, subjects are referred to by a "subject number." As the researchers, the participating instructors and I can associate the subject number with the participant at any time to retrieve further information, but it would be impossible for anyone else to discern the participant from the number.

**Legal constraints**

In general, most of the legal constraints do not impact research designs which follow the APA ethical guidelines, but intend to provide legal recourse against researchers who do not follow such principles. The two laws which most affect research involving people are described in the following sections.

**The Family Educational Rights and Privacy Act of 1974.**

This act protects the confidentiality of educational records, requiring written consent (from the student or parents) to obtain any educational records from which the student can be identified. Fortunately, school personnel with "legitimate educational interest" are exempted from this process, which significantly relieves professors and
graduate students from violating this law when working with students in their university. We must still be concerned to ensure that informed consent is obtained when appropriate, however. The influence that professors have over students can subtly coerce students into participating in experiments against their desires.

The National Research Act of 1974. This act established an Institutional Review Board which reviews research proposals when human subjects are involved. This review board is concerned with ensuring the rights of participants and the procuring of informed consent. Again, this act names specific categories of research which are exempt from regulation, among which is most common educational research, including research on instructional strategies, techniques, curricula, and classroom management. Engineering By Design methodology meets this proviso, and so is unaffected by the legislation discussed.

Human relations

Of a more practical nature is the fact that with human participants, educational research must consider human
relations in the structure of the research. Public relations and interpersonal relations will both be important in gaining access to information and obtaining permission to conduct research.

Effects in Research Involving People

It is commonly understood by researchers in all fields that the observation of a system necessarily has an affect on the system itself. This is the fundamental cause of these effects listed here, but in research involving people, we must not only worry about direct effects (e.g., a researcher investigating employee dynamics has changed the dynamic because another individual has been added to the office), but also about indirect psychological effects (e.g., the employees are likely to behave differently if they know they are being studied). Four commonly observed effects are described in the following sections.

The Hawthorne Effect

This effect takes its name from the Hawthorne Plant of the Western Electric Company which first discovered how
participants' awareness can affect the outcome of the experiment (Roethlisberger and Dickson, 1939). In that case, the experiment demonstrated management's concern for their workers, which yielded an increase in morale and productivity. The Hawthorne Effect, in general, refers to improvements that are witnessed due to participant awareness or the special attention associated with the experimental procedure.

Measures to curtail the Hawthorne Effect include special structuring of multiple control groups, and reducing the level of special attention, novelty, and participant awareness.

**The John Henry Effect**

This effect is named after the legend of John Henry, a railroad worker who pits himself against a steam hammer in a competition to drill holes for blasting powder. In John Henry's case, the confounding effect was the participant's awareness of a threat to job security which drove him to improve his performance. In the general case, the John Henry Effect refers to any unusual effort put forth from the control group (the comparison reference for the experimental
group) due to a threat to job, status, salary, and other measures of worth (Saretsky, 1975).

The Pygmalion Effect

This effect, its name drawn from Pygmalion in the Classroom (Rosenthal and Jacobson, 1968), characterizes the phenomenon witnessed in George Bernard Shaw’s Pygmalion (also known as My Fair Lady). In the Rosenthal and Jacobson study, teachers’ expectations influenced the achievement of their students. Here it is the expectations of the observer which influence the participant’s behavior. The best approach to avoiding this effect is for the researcher to refrain from communicating any expectations to the research participants. This effect can be positive or negative, following the experimenter’s expectations.

Demand characteristics

The effect due to demand characteristics are essentially the converse of the Pygmalion Effect. Demand characteristics are the collective evidence which the participant perceives in an attempt to discern the research objective. This is caused by a person’s curiosity as to
what the experimenter is trying to find out about them as a subject. This effect can also influence the research outcome in either direction—the subject might or might not discern the actual research objective, and if discerning it correctly, the subject might or might not wish to fulfill the objective (some subjects will always attempt to stymie the researcher).

Evaluation of Engineering By Design

The purpose here is to evaluate the methodology itself. One approach to this problem was to ask those who had used the methodology in creating an activity to evaluate the effectiveness of the methodology in aiding that process. It rapidly became clear that this method of evaluation would be ineffective. The primary difficulty was one of evaluator bias, which has two contributing factors, which follow.

The first cause of bias is that I am too closely associated with the methodology, because of my extensive involvement with those testing it. This confuses the evaluator’s opinion of me and my efforts with their opinion
of the methodology. The second difficulty is caused by the interdisciplinary nature of the methodology. One of the evaluators, Dr. Duane S. Ellifritt, Professor of Structural Engineering at the University of Florida, has much practical teaching experience but is less aware of the fundamentals of learning and teaching which are applied in the methodology. The second evaluator, Dr. Cynthia Holland, a secondary teacher of Physics and Chemistry, has a strong understanding of educational principles, but is less well-versed in design and creative problem solving. The result is that each is biased by their respect for the elements of the process which are less familiar.

Fortunately, there is another approach to evaluating the methodology—through the activities it produces. If the methodology is beneficial, the activities produced using it should be educationally superior to those traditionally used. The ideal model of this type of experiment would include two randomly selected populations of students who are well-matched with respect to any attributes which may effect the outcome of a learning experiment, such as aptitude, learning style, demographics, and attitudes. These populations should be representative of the population
as a whole (e.g.: that of all students who take high school Physics) for the results to be generalized.

One of the populations (called the control group) would be taught with the traditional approach, while a matching population (called the experimental group) would be taught with a product of the Engineering By Design methodology. Unfortunately, the constraints discussed earlier apply—the students within a class have already been established, and students cannot be moved between classes for the purposes of the experiment.

As a result of various constraints, each of the two experimental activities will fall short of the ideal case in a number of ways. The first, conducted with the aid of Dr. Duane S. Ellifritt, was intended to teach the concept of "tributary area" to students in CES 4605—Analysis and Design in Steel at the University of Florida, Fall 1995. In the second, I worked with Dr. Cynthia Holland to develop an activity to teach statistics to a group of high school Physics students. These two activities and the results of their implementation will be discussed in the following sections.
Design of a Tributary Area Activity

Tributary area is a concept which is used to determine the surface loads carried by a particular member. Tributary area is used to determine reductions of movable, or live loads. Since such loads are determined statistically, based on how close together desks can reasonably be placed and other such parameters, it is reasonable to assume that a column which carries load from a number of sources will not be loaded at the maximum load from each simultaneously. Therefore, reduction of live loads is permitted under certain circumstances, as will be discussed later.

Simply stated, the tributary area of a member is that area directly above that member plus half the area between it and its neighboring members on all sides. The figure below illustrates the tributary area of the center beam.

![Figure 4 Beam Tributary Area](image_url)

Of course, if the one sentence description of tributary area given in the last paragraph were adequate to impart a
full understanding of the concept, an activity designed to teach it would not be necessary. In fact, it was students' difficulty with the concept which prompted Ellifritt to test the *Engineering By Design* methodology. The entire process of creating the activity is detailed here as an example of the use of the methodology.

**Establish goals and select a focus**

The focus is sufficiently narrowed through the goal-setting process in this case. As a result, the second step of the process has been subsumed by the first. The goals of the activity are listed below.

To teach students the concept of tributary area
To justify and demonstrate load reduction
To enable students to specify member loading

With these goals established, we sought a model to make the tributary area concept clearer, and moved into the idea generation phase.

**Brainstorm for ideas**

The idea generation phase of the process was conducted by three diverse individuals: Dr. Duane S. Ellifritt is a structural engineering professor and artist; Don J.
Herrington (my brother-in-law) has worked as a mechanic (including race cars), a farmhand, and a carpenter; I received masters degrees in both mechanical and materials engineering prior to my current work in civil engineering. In addition to my minor in education, I also have a humanities bachelors degree.

Our goal was to explore ideas for a physical model which would help students visualize the layered nature of structural systems and picture the manner in which all loads have a path to the ground. The location chosen for the brainstorming exercise was Dr. Ellifritt’s office, which aside from a providing a central location, has a variety of interesting wall hangings to foster creative stimulus. The rules of brainstorming were explained, I assumed the role of recorder/facilitator. The session was kicked off with the question, “What things are layered?” Other prompting questions were added when idea generation slowed, including, “What things in nature are layered?” which introduced a number of divergent concepts. The list of ideas generated during the session are included Appendix C. I have attempted to order the list as it was generated, but some rearrangement has probably occurred.
Evaluation of ideas

Once the list of ideas in Appendix C had been generated, we moved into a critical thinking mode to evaluate those ideas and develop the activity. The Jenga game, with which I was not familiar, was very intriguing to me, and I asked the others to describe the game and its rules. It quickly became clear that the game would provide a quick, cheap, and exportable solution.

Jenga is a game played with a tower of blocks, with three uniformly sized blocks in each square layer, with each layer’s blocks perpendicular to the layers above and below. The standard rules specify that players in turn will remove a block from any but the top layer and move it to the top. The game lends itself well to seeing loads in layers. The growing instability of the tower forces students to look carefully at load path to the ground. With the groundwork laid for this opening activity, we set out to establish specific objectives for the lesson as a whole.

Figure out the details

The block tower activity was intended to initiate team behavior and enhance student excitement. The rules of the
block tower game were modified to achieve this. The students would work in teams, even though only one team member could touch the tower at any one time. This would allow the team to develop the desired camaraderie during an activity which was clearly not being graded. It was hoped that an activity seemingly separate from the educational pursuit could establish an atmosphere of friendly competition among teams and raise the students’ excitement level. The team’s objective was to build the tallest tower possible in five minutes. With two sets of blocks available, the eight teams could be completed in approximately 20 minutes. The instructions were placed on an overhead, and are shown in Appendix C titled “Block Tower Activity.”

With a fairly clear view of the structure of the block tower activity, we set out to design the remainder of the laboratory. In the three hour laboratory, the professor would first need to explain laboratory and homework procedures (since this unit is the first laboratory of the semester).

Then we decided the lesson would open with a five minute discussion of how structures are layered and an
overview of the format of the laboratory, which was somewhat different from the usual fare for engineering students. We moved directly into the block tower activity for twenty minutes. Students remained in their tower construction teams for the remainder of the laboratory.

Student teams then began a brainstorming session in which they speculated as to the distribution of floor loading to the floor's load carrying members. The handout used for this exercise is included in Appendix C, and is titled "Floor Load Distribution Exercise." This exercise, in addition to fostering higher level creative thinking, was also intended to identify different perspectives and ferret out misconceptions prior to continuing.

The three separate examples in the exercise explore different concepts. The first, shown below, indicates a floor with regularly spaced floor joists.

![Diagram of Load Distribution 1](image)

**Figure 5 Load Distribution 1**
The student teams are asked to indicate the floor areas carried by joists a, b, and c. Joist b is a typical interior member, for which students are expected to easily agree that half of the area between b and its neighbors is carried by b. Joist a is on an edge, forcing students to decide what sort of effect applies there. What is actually appropriate is dependent upon student assumptions, which they are asked to declare. Joist c shares load with an interior and an exterior joist. If students are consistent in the application of their method (regardless of their agreement with the established method of calculating tributary area), c should carry half of what b carries plus the portion of an exterior bay not carried by the edge joists, indicated by the area assigned to a.

Although jumping right into defining tributary area prior to formally defining it is great for global learners, these problems are ordered so that sequential learners will be able to piece together smaller concepts into a larger picture. In this manner, the second problem of the set introduces a new level of complexity: non-uniform joist spacings.
In this exercise, the regularity is removed; exterior joists no longer carry half of exterior joists, and the area carried by c is not symmetrical.

In the third problem of this exercise, the floor becomes a true two-dimensional system. Students are now asked to distinguish between the area carried by a corner column (a), an edge column (b), and an interior column (c). For simplicity, uniform spacing has been reintroduced.
Students would be given approximately 10 minutes to complete all three problems in this exercise. This would be followed by a discussion of the problem set, in which the established method of tributary area and its assumptions would be defined, and misconceptions noted in the problem set would be addressed (the simple nature of the problems was expected to facilitate rapid interpretation of the answers turned in by each group). This formal treatment of the concept of tributary area and load distribution would include the transfer of load from smaller members to larger members (such as from joists to beams or from girders to columns), and would last 15 minutes.

A more complex tributary area problem would then be assigned to the groups. This problem had irregular spacings, multiple modes of load transfer (joist to beam, beam to girder, beam to column, girder to column, etc.), and overlapping layers (joists and girders both reached floor elevation, but beams, which received load from joists and transferred it to either girders or columns, were below floor level). The floor plan and the elevation are included in the handout shown in Appendix C, titled "Tributary Area Lab Assignment." Student groups would have 15 minutes to
work on this problem, after which the instructor would go over the problem for 10 minutes.

At this point in the laboratory, we would want to develop the concept of live load reduction. The introduction to this, we decided could also be done through brainstorming. This brainstorming exercise was defined as a real-world application, which was intended to benefit the sensors (the first such exercise was more abstract, since little was defined, and was thus more suited intuitors). The instructions are shown below (and included in Appendix C), to demonstrate the concrete (as opposed to abstract) framework in which the problem was cast:

**Introduction:** Since live loads are movable, they do not occur simultaneously over all parts of a structure. Building designers have argued that this causes load calculations to be too conservative. Your team has been enlisted by the American Institute of Steel Construction to devise a method of reducing live loads which assures safety but is not overly conservative.

**Objectives:** Brainstorm in your groups to list as many different approaches to this reduction as possible. Then select one or a combination of those ideas and develop it further. Make sure that the reduction is limited and has clear criteria which define under what circumstances it may be used.

This exercise is also intended to give reflective students the time to understand why live load reduction is possible
without excessive risk. This has traditionally been a difficult point for students, who think a quantity of actual load is simply being neglected. This exercise also contains more critical thinking than the first. Students must not only evaluate their ideas, but then establish criteria for their use. This should encourage students to understand why limits and criteria are necessary (e.g., if the reduction as a percentage is allowed to grow unbounded, it may eliminate the load entirely—obviously well after the limits of safety have been exceeded). We allowed 10 minutes for this exercise.

Next on the agenda we decided to give a formal presentation of the live load reduction method recognized by the LRFD design code (AISC, 1986). We estimated that 15 minutes would be sufficient for this. Following the formal presentation, student teams returned to the complex tributary area problem and calculated service loads (comprised of dead load plus reduced live load, not factored) for a typical joist, beam and girder. Student teams were allotted 30 minutes to show their results in the form of free body diagrams of each member type. Students were not required to consider the columns.
The laboratory would conclude with 15 minutes of discussion regarding the solution to the last problem. An outline of the lesson plan for the entire laboratory is included in Appendix C. A 15 minute post-test would be administered on a later date, to evaluate students' mastery of the subject—this quiz and the results from its administration will be discussed later.

Establish Specific Objectives

Some of the objectives are specified directly on the handout sheets in Appendix C, discussed in the next section. The instructional objectives consistent with the activities listed in the previous section are included here.

**Introduction:**

The instructor will describe the laboratory and homework procedures as well as the format of this laboratory.

The instructor will describe and illustrate the layered nature of structural systems.

**Block Tower Activity:**

Student teams will begin with the same configuration of starting blocks and, following the rules of play, attempt to construct the tallest tower possible before it topples.

**Load Distribution Brainstorming:**

Student teams will indicate on the provided diagram how the surface area of a floor is distributed to various supporting structural members.
Student teams will list on the assignment sheet all the assumptions they make during the brainstorming process.

Student teams will calculate the total area carried by each delineated structural member.

**Problem Set Discussion:**

The instructor will then describe the assumptions and procedure pertaining to the established method of calculation of tributary area.

The instructor will make special note of those assumptions which do not apply to the calculation of tributary area.

**Tributary Area Lab Assignment:**

Student teams will compute tributary areas of various members in a more complex problem involving irregular member spacing and members at mixed elevations.

The instructor and teaching assistant will circulate throughout the room to answer questions.

**Lab Assignment Discussion:**

The instructor will discuss various approaches to the previous assignment.

The instructor will respond to any student concerns regarding the computation of tributary area.

**Live Load Reduction Brainstorming:**

Student teams will generate ideas as to how live load reduction might be accomplished.

Student teams will evaluate their ideas to choose the most practical approach.

Student teams will establish guidelines for the use of their live load reduction method including criteria and limits.

**Live Load Reduction Brainstorming Results:**

The instructor will write on the board a set of unique approaches to live load reduction contributed by the class.

The instructor will write on the board the limits and criteria suggested by the various student teams.
LRFD Live Load Reduction:
The instructor will make a formal presentation of the approved LRFD live load reduction method. The instructor will compare and contrast the methods suggested by students to the LRFD method.

Live Load Reduction Lab Exercise:
Student teams will compute service loads using live load reduction for the joists, beams, and girders of the Tributary Area Lab Assignment. Students will draw free-body diagrams of all three member types, showing all service loads. The instructor and teaching assistant will circulate throughout the room to answer questions.

Live Load Reduction Problem Discussion:
The instructor will discuss the solution of the problem described previously. The instructor will address any student concerns regarding live load reduction.

Improve the activity

Improvements to the activity are best discussed after analyzing the activity’s performance when conducted. In the following sections, a case study of the activity as it was conducted will highlight areas for improvement as well as closely study the learning which occurred.

Tributary Area Activity Implementation

One constraint on the implementation of this activity was one of human relations—the instructor (Dr. Ellifritt)
was unable to separate the class into two groups to provide a control group. This eliminates the possibility of conducting a comparative study, because all available students would be taught by the same method, the one created through the Engineering By Design methodology. It will not be possible to objectively conclude that the new approach to teaching tributary area is better than the method previously used. In lieu of this more preferable method of evaluation, other more subjective methods of evaluation are used. A post-test was administered to all students which, rather than measuring their performance against a control group, can be used to measure their performance against a standard of mastery.

The case study approach to studying the method is also beneficial—evidences of the learning fostered by the new lesson are insightful as to its effectiveness. A number of such incidences are reported. Another evaluation instrument is a survey which was administered to the students and the student comments which supplemented it. This survey measured student opinions of the lab, of group work, and other relevant information. By relating the survey results to the quiz scores, it is hoped to discover interesting
trends which may further contribute to the evaluation of the activity, and therefore of the method used to develop it.

The evaluation of the tributary area laboratory will proceed in the same order as the objectives were presented.

**Introduction to laboratory**

The students were generally quite receptive to the idea of their involvement in an educational experiment. They seemed enthusiastic to hear of the instructor's and my concern for their learning. After a brief explanation of the motivation for the block tower activity, we quickly began.

**Block tower activity**

This activity certainly achieved some of the desired objectives. Student teams quickly established an atmosphere of friendly competition, as expected. In fact, the peer interaction was very similar to that observed with middle school groups, for whom peer interaction is most important—the winning group even pronounced itself "The Tower Masters," writing that epithet on the group work they turned in. The activity certainly reduced the level of
lethargy commonly present in an afternoon laboratory. For the remainder of the afternoon, the classroom somewhat resembled a beehive.

Student comments indicated a mixed reaction as to the success of the block tower activity in helping visualize the natural of structural loading. One student commented, "I thought the blocks gave us a good conceptual understanding of [structural] weaknesses," which is very encouraging, since that explicit goal of the activity was not clearly communicated to the students prior to the activity. However, another student indicated, "The block tower activity was fun, but I failed to note a significant or helpful connection between it and tributary areas." This would seem to indicate that the activity only achieved its intended purpose for students with certain learning preferences.

Not surprisingly, the most significant weakness of the block tower activity was the fact that we only had two sets of blocks. This caused some groups to watch and wait while other built towers—two students made special note of the delay in their comments. One student made a specific recommendation for improvement of the activity, indicating
that the opportunity to build the tower from the ground up would have provided additional freedom for the team to design the structure, rather than be constrained by the instability caused by moving blocks.

Load distribution brainstorming

Initial resistance is always expected when introducing group methods and challenging students to formulate a concept rather than teaching it. Students did not hesitate to express their uneasiness with the approach: "...I think it would benefit the students to know how to do something (e.g. tributary area) before problems or quizzes be given." This uneasiness is acceptable, because it can be like sand to an oyster—an irritant from which a pearl may grow. The challenge and the higher order thinking can shake out principles which students take for granted and encourage thinking, like a "whack on the side of the head," as Von Oech put it (1983). The format of this activity is especially threatening if the students feel that they will be penalized for errors. When we introduced the activity, we explained that the objective was simply for the teams to speculate as to how load was distributed—wrong answers would
not penalize the team. One student’s comment made it clear that we had not clearly conveyed that approach: “I like to have some knowledge of a method before trying to complete a graded homework on that method.”

In their solution to the exercise itself, teams 1, 2, 4, 5, 6, and 7 defined all of the tributary areas consistent with the standard definition of the concept. Team 3 identified all but one area correctly; in the second problem, they forced the area surrounding joist c (and its reflection) to be symmetric, leaving no floor surface to be carried by joist b. Essentially, the team removed joist b to create uniform spacing. Team 8 postulated an edge effect, which would be consistent with that which occurs with uniformly loaded continuous beams, where interior supports carry considerably more than twice the load of exterior supports (AISC, 1986, p. 3-142). This error is simply caused by a different set of assumptions, where the assumptions made in the established definition of tributary area make the area simpler to compute, forgoing the increased accuracy of the more complicated set of assumptions.
We were encouraged that, in all, six of eight teams defined the areas according to the established method before tributary area was formally introduced. It is also important to note that both students who made negative comments about this exercise were on teams which completed the problems in such a manner (i.e., that their comments are not due to a perceived attack on their self-image).

**Problem set discussion**

Immediately after one team turned in its solution, one of the members approached me. He had proposed a different solution to the last problem, and his teammates had rejected his approach. Unfortunately, his teammates had not been patient or persuasive enough to reconcile his approach with theirs. The third problem is shown again below; the student’s proposed solution for column c is indicated by the hatched area, and others are typical.

The student’s logic is quite reasonable—to view the load carried by a column as a radius of effect. Unfortunately, his teammates had not worked with him to follow through on his logical approach.
Figure 8 Reconciliation of a Radial Tributary Area Method with the Traditional Method

I asked the student, "So how shall we divide the areas of the floor which are not yet accounted for?" (pointing to the curved-diamond-shaped gaps between the circles). He indicated dividing those areas into quarters with the dotted lines shown. At that point, I encouraged him to complete the logical process he had begun: "and where does each of those quarters go?" He had already seen the result—when the quarter indicated by the thick line is added to column c's circle, and the other quarters that adjoin the circle are also added, the area assigned to column c has increased to form a square. He was clearly satisfied that his logic was not faulty; more importantly, he clearly had a deeper
understanding of the material by presenting it in this manner.

The next occurrence came as a big surprise to me and to Dr. Ellifritt—we had not yet formally introduced the concept of tributary area, and had therefore not yet referred to it by name, when one of the students asked, "Is what we’ve been doing something like tributary area?" The question of prior experience had arisen in the planning the laboratory—we were both confident that the concept was not covered in any other classes that these students would have taken, and we were both wrong, apparently. At that point, I asked for a show of hands as to how many students in the class had heard of tributary area before the lab—9 of 33 students, more than a quarter of the class, raised their hands. This caused two problems: the experience was not evenly distributed among the groups, and it raised questions as to what effects experience might have on the results. However, by measuring experience as a continuous variable (assigning numerical values to different levels of experience), it made it possible to test if experience was a factor. This will be discussed in detail later in this chapter.
We then moved on to discuss the problem set; the assumptions associated with the established method of computing tributary area were introduced and justified. It was explained that, while the edge effect assumption is often valid, it further complicates the computation of tributary area. Team 3's misconception that a particular floor joist carried no load was discussed privately with the group immediately after they handed in their solution, in order to avoid the intimidation of correcting such a mistake in front of their peers.

Tributary area lab assignment

When students seemed confident in the concept of tributary (when there were no more questions), the laboratory assignment was handed out, and the professor, the teaching assistant, and I were available to assist student teams and answer questions. As these assignments were turned in, it was clear that the most common error was ignoring elevations, i.e. strictly dividing up the area between both girders, half to each. In doing this, the girders carry an extra load: that load which some of the joists deliver to beams which, in turn, frame into the
columns directly. Some students did the same with the area between the beams, i.e., they failed to realize that a portion of the uniform load was applied directly to the girder (at a higher elevation) and was not seen by the beams. Both of these errors are conservative, because they apply more load to the intermediary members. Both will, however, correctly yield the resultant column loading. Two of the teams (4 and 5) completed the assignment without error.

Lab assignment discussion

Having quickly reviewed the assignments as they were turned in, the instructor reviewed the implications of elevation, and how load is transferred from one layer to another, sometimes bypassing an intermediary layer. When we had finished going over the laboratory assignment, we proceeded to introduce live load reduction through the next brainstorming exercise.

Live load reduction brainstorming exercise

By the time we had reached this point in the laboratory, the instructor was concerned that we were
running late, and modified the lesson plans slightly, but with my full agreement. This exercise was conducted with the whole class participating in one large brainstorming group. At first, students were concerned that the reduction was a safety risk (as was expected). Eventually, after some reflection, some students suggested that the statistical nature of live loads warranted some kind of reduction.

Students were then asked to suggest how the reduction might be computed, and a percentage approach was soon proposed, which was rapidly approved by the class. Then the instructor asked what limits should be placed on it. Students eventually suggested two of the three limits used by LRFD in live load reduction: a limit on the maximum reduction percentage (the instructor did not ask the class to choose the numerical value of the limit), and a minimum area to consider live load reduction. Students did not suggest the third criterion, that for very large loads (100 psf and larger), reductions are not permitted except under special circumstances. The instructor and I were pleased with the results in this case—in a short time, students had figured out much of the established process of live load reduction.
Live load reduction brainstorming results

Due to the modification of the lesson plans, this stage was subsumed by the previous. All students were instantaneously aware of the input of the entire class.

LRFD live load reduction

After the brainstorming session had yielded most of the concepts important to live load reduction, the method sanctioned by AISC/LRFD was introduced, including the criteria and formulae. Students seemed to find this presentation very clear, likely because the new information was just an application of what was already understood through the brainstorming session.

Live load reduction laboratory exercise

Students were then asked to compute live load reductions using the tributary areas from the previous laboratory exercise. Since students all had the same starting point (they had the correct tributary areas after the previous exercise was reviewed), this exercise was essentially plug-and-chug (a good one for the sensors and sequentials). The primary problems observed during this
part of the laboratory were students failing to consider all the criteria in evaluating the reduction. Practice, of course, is the only way to hope to reduce the likelihood of such errors.

Live load reduction problem discussion

This part of the laboratory was done informally, as the instructor, the teaching assistant, and I were available to review the results of teams individually.

Evaluation of the Tributary Area Activity

As discussed before, the two most objective methods of evaluating the laboratory were through a survey filled out by the students ("Tributary Area Laboratory Student Evaluation" in Appendix C) and a quiz to measure the mastery level of all students ("Tributary Area Post-test" in Appendix C). As indicated before, there is some opportunity to examine the interrelation of the survey responses and the quiz scores, especially with the added factor of experience level to consider. The survey, the quiz, and their interrelation will be discussed in the following sections.
Student evaluation

The student evaluation measured a number of things. Initially, it was intended to assess student attitudes toward various aspects of the laboratory. When experience was noted as a factor in the course of the laboratory, a means of measuring it was added to the evaluation. The results of the student evaluation are also discussed in this section. Agreement level for individual statements as well as statement groupings were tested for statistical significance.

Measurement of experience. Experience was measured as a continuous variable by classifying the experience level into six categories. The first category was no experience, assigned the value of zero. This level and the others were classified as indicated below with the associated experience score (Exp). Experience here must be an independent variable, because we cannot affect it—it is a measurable characteristic of each student. It can, however, affect various dependent variables such as quiz score and survey responses.
Table 7 Classification of Experience as a Continuous Variable

<table>
<thead>
<tr>
<th>Exp</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Answered &quot;N&quot; to the question &quot;Had you been introduced to the concept of tributary area prior to the activity?&quot;</td>
</tr>
<tr>
<td>1</td>
<td>I had the concept described to me.</td>
</tr>
<tr>
<td>2</td>
<td>A sample problem was done on the board.</td>
</tr>
<tr>
<td>3</td>
<td>I did a problem informally by myself or with a group.</td>
</tr>
<tr>
<td>4</td>
<td>A problem was assigned for homework and graded.</td>
</tr>
<tr>
<td>5</td>
<td>I had a test on it.</td>
</tr>
</tbody>
</table>

Likert scale measurements. Also measured on the evaluation form were student agreement with a variety of statements. Student agreement was measured on the scale shown in the table below, known as a Likert Scale (Likert, 1932). The most significant disadvantage of Likert measurements is the fact that the scale is not consistent for all individuals (Kubiszyn and Borich, 1993). In fact, the most likely factor to cause an individual to distinguish between "Strong Agreement" and simple "Agreement" seems to be personality. Some individuals make a conscious attempt to use the full range of the measurement scale, while others are more likely to use the extremes in their opinions because they wish to be decisive. This will be discussed
further (and demonstrated) when the results of the evaluation are presented.

Table 8 Likert Scale Definition

<table>
<thead>
<tr>
<th>Subject Opinion</th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value if positively phrased</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Value if negatively phrased</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Both positive and negative phrasing of questions is used in order to ensure that students do not anticipate the meaning of the statement, but rather read it and respond to it. Using both positive and negative statements increases the number of ways available to gather the same information without seeming repetitious. By assigning the values to the negative statements in the reverse order, the scores from multiple statements intended to measure the same attitude can be averaged.

The scoring of the Likert scale is a bit inconvenient for modern methods; when students fill in circles on sheets which are scanned, the value assigned will be independent of the phrasing of the question, and thus negative numbers will
have incorrect values. This discrepancy requires additional manipulation of the data in order to obtain an average.

In previous work with Likert scales, I analyzed their behavior and discovered a simplifying scoring principle. The table below shows that for a negative phrase, the sum of the assigned value and the desired value always equals 6.

**Table 9** Manipulation of Negatively Phrased Statement Scores

<table>
<thead>
<tr>
<th>Assigned Value</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired Value</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Sum</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Thus we find that \( \text{desired value} = (6 - \text{assigned value}) \). By making this substitution in formulae which sum negatively phrased statement values, averages can be correctly computed.

**Student Evaluation Statements.** The table below gives the statements included in the Tributary Area Student Evaluation and their corresponding numbers.

**Concept groupings.** The groupings are abbreviated as follows: LF=lab format, GW=group work, TT=this team,
<table>
<thead>
<tr>
<th></th>
<th>Table 10 Tributary Area Evaluation Statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I prefer working/studying alone.</td>
</tr>
<tr>
<td>2</td>
<td>We spent too much time waiting for other teams to finish their towers.</td>
</tr>
<tr>
<td>3</td>
<td>I still don’t understand tributary area.</td>
</tr>
<tr>
<td>4</td>
<td>The block tower activity helped make me alert for the rest of lab time.</td>
</tr>
<tr>
<td>5</td>
<td>I would have done just as well or better individually.</td>
</tr>
<tr>
<td>6</td>
<td>I would prefer a formal presentation of the concept of tributary area before attempting problems.</td>
</tr>
<tr>
<td>7</td>
<td>It was educational to try to figure out tributary area without being told the method right away.</td>
</tr>
<tr>
<td>8</td>
<td>The block tower activity helped me start thinking about how load is distributed.</td>
</tr>
<tr>
<td>9</td>
<td>Working in a group is better than working by myself.</td>
</tr>
<tr>
<td>10</td>
<td>My team formed a strategy before doing the block tower activity.</td>
</tr>
<tr>
<td>11</td>
<td>My team formed a strategy based on the results of other teams.</td>
</tr>
<tr>
<td>12</td>
<td>My team’s strategy was ineffective because of the limitations of the block tower.</td>
</tr>
<tr>
<td>13</td>
<td>Other members in my group helped me see things from a different perspective.</td>
</tr>
<tr>
<td>14</td>
<td>Someone else in my group helped me understand something.</td>
</tr>
<tr>
<td>15</td>
<td>The block tower activity was a good use of my lab time.</td>
</tr>
<tr>
<td>16</td>
<td>The lab was too long.</td>
</tr>
<tr>
<td>17</td>
<td>Stretching exercises would have been just as good as the block tower activity.</td>
</tr>
<tr>
<td>18</td>
<td>Being asked to suggest methods for load reduction made me look more closely at the problem.</td>
</tr>
<tr>
<td>19</td>
<td>Trying to guess how live load reduction is accomplished was a waste of my time.</td>
</tr>
<tr>
<td>20</td>
<td>We spent more time than usual in the lab, but it was worth it.</td>
</tr>
<tr>
<td>21</td>
<td>In the past, I have not enjoyed assigned groups.</td>
</tr>
</tbody>
</table>
TG=total group, C=confidence, TW=time/worth. An “x” indicates that a statement measures that concept.

**Table 11 Tributary Area Survey Statements and Groupings**

<table>
<thead>
<tr>
<th>Statement</th>
<th>Sense (+/-)</th>
<th>LF</th>
<th>GW</th>
<th>TT</th>
<th>TG</th>
<th>C</th>
<th>TW (I)</th>
<th>TW (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>+</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>+</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>+</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>+</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>+</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>+</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>+</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>-</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The "lab format" grouping measures students' attitude toward the format of the laboratory overall; "group work" measures their general attitude toward group work; "this team" represents a measure of the group experience they had in the tributary area laboratory; "total group" includes all the components of the previous two groupings; "confidence" assesses students' perceived understanding of tributary after the laboratory; "time/worth" is a measure of whether or not students valued the laboratory as a whole, i.e., if it was worth their educational time.

**Case I research and the t statistic.** If the population of students as a whole truly has no opinion regarding a particular statement, the response should be normally distributed with a mean of 3, the neutral response. This provides us with a hypothetical mean to conduct a t-test for "Case I" research, which answers the question (Shavelson, 1988, p. 317), "Does a particular sample belong to a hypothesized population?" The t statistic is the difference between the measured average, $\bar{x}$, and the hypothesized population mean, $\mu$ (in this case, 3), normalized by the standard error (the sample standard deviation divided by the
square root of sample size; used as a measure of the
standard deviation of various measures of the mean). Where
\( N \) is sample size and the standard deviation is given by \( s \),
the observed \( t \) statistic is given by equation 1:

\[
\frac{t_{\text{observed}} = \frac{(\bar{x} - \mu)}{(s / \sqrt{N})}}
\]

**Equation 1** The \( t \) Statistic

Once an observed value of \( t \) has been obtained, the
probability that the measured mean is truly different can be
calculated from the \( t \) distribution. If this probability is
lower than the criterion established, \( \alpha \) (normally 0.05),
then it can be stated with 95% (1-\( \alpha \)) confidence that the
observed difference between the average and the hypothesized
mean is a true difference. The \( t \)-test was used in the
manner described above on both the raw data for each
question and on the question groupings described above. The
former is shown in Table 1 and the latter in Table 2, both
in Appendix C.

**Statistical and Practical Significance.** It is always
important to note the difference between statistical
significance and practical significance. Three factors can contribute to statistical significance: a tight distribution (a small value of $s$), a high number of samples ($N$), and a large gap between the measured $\bar{x}$ and the hypothetical $\mu$ will all yield a high value of the observed $t$ statistic. Only one of these, the difference between $\bar{x}$ and $\mu$, contributes to practical significance. For example, a study measuring the I.Q. (in the general population, $\mu=100$) of students may conduct a special thinking skills training program, might measure I.Q. in a post-test to discover $\bar{x}=105$. Appropriate values of $s$ or $N$ can make the resulting $\bar{x}$ statistically significant, but it is difficult to justify the expense and effort of such a special program to gain only 5 points in I.Q.—the result does not have practical significance. Unfortunately, while statistical significance is an objective and calculated quantity, practical significance can be the subject of disagreement.

**Special notes regarding the survey data.** Before discussing the results of the evaluation, it is important to draw attention to a number of notes regarding the table of raw data (these notes are also included in Appendix C with
the data). Student #8 did not complete a survey or take the quiz; as a result, that student was eliminated from consideration in any calculations.

Answers to statement 11 indicated in bold in Appendix C were irrelevant, since that statement did not apply to the two teams that went first. As a result, those numbers were not included in the computation of the average or standard deviation, and two computations of the Time/Worth grouping were made -- Time/Worth I includes Q11, but does not include the teams which went first; Time/Worth II does not include Q11, but includes the results from all teams.

Unfortunately, we must also expect that some survey respondents will neglect to respond to all statements. Answers in bold italics (St28/Q5 and St25/Q18) were blank, and neutral responses were substituted to avoid sample size differences. Given the limited number of them, and the availability of a neutral response, this approach should not compromise the integrity of the reported data.

**Tributary area evaluation results**

As discussed earlier, three aspects of the survey results can be studied: student responses to individual
statements, student responses to grouped statements representing a larger concept, and the relation of those responses to the quiz results. The last of these will be discussed after the post-test itself is presented, and the first two are presented here. There were quite a few statements which achieved statistically and practically significant opinions. These have been arranged in such a manner as to paint a logical picture which draws connections between the various significant responses. The pre-established groupings will always appear in quotes (with their abbreviations) to identify them as such.

Student responses to 13 of the 21 statements were statistically different from the mean of 3 (neutral). In considering these, I have additionally established the level of practical significance at halfway between 3 and its nearest neighbor values (2 or 4)—anything at or above 3.5 (for agreement) and anything at or below 2.5 (for disagreement). The statements which earned agreement according to these two criteria were statements 6, 9, 10, 13, 15, 16, and 18. Statements 5, 17, 19, and 21 earned disagreement in the same manner.
Students resist, then accept discovery method.

Students agreed with "I would prefer a formal presentation of the concept of tributary area before attempting problems," indicating their uneasiness with what was likely their first exposure to this teaching method. As was discussed earlier, however, the student teams all did remarkably well at predicting the most basic tenets of the established method of calculating tributary area. Later in the same laboratory, after students had such success with the first application of the method, students attitudes toward its second application, speculating a live load reduction technique, was positive as measured by responses to two statements: students agreed with "Being asked to suggest methods for load reduction made me look more closely at the problem" and disagreed with the statement "Trying to guess how live load reduction is accomplished was a waste of my time."

Students saw educational benefit in the tower activity.

Responses to two statements point to the fact that students took the block tower activity seriously (agreement with "My team formed a strategy before doing the block tower
activity”) and saw educational benefit in it (agreement with “The block tower activity was a good use of my lab time”). The time delay incurred due to it was seen as a drawback to the benefit, however (agreement with “The lab was too long”).

Students are positive about cooperative learning. The remaining significant statements all indicated positive attitudes toward cooperative learning in general or toward this specific experience working in a team. Agreement with “Working in a group is better than working by myself” and “Other members in my group helped me see things from a different perspective” as well as disagreement with “I would have done just as well or better individually” are a good indicator that the cooperative learning goals were met by this laboratory design.

By the same criteria of significance used for studying the responses of the population to individual statements, the groupings can be analyzed. Among the groupings, only three measures met both standards of significance—all three which measured group interaction: “Group Work (GW)” (3.54), “This Team (TT)” (3.63), and “Total Group (TG)” (3.54).
This was no surprise, given the previously discussed responses to statements 5, 9, 13, and 21 all indicated a positive opinion of cooperative education in general and of the teamwork experience in the tributary area laboratory specifically. Of these groupings, the opinion in support of "This Team" was the strongest (3.63).

**Strength of opinion is personality driven.** As noted earlier, the likelihood of indicating a "Strong" opinion is heavily influenced by individual differences (Kubiszyn and Borich, 1993). Students 9, 22, 23, 25, 26, 31, and 32 had no responses of strong agreement or disagreement, and even more surprising, student 12 indicated simple agreement or disagreement for only two of the 21 statements. Agreement and disagreement, when indicated, were consistently "Strong."

**Tributary area post-test**

A post-test designed to measure the mastery level of the students was designed by the instructor. The post-test, which required application of all the principles of tributary area students had been taught, is shown below.
This is also shown in Appendix C as "Tributary Area Post-test." Here, however, the joists have been numbered in order to describe the grading system devised. The instructions given to the students are given following the diagram for reference.

![Diagram of the Tributary Area Post-test](image)

**Figure 9** Tributary Area Post-test

Calculate the tributary area to the beam AB. Sketch it on the plan view. Assume all joists are equally spaced and in contact with the slab. The beams AB, DC, and CE are all at the same elevation but are **not** in contact with the slab. There is no column at C.

Students were given approximately 15 minutes to complete this exercise.
Grading system. A grading system was necessary which would be as objective as possible. The approach taken to address this need was to systematically evaluate all the members in discrete steps. With a complete list of all these steps, a review of student papers would show which steps each student had completed satisfactorily. The list follows—each step was assigned a single point for its correct completion.

1. Joist 1 shares load with the bearing wall
2. Joist 1 contributes to AB
3. Half of Joist 1 rests on the left bearing wall
4. Joist 2 contributes to AB
5. Half of Joist 2 rests on the left bearing wall
6. Beam DC contributes to AB
7. Half of Beam DC rests on the left bearing wall
8. Joist 3 contributes to AB
9. Half of Joist 3 rests on the north bearing wall
10. AB shares load with Joist 3
11. Half of Joist 4 rests on the north bearing wall
12. Joist 4 shares load with the bearing wall
13. Beam CE contributes to AB
14. Half of Beam CE rests on the right bearing wall
15. Joist 5 contributes to AB
16. Half of Joist 5 rests on the right bearing wall
17. Joist 6 contributes to AB
18. Half of Joist 6 rests on the right bearing wall
19. Joist 7 contributes to AB
20. Joist 7 shares load with the bearing wall
21. Half of Joist 7 rests on the right bearing wall

The numbers indicated above correspond exactly to the quiz scoring numbers t1-t21.
Post-test results

As is normally the case in grading tests in a design class, the different approaches students take to problem solution prove a challenge to the grader. The objective system described above was helpful in meeting this challenge. In the case of certain students, enough information was written on the quiz to indicate the student's line of thinking. This provided the ability to diagnose certain errors. Even more useful is identifying the errors which are common to most of the class.

Quiz score distribution. The distribution of quiz scores indicated a high level of mastery of the class as a whole. This corresponds with the improvement which was noted anecdotally by the instructor, although no quantitative comparison to previous classes of students exists. The histogram which follows shows the distribution of quiz scores. The full range of possible scores is shown in the histogram to show the high level of mastery achieved by the students. The mean, median, and mode of the score distribution are all equal to 18.
Range restriction. While this high level of mastery is good evidence of the teaching benefit of the laboratory, the very narrow range precludes the use of the quiz grades to compare various groups of students (among teams, experienced students vs. inexperienced students, etc.) due to a principle known as range restriction. This is especially true in measuring correlation coefficients, as noted by Shavelson (1988).

Because range restriction has occurred, it is therefore impossible to use the quiz score as a predictor of anything other than the mastery level of the class as a whole. It is possible, however, to study which steps were missed most frequently. This study may yield additional information which is useful to the educational process.
Using quiz results to diagnose educational shortfalls.

The raw data from the quiz (see Appendix C) also included a calculation of the percentage of the students who completed each step correctly. It is hardly necessary to review the percentages, since the marks for incorrect responses in three of the columns define a clear line because there are so many of them. Steps 1, 10, and 20 were completed correctly by only 55%, 52%, and 48% respectively. The next lowest is 73%, indicating that these three were not clearly demonstrated.\textsuperscript{10}

Completion of Step 10 requires some engineering judgement. The instructor and I concur, with the following reasoning: although Beam AB is not in contact with the slab, it must carry half the load between it and Joist 3, because the Joists 1 and 2, which rest on Beam AB, are in contact with the slab. The fact that Beam AB is not in contact with the slab could easily cause a large number of students to

\textsuperscript{10}A statistical test could be performed to compare measured frequency to expected frequency of step completion. This would employ a Chi Square design. This analysis was skipped for brevity's sake since Steps 1, 10, and 20 had such clearly poor completion percentages.
miss Step 10. This is not a shortfall of the educational process, but is inherent in the process of engineering, wherever judgement is involved.

Steps 1 and 20, however, are essentially the same error: failing to see that, when a joist is parallel to a bearing wall, the wall will carry half of the load between them. Since students have a firm grasp on load sharing between two joists (based on their completion of other steps with a much higher success rate), but do not see as well that walls share in the same manner, I hypothesize that the root of the error lies in students' inability to relate the picture in plan to a physical structure.

In a physical structure, for a bearing wall to carry a vertical load, it must somehow be attached to it. In some cases (such as in the basement garage at my house), this is done by anchoring a ledger beam to the bearing wall with carriage bolts. In the plan view provided to students (such as in the post-test), however, this ledger beam is not shown. In fact, there is no indication in the picture provided as to how load transfer to the bearing wall might occur. As a result, I have hypothesized that students fail to assign any load to the bearing wall simply because they
cannot see the path by which the floor load is able to transfer to it.

This hypothesis can easily be tested. The instructor plans to address this specifically upon teaching the class again, in order to clarify the misconception. If the same test is administered again, the students’ success rate in completing Steps 1 and 20 should be much more in line with the other frequencies.

**Student comments on the lab as a whole**

Two students contributed made comments on the lab as a whole. These two comments are included here. One student said simply, “Great idea.” The other comment was more specific (and longer): “Good lab ... different approach was good ...”

**Design of an 11th-12th Grade Statistics Activity**

The greatest barrier to evaluation of the methodology in an experiment with a teacher in the public school system is a human relations phenomenon. The teachers who are most
interested in assisting in this educational research are the teachers who are already good teachers. There is little which could be done to avoid this, since the collaborating teacher would undergo additional effort in order to conduct the educational experiment in addition to teaching the students. Further, teachers in the public school system are more bound to established curriculum materials than are university professors. Using university contacts within the local teaching community, a high school physics teacher, Dr. Cynthia Holland (of Newberry High School, Newberry, Florida), was located who would assist in testing the Engineering By Design methodology.

The Design of the Activity

The design of the lesson was initiated when Dr. Holland met with me at her school to develop goals. She indicated that statistics was not included in the curriculum, but that she wanted to introduce it along with a spreadsheet/graphing/statistical analysis software product she wanted to test out. We agreed that the goal would be to develop a lesson to teach certain principles of descriptive
statistics. Descriptive statistics are statistics which organize and describe a group of data. Those statistics we decided to specifically address in the lesson were measures of central tendency (mean, median, mode) and measures of variation (range, standard deviation).

Once the goals had been set, we decided that the class would be divided into two groups, a control group which would be taught by a typical lesson, and an experimental group which would be taught by the lesson developed by our collaboration. In order to avoid having our collaboration contaminate the process by which Dr. Holland normally develops lesson plans, we postponed the further development of the experimental lesson until she had already made her own plans. Three problems arose at this point—the first was already mentioned briefly, that Dr. Holland is already accustomed to using active and cooperative educational techniques. It would be unethical to ask her to teach by techniques which she knows to be less effective—both for ethical reasons and because it would contaminate the experiment by making her teach in an unfamiliar manner to the control group. The second complication was that the goal was sufficiently vague that although she had envisioned
the educational process surrounding the data, she had not established exactly what data was to be collected. The third difficulty compounded the second—because I began to discuss the lesson with Dr. Holland and then postponed completing it with her, I entered into what is referred to as an incubation period, where idea generation begins (Lumsdaine and Lumsdaine, 1995a). During this time, I recalled an account related to me by a former classmate of mine, now Dr. Robert Smith of Sandia National Laboratory, who was demonstrating projectile motion for some public school students in an “Ask Mr. Science” educational format. During his demonstration, students had noticed that the projectile did not always appear to land in the same place, even though conditions appeared identical for each trial. As a result, a broad discussion of variation and error ensued.

Seeking to create the same climate of inquiry that my former classmate had achieved, I was very interested in capturing the excitement of a projectile experiment to spark the thinking of the high school students. When Dr. Holland and I met again, she was very interested in the approach I suggested. Unfortunately, simplicity (and generating a
larger total set of data) required that all students work with similar equipment collecting the same type of data. As a result, an element of my creative process was integrated into the lesson plans for both the experimental and control groups. This flaw in the research design would cause problems later on in distinguishing between the experimental and control groups.

The remainder of the lesson was developed as follows: the experimental group would begin with brainstorming and discovery activities which are discussed later in this section—the control group would receive a brief introduction and collect data during that time; data collection for each group would last three class periods. Since the control group would start collecting data one day earlier, the instructor would formally introduce the concepts of descriptive statistics in her usual manner on day 4, while the experimental group was still collecting data. The two groups would then receive instruction as a single group on how to use the software being introduced. Individual laboratory pairs would remain together to complete a laboratory report—referred to as a "Final Exam Project" by Dr. Holland. After the laboratory reports were completed, a
post-test (described later) would be administered to all students.

**Designing Experimental and Control Groups**

The physics class used for the experiment had sixteen students. Dr. Holland divided the students into two groups, an experimental group and a control group. The two groups were designed to be similar with respect to the ability level of the students. The groups were also gender-balanced. By balancing ability and gender between the experimental and control groups, these would not have to be considered as factors contributing significantly to any measured effect.

**Introductory Brainstorming Activity**

The brainstorming activity occupied one class period. Students were shown the experimental apparatus, a NERF® device which launches foam darts, attached to a hinged platform which can be adjusted to fix the launcher continuously over a great range of launch angle. Students were allowed to test it out for a while.
Central tendency

Since students quickly notice (or assume a priori) that darts launched from the same trajectory do not always land in the same spot, it was soon natural to move into the brainstorming exercise. Students were then asked, "How should we determine the "ideal" landing spot—the one we would predict?" The various ideas recorded by the teams in the experimental group were as follows (in no particular order):

A. Shoot from the floor (presumably to avoid ceiling)
B. Use the same dart for each test
C. Measure how far to left or right the dart goes
D. Graph the results
E. Calculate time in the air by measuring maximum height and doubling the free fall time
F. Weigh the dart
G. Take average of where the darts land
H. Find the center of the smallest circle which encompasses all the data points
I. Determine the landing zone hit the most
J. Draw a circle with the average as the center
K. Find out how far each dart lands from the average

The ideas above range in scope, including experimental procedure, prediction of sources of error, data analysis, and descriptive statistics. The last two are particularly interesting—even before any discussion of variation, these two ideas, especially K, essentially describe the procedure.
by which standard deviation is calculated (standard deviation is essentially the average distance from the mean). Idea I is precisely the definition of mode. It is no great surprise that students did not suggest anything corresponding well to the median as a measure of central tendency—the median has no meaning in a two-dimensional problem. If the problem had been restricted to a one-dimensional problem (say strictly to distance from the launcher) rather than a two-dimensional estimate of the actual landing spot, students may have been more likely to describe the median as a measure.

**Decreasing observer dependence**

The instructor then illustrated the effect of the observer on measurement—if the dart doesn’t stick when it lands, different observers will think the dart landed in different places. Students asked to speculate, "How can we more accurately determine the landing spot?" Student ideas are listed below—in this list as in the others, redundant ideas are not repeated, but all ideas are included.

A. Put chalk/paint on the end of the dart  
B. Have one person watch very closely  
C. Use a video camera to record trajectory
D. Shoot the dart into sand/whipped cream
E. Coat the floor with carbon paper
F. Coat the dart with a sticky substance
G. Use radar/laser tracking system

Sources of error

The teams in the experimental group then brainstormed the question, "Why is there variation in the landing spot?" to generate the following list of possible sources of error:

A. Shooter technique
B. Aerodynamics are different for each dart
C. The dart is different each time you shoot it
D. Air currents
E. Chaos
F. Dart weight differences
G. Recoil of apparatus
H. Movement of apparatus by pulling launch string
I. Apparatus has instability in base
J. The apparatus is just a toy
K. The darts are different sizes
L. The way that the dart is loaded

Students have covered three major categories of sources of error: the effects of experimenter inconsistency (A, H, L), equipment accuracy (C, F, G, I, J, K), and uncontrolled environmental conditions (B, D, E).

Measuring variation

Having identified sources of variation, students were asked to speculate, "How should we measure how much
variation there is?" This question yielded the following responses:

A. Calculate the total area over which it lands
B. Find out how far each dart is from the mean
C. Draw a line at the average distance and measure the perpendicular distance to the landing points
D. Let the computer do it for us
E. Graph data, see how it looks visually
F. See how far each value is from the mean/median/mode
G. Graph mean/median/mode along with rest of data.

The ideas generated here are also excellent—A describes the range (again, in two dimensions); methods similar to standard deviation are suggested by B, C, and F; C additionally constrains the problem to one dimension by measuring only perpendicular distance. While suggestions like D are an anathema in education, it is certainly a possible approach to the problem, and is appropriately included in a list of ideas.11

The Post-test and Results

The post-test is included in Appendix D, with the scoring system indicated with each question. The test

11An all too common one, apparently—the first post-test question was "Why are deviations from the mean squared in computing standard deviation?" Of the 16 students tested, four students responded "the computer did it" or similar.
administered was intentionally difficult to avoid range restriction. Some questions allowed students to speculate far beyond the descriptive statistics taught through the lesson—even to the point of defining principles of inferential statistics. The various concepts addressed by the questions on the post-test are listed below. Each concept is designated by a letter for reference in the table of questions which follows.

**Table 12 Concepts tested by the Statistics Post-Test**

<table>
<thead>
<tr>
<th>Key</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Measures of central tendency</td>
</tr>
<tr>
<td>B</td>
<td>Limitations of measures of central tendency</td>
</tr>
<tr>
<td>C</td>
<td>Measures of variability</td>
</tr>
<tr>
<td>D</td>
<td>The magnitude of standard deviation</td>
</tr>
<tr>
<td>E</td>
<td>Statistical inference (predicting population behavior from a sample of the population)</td>
</tr>
<tr>
<td>F</td>
<td>The effects of sample size</td>
</tr>
<tr>
<td>G</td>
<td>Accuracy and precision</td>
</tr>
<tr>
<td>H</td>
<td>Factors which affect distribution shape / skew</td>
</tr>
<tr>
<td>I</td>
<td>The effect of “curving” by adding a constant</td>
</tr>
<tr>
<td>J</td>
<td>The principle of range restriction</td>
</tr>
</tbody>
</table>

Note the advanced nature of some of these concepts, which require the students not only to prove their understanding of what was covered in the lesson, but to extend their understanding well beyond that coverage. The
concepts addressed in each post-test question are listed in the following table.

**Table 13 Post-Test Concept Coverage**

<table>
<thead>
<tr>
<th>Question</th>
<th>Concepts covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>2</td>
<td>A, B</td>
</tr>
<tr>
<td>3</td>
<td>A, B, H</td>
</tr>
<tr>
<td>4</td>
<td>A, C, J</td>
</tr>
<tr>
<td>5</td>
<td>A, C, D, I</td>
</tr>
<tr>
<td>6</td>
<td>A, B, H</td>
</tr>
<tr>
<td>7</td>
<td>C, D, H, J</td>
</tr>
<tr>
<td>8</td>
<td>C, E, H</td>
</tr>
<tr>
<td>9</td>
<td>A, B, H</td>
</tr>
<tr>
<td>10</td>
<td>A, B, H</td>
</tr>
<tr>
<td>11</td>
<td>E, G</td>
</tr>
</tbody>
</table>

Although the test was very difficult (the class average score was 24.25 out of a possible 56), there was not a single scoring category (some questions were asked in two parts) in which no students received credit.

Unfortunately, there was no statistical or practical significance in the difference between the experimental group average (25.0) and the control group average (23.5). Since it cannot be inferred as to whether the activity created using the *Engineering By Design* methodology yielded
any improvement over the educational method used with the
control group, all that is left is to analyze the effects
which could have made such an improvement impossible to
detect.

Effects Operating in this Experiment

Each group was aware of the experiment; it was
impossible to prevent this occurrence—students were
constantly about working on projects while Dr. Holland and I
met, they witnessed the testing of the apparatus (which was
a good deal of fun for us and a few other interested
teachers), and they knew that the class was being divided
into two groups. This awareness opened up the possibility
of a number of the effects described earlier. The John
Henry effect was certainly operating, as noted by the
instructor from the first day forward. She reported that
the control group had developed a sense of competition,
since they had not been chosen for the "experimental" group.
Students in the control group viewed the success of the
experimental group as a threat to their peer status (a
critically important factor). This threat to status is
clearly a hallmark of the John Henry effect. This same objective may be commingled with the demand characteristic motivation to thwart the research in order to achieve superiority over the researcher and the experiment itself. Anecdotally, the instructor indicated that a lot of learning went on in the entire class, and that she was very pleased with the results of the "Final Exam Projects" submitted to her.\textsuperscript{12}

\textsuperscript{12}These projects, however, are not appropriate as an evaluation of the experimental lesson, since they tested a great many objectives not addressed specifically by the lesson, such as laboratory procedure and writing syntax.
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The success of an individual activity can only be measured against its objectives. The Truss Bridge Laboratory, which served as a prototype activity in the development of the Engineering By Design methodology, has fulfilled its objectives within the Introduction to Engineering class, as indicated in chapter 4. These objectives included informing students about Civil Engineering and improving recruitment and retention. Similarly, the tributary area laboratory met its primary objective: to teach students tributary area.

The objectives of Engineering By Design are different from the objectives of the activities the methodology is used to generate. The statistical results of the tributary area post-test and student questionnaire indicate that the methodology produced a lesson of educational value which was favorable to the students. The present work cannot claim to have produced an improved lesson delivery, since a control
group was not present. No claim can be made based on the high school statistics lesson generated.

Dissemination of the methodology by publication in educational journals alone is not likely to reach the greater population of K-12 teachers. Instead, an engineering activity curriculum design aid might more effectively reach a wide audience. I will also continue my work by developing K-12 curriculum materials, in collaboration with K-12 teachers.

This research can be infused into engineering academia through the development of an educational psychology primer for engineering professors. Relation of the principles of education included in chapter 3 to traditional engineering teaching methods makes this practical. The learning and teaching principles of chapter 3 and the design methodologies discussed in chapter 2 have direct application in creating engineering activities, as shown in chapters 4-5. The discussion of human development included in chapter 3 is more pertinent to in-class assessment of students. A primer would be able to provide those in engineering academia with the framework to understand the educational process as developed through educational research.
The results of the tributary area post-test indicated a path for future research. It would be of great benefit to remediate frequent errors dealing with a particular concept. The new lesson can be tested more definitively in the coming year, made possible by a larger number of enrolled students which has been divided into two classes. Using the same post-test to evaluate a group taught with the new laboratory and a control group taught with the more traditional problem set approach would more adequately test the real benefit of the Engineering By Design methodology.
APPENDIX A
INTRODUCTION TO ENGINEERING HANDOUTS

The complete handout for the Civil Engineering component of the University of Florida Introduction to Engineering class are included here. The class as a whole has components representing all the undergraduate engineering programs at the University of Florida and two sessions focusing on various computer skills.

Included in this Civil Engineering component is the Truss Bridge Laboratory, the prototype activity used to develop the Engineering By Design methodology.
Introduction to Engineering
University of Florida
Civil Engineering Laboratory Agenda

1. Roll Call - Brief Introduction
2. Summary: the Various Specialties of Civil Engineering
3. Explanation of Tests to Be Performed
4. Concrete Compression Test - Discussion of Quality Control
5. Steel Tension Test
6. Introduction to the Truss Bridge Laboratory
7. Truss Bridge Design and Construction
8. Truss Testing and Scoring
9. Discussion of Results
10. Dismissal - Students may stay after with questions
WHAT IS A CIVIL ENGINEER?

Civil Engineering is a broad engineering discipline that incorporates many different aspects of engineering. As a CE, you generally would work in one of the following areas:

1. **In Private Practice**
   Plans, designs, constructs and operates physical works and facilities used by the public.

2. **In Academia**
   Teaches students the fundamentals of civil engineering. Also involved in research in order to advance the state-of-the-art.

3. **In Public Practice**
   Plans cities and/or regions, oversees layout and construction of highways and pipelines.

4. **In Combination with other Disciplines**
   A civil engineering degree combined with another degree such as: Engineering Geologist, Engineering Economist, or Engineer/Attorney

Civil Engineering itself is composed of various different areas of engineering. The general types of civil engineers include:

- Structural Engineer, Water Resources Engineer, Geotechnical Engineer, Transportation Engineer, and Construction Management Engineer

Below is a short description of each of the above types of Civil Engineers.

A. **Structural Engineer** - Plans and design of buildings of all types, bridges and specialized structures (power plants, nuclear reactors, television towers and radar facilities). Wherever concrete, steel, aluminum or wood are required to carry loads, Structural Engineers do the planning and design. Usually works closely with the Architect.

B. **Water Resources Engineer** - Works with water, its control and the development of water supplies. There are several areas that one can work in:

1. Hydraulic Engineer/Hydrologist - Analyzes rain fall data, characteristics of flow in open channels and pipes, designs, reservoirs, studies pollution migration and coastal and shore line protection.

2. Sanitary Engineer - Plans and designs municipal water facilities such as water treatment plants and sewage treatment plants. Also may operate and maintain these facilities.

3. Water Related Structural Engineer - Design such project as: hydroelectric plants, canals, docks and piers.
C. **Geotechnical Engineer** - Works in the field of soil and rock mechanics. Analyzes subsurface conditions and determines and designs the type of foundation to be used for the particular structure. Also designs dams, tunnels, and mining facilities.

D. **Transportation Engineer** - Designs highway systems (layout, routing), pavement material, airport runways, and rapid transit projects. Also involved in computer control of traffic signals.

E. **City Planner** - Urban planner, zoning requirements, member of advisory board.

F. **Construction Management** - Major responsibility for insuring that a project is being built properly and according to schedule. In charge of actual construction.

G. **Research Engineer** - Works for a University or large firm (R&D). Might study stronger concrete, better wearing asphalt, new construction materials and methods.

**CIVIL ENGINEERING JOB CHARACTERISTICS**

Below is an outline of typical jobs a civil engineer might do. If the company is large, you might be involved in one of the items. If, on the other hand, you go to work for a small company, you may be involved in all aspects of a project.

1. **Accumulation and Analysis of Basic Data**
   a. Runoff information of a river and/or rainfall data
   b. Subsurface information for the foundation design of a structure
   c. Population growth statistics
   d. Earthquake data
   e. Laboratory analysis of soil, cement and water

2. **Preliminary Design**
   a. Foundation type and design
   b. Structural frame and material
   c. Earth or rock filled dam
   d. Highway
   e. Sewage treatment plant

3. **Cost Estimate**
   a. Determine quantity of material needed for the project
   b. Figure out total cost of the structure
c. From this you may have to reduce the scope of work to fall within the budget

4. **Design Drawings and Specifications**
   
a. Prepare contract plans and specifications for bidding contractors
b. Answer any questions they may have regarding the project.

5. **Supervision of Construction**
   
a. Responsible for inspection during construction
b. Certifies that the facility was built according to the plans/specs

6. **Operations and Maintenance**
   
a. Monitor the operation of the facility
b. Suggest improvements to enhance the operation

Of course, as a recent graduate, you would not be expected to perform the above tasks on your own. You would be assigned to an engineer who would teach you "the ropes." As you gained experience, you would be given more and more responsibility.

Generally speaking, you will work a standard 40 hour week, or 8 hour/day. Civil engineering jobs usually start early in the morning - 7:30 to 8:00 a.m., since that is when construction begins. The days ends around 4:30 to 5:00 p.m. One usually does not work on weekends, unless there is a disaster. Civil engineers will almost certainly conduct field work regularly. A lot of civil engineering involves work outside of the office. Another attribute is that since you have taken a lot of different types of engineering courses, you can work on a variety of different types of jobs - say a shopping center one month, an earth dam another and a highway project the next. Finally, civil engineers travel a lot. Since you are involved in the construction of a project, you must go where the work is being done. Many of our graduates travel to Saudi Arabia, the Orient and South America.

**EDUCATIONAL REQUIREMENTS**

All civil engineers have attended a 4-5 year curriculum at an accredited college and received their Bachelor of Science in Civil Engineering (BSCE) degree. Many then continue on to obtain their Master of Engineering degree. This usually takes an additional 1 to 1.5 years. If you are really into research, you may continue on with your education and attempt to earn your Doctor of Philosophy (PhD). This degree can take anywhere from 2 to 6 years beyond the Master's degree. While most students finish college with their BSCE degree, remember that a long time ago it was a big deal to have your high school diploma. Today, more and more companies are hiring Master's degree recipients - and the trend is continuing.
A bachelor's degree at the University of Florida is broken down into two phases: general education/pre-professional and upper division. During the first two years in college, you will take all the general college courses and the pre-professional courses. Once having completed approximately 64 semester hours, you will need to apply to the Department of Civil Engineering in the College of Engineering. After admission to the Department, you will take those courses which apply to the field of civil engineering.

First Two Years

<table>
<thead>
<tr>
<th>General Education</th>
<th>Preprofessional</th>
</tr>
</thead>
<tbody>
<tr>
<td>English</td>
<td>*Calculus</td>
</tr>
<tr>
<td>Social Science</td>
<td>*Chemistry</td>
</tr>
<tr>
<td>Humanities</td>
<td>*Physics with Calculus</td>
</tr>
<tr>
<td>Those courses marked with an asterisk</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td></td>
<td>*Fortran for Engineers</td>
</tr>
<tr>
<td></td>
<td>*Biological Sciences</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engineering Core</th>
<th>Civil Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statics</td>
<td>Construction</td>
</tr>
<tr>
<td>Dynamics</td>
<td>Hydraulics</td>
</tr>
<tr>
<td>Strength of Materials</td>
<td>Geotechnical</td>
</tr>
<tr>
<td>Electrical Engineering</td>
<td>Structural</td>
</tr>
<tr>
<td>Thermodynamics</td>
<td>Transportation</td>
</tr>
<tr>
<td>*Engineering Statistics</td>
<td>Surveying</td>
</tr>
</tbody>
</table>

If, after graduation, you continue on for your Master's degree, you will take advanced courses as well as perform some supervised research. A requirement for this degree is the submission of a Thesis (or report) on your particular research topic. A Ph.D. requires a substantial amount of unsupervised research, and in addition, it must be original work.

During your senior year in college, you should take the EIT (Engineer Intern) exam. This is a test given by the State of Florida that will eventually allow you to become a Professional Engineer. After passing the EIT and working under a PE for 4 years, you may take the PE exam. Once you pass this, you are considered a licensed engineer and may offer services to the public.

SALARY ESTIMATES

From our recent graduates, a BSCE engineer can expect to start at approximately $27,000 - $31,000. A master's degree recipient can earn initially $32,000 - $36,000. Ph.D.'s usually go to work at a University or else with a large company that does a lot of research. They usually start at $45,000 - $50,000.

ADVANCEMENT IN THE PROFESSION

As in many professions, unless you own your own firm, you will probably go into management in order to advance up the corporate ladder. This means that you will do less and less real engineering and more and more paper pushing. If this is of interest to you, it would help to take some elective courses in management during your college career.
DEFINITIONS OF TERMS

During the course of this lab, you will be introduced to and use the following terms. You will need to know the meaning of these terms in order to understand the tests. These terms are used by many types of engineers - all the time.

**Compression** - This, as you would expect, describes a "squeezing" action or force on an object.

**Tension** - The opposite of compression, or a "stretching" action or force on an object.

**Stress** - A measure of force per unit of area, lb/in² (psi), kN/m² [the same units as pressure]

**Strain** - A measure of deformation or elongation of a material, its units are inch per inch; it is the ratio of a change in length to the original length of a specimen.

**Strength** - The stress value at which a sample of material fails.

**Modulus of Elasticity** - Relates stress to strain and visa versa. It is the ratio of the stress on a sample to the amount of stain that level of stress causes. It is also the slope of the straight line portion of the stress-strain curve for a specific material.

**Elastic Range** - The portion of the stress-strain relationship for a material where if the specimen loaded and then unloaded, it will return to its original undeformed shape. The straight line portion of the stress strain curve.

**Moment** - Bending forces in a beam characterized by compression at the top and tension at the bottom of the beam, or vice versa.

**Neutral Axis** - A line which runs along the length of a beam where stress and strain are equal to zero.

**Moment of Inertia** - This is one measure of the stiffness of a beam. It relates cross sectional area and the distance from the neutral axis at which the majority of the area is located to the ease in which the beam is bent. Example: An "I" beam has a greater moment of inertia than a flat plate of the exact same cross sectional area.
Materials Used in Civil Engineering

Concrete

Concrete is a structural material which consists of cement, aggregate (sand, stones, gravel, etc.), and water (to make a chemical reaction called hydration occur). Concrete can sometimes contain other substances, such as fly ash from industrial smoke stacks. The strength and other properties of concrete are dependent on how the various ingredients are proportioned and mixed.

Concrete is a very strong material when it is placed in compression. It is extremely weak in tension, however. It is for this reason that we use reinforcement in concrete structures. The reinforcement, usually steel, gives concrete support in tension.

There are many ways to test the strength of a batch of concrete. The tests used can be categorized as destructive and nondestructive tests. We will perform only the first. Usually when a batch of concrete is ordered on a job site it is specified to be of a specific compressive strength -- 4,000 psi, for instance. When the concrete comes to the job site in a ready-mix truck, the contractor places some of the batch in cylinders which are 6 inches in diameter and 12 inches in height. These cylinders are cured for 28 days and tested by compression until they are crushed. This will give the contractor or the engineer the compressive strength for that batch of concrete. He or she can then compare that value to the design value used to make sure that the structure meets the designed specifications.

A concrete cylinder will be tested to crushing in a compression testing machine in the structures lab. Generally, the cylinders we test will be of concrete designed to be 6000 psi. For a 6 inch diameter cylinder, the cross-section in compression has an area of approximately 30 square inches. We therefore expect the cylinder to carry at least 180,000 pounds. There is a digital read out of the specimen load. This will read one tenth of the load, or the load in tens of pounds. The easiest way to read the meter is to imagine an extra “0” digit at the end of the display.

Concrete Strength

Concrete and steel are the most widely used materials in engineering design. Concrete is very important material for the civil engineer designing in Florida because steel is not readily available and can be very expensive to bring to the site. Some advantages of using concrete in design are as follows: high fire and weather resistance, relatively low cost (most of the materials can be obtained locally), can be poured to fit odd shapes (good for unusual architectural designs). As you drive down I-75, I-4, or on the turnpike you will notice that almost all the bridges are constructed of concrete. As you walk around Weil Hall (the building you are in now) you will notice that the beams and columns are made of concrete. The new South End zone for the University of Florida's Football Stadium and the new addition to the commuter parking garage were constructed using concrete. These are just a few examples.
Unlike steel, concrete is adequate in strength in only one direction. Concrete is very good in compression but useless in tension. Engineering design is based on concrete's compressive strength. Compressive strength, $f_c$, refers to what concrete is capable of resisting from loads when they are pushing on the concrete (compression). Compressive strengths for concrete are usually in the range of 3,000 to 6,000 psi (pounds per square inch). To correct for the lack of tension strength in concrete, high tensile strength steel is placed in the tension side of concrete. The steel used for reinforcement usually consists of round steel bars often called rebars. When this combination occurs it is called reinforced concrete.

When civil engineers design, they obviously need to know the strength of the material that they are using. By knowing the strength of the material that is being used and the loads (forces--- i.e. people, cars, furniture, wind) that will be acting on the particular member (beam, column, arch, etc.) the engineer can pick the correct dimensions for the design.

In today's lab, two tests will be introduced to check the structural quality of concrete (find its strength). The first test involves loading the concrete cylinder shown in the drawing until failure. This test is useful for checking the strength of the concrete that is presently being used for a construction site. The American Concrete Institute's Code specifies that a pair of cylinders shall be tested for each 150 yd$^3$ of concrete or for each 5000 ft$^2$ of surface area actually placed. This is a quality control measure.

![Measurement of Compressive Strength of Concrete, $f_c$.](image)

6" x 12" concrete cylinder used for testing.

Possible sources of error:
Steel

Steel is a structural material which consists mostly of iron and carbon. It can, however, contain other additives which might change the steel's properties. Steel can be hot rolled or cold formed into structural shapes, such as the familiar "I" beam--known today as a wide-flange. Unlike concrete, steel has the same strength in tension as it has in compression.

We will perform a tension test, which can be used to measure the material properties of a steel specimen (or a specimen of any material, for that matter).

We will perform the tensile test first. A cylindrical "coupon" made of steel will be placed in the tensile testing apparatus. The coupon will then be pulled until it breaks. A displacement indicator will be attached to the coupon to take measure the elongation of the specimen.

From the information gathered from this test, we can calculate the modulus of elasticity (a measure of the steel's stiffness), the stress experienced by the coupon, and the strength of the steel which made up the coupon.

Some of what you have done is very similar to what actual engineers do in "real life". Congratulations - if you like doing this type of work, you are on your way to an exciting career in engineering.
Civil Engineering Truss Bridge Laboratory

Bridges are essential to our nation's infrastructure. A simple bridge can be made by spanning a gap with planks. As the gap becomes wider, however, the planks will begin to sag excessively even under the weight of a person. If the bridge is longer still, the planks may break. When one of the planks, called a beam, is loaded, it bends as shown below. Lines are drawn on the beam for illustration.

A close-up view of a short segment of the beam is shown below. The top part of the beam is being squeezed (in compression) and the bottom part of the beam is being stretched (in tension). The force in the beam actually changes continuously from the top of the beam to the bottom. That means that in the middle (top to bottom), it is neither in compression nor tension. These forces act so as to bend the beam. This bending force is referred to as moment, as shown in the diagram.
If a plank bridge breaks, it is likely to splinter in the middle leaving the rest of the plank undamaged. This is because the center of the plank experiences much more moment than the ends, which experience none, because they are free to rotate without resistance. So the moment, or bending force, varies continuously from zero at the left end to its highest value in the middle and back to zero again at the right end. The result is that, although it is simple to build, a plank bridge does not make very efficient use of material.

One way of making more efficient use of wooden beams is to stand them on edge. If you have ever been in an unfinished attic, you may have noticed that the floor beams (and the rafters) are in this configuration. The beams don't bend as much in the upright orientation. This is because of a property called moment of inertia. The basic principle of moment of inertia follows. As we saw before, the highest compression and tension occur in the very top and the very bottom of the beam, respectively. We also found out that the middle of the beam (top to bottom) isn't working very hard at all. So what we want is to have as much material at the outer edges as possible and have as little material in the middle as possible. The pictures below show some beams to illustrate moment of inertia.

![Diagram of beams with moment of inertia explanation](image)

The two beams above are called I-beams because of their shape (when looked at on end). The left beam would be made of steel and the right of concrete. These show how material is concentrated at the top and bottom of the beam.
The more material and the farther away from the center it is, the higher the moment of inertia, and hence the stronger the beam. As nature would have it, achieving greater distance from the center is more beneficial than adding more material, because the moment of inertia increases as the square of that distance.

Obviously, we cannot remove all the material from the middle of the beam, because the top and bottom must be connected. The material in the middle also keeps the top and bottom from sliding with respect to each other in what is called shear. Yet there is a more efficient way to focus material at the top and bottom and provide resistance to shear. The middle part of the beam does not need to be solid and continuous, but can instead be made up of thin rods. This is shown in the figure below.

![Truss Diagram]

This configuration establishes the basis for what is known as a truss. A truss is the oldest and most often used method of making more efficient bridges, and you will be building one today. A truss is a structure made from straight links connected at joints. The joints are always at the ends of the links, never in the middle. The links are called members, and in your case, they are craft sticks with drilled holes. The joints are assembled with small bolts in your case. If the term members makes you think of a team, you are on the right track. When a load is applied to any joint, the members will share the load, although not equally.

**Stability and Simple Trusses**

There is an important characteristic of a useful truss: it must be stable, which is to say that it should not move freely in any direction. Below are some configurations of members joined at the ends. The first shown is the most basic triangular truss. The left support only allows connected members to rotate. The right support additionally allows horizontal movement. This configuration is stable, because there is no motion which can freely occur.
Two members connected at a joint form a *hinged arch*, as shown below. A hinged arch may be added to any stable truss to form another stable truss, as long as the angle of the arch is other than 180°. A truss which can be assembled in this manner is called a *simple truss*.

Shown next is a square configuration. This is unstable, because the side pieces will lean over freely as the top is pushed horizontally. How would this be stabilized?

A pentagonal configuration is also unstable, because as points A and B move apart, point C is free to move. How many members are required to make this stable? In a similar fashion, all but the triangle (or more precisely, a hinged arch attached to a stable structure) will be unstable, so this is the basis of any truss structure.
The Long and Short of It

Another special feature of trusses is that the members don't bend. They get pulled apart (in tension) and pushed together (compression), but they aren't loaded in the middle like the plank is when you stand on it. The members stay straight from end to end until they fail. This doesn't mean the bridge will stay straight, though. As heavier loads are put on the bridge, it will still sag. This is because the individual members of the truss are getting longer (if they are in tension) and shorter (if they are in compression).

A Belt Isn't the Only Thing that Buckles

Many materials, in theory, have the same strength when being squeezed together (in compression) as they do when pulled apart (in tension). The problem is that if you press the two ends of a thin member (like a ruler) together, it doesn't simply stay straight and get shorter, but instead it bends out to the side. This is called buckling, which is the way that most tall, skinny things break when compressed end-to-end. In general, when a member buckles, that member cannot sustain any more load.

How Could My Truss Fail?

There are three ways (called modes) in which your truss can fail. If a member buckles enough, it will bend and break in the direction in which the craft sticks have a low moment of inertia. This may be prevented if the loading frame supports partially buckled members. This may also be prevented because when buckling occurs, the geometry of the truss changes, which can reduce the load on the buckled
member, preventing it from breaking. Another type of failure is that a craft stick pulls apart in the middle in tension. This mode of failure will be uncommon. The third type of failure possible is joint break-out. This is when the craft stick breaks right where the bolt is connected. Because buckling strength and joint strength are the least predictable, these will be the most common modes of failure.

**Sample trusses**

Below are some samples of common trusses used in bridge construction. These are generally built by paid professionals from steel rather than a limited number of craft sticks and bolts. These are provided to give you an idea of how other designers approached this problem historically, and these are not the only designs possible.

![Warren Truss](#)

Warren Truss

![Howe Truss](#)

Howe Truss

![Pratt Truss](#)

Pratt Truss
Problem Statement

Objectives:
Build a truss bridge which will span at least 18".
Build it to support as much weight as possible.
Use as little material as possible.

Materials:
27 full-size craft sticks with holes drilled in the ends
29 shortened craft sticks with holes drilled in the ends
20 of #7 bolts and matching nuts

Equipment:
Ruler, Screwdriver, Wrench

Loading:
You must designate one or two bolts to which a wire will connect to attach the load as shown in the figure. Each load point must be more than 4 inches from the inside edge of the support (toward the center).

Procedure:
You will work in teams.
Count your sticks, bolts and nuts.
Verify that all your materials are of acceptable quantity and quality.
Craft sticks which are damaged or improperly drilled may be replaced.
Assemble a truss which meets the three objectives keeping in mind the principles we have discussed today.
Keep a record of the following for your completed truss:
a diagram of your design
the number of long members used
the number of short members used
the number of nut-bolt pairs used
the weight at which your truss fails

Excerpts from the ACSD (American Craft Stick Design) Code:
Nuts must be fully seated (bolt threads show).
All structures must be stable or they cannot be loaded.
Loading diagram:

Plexiglass loading frame

Support

Wire

Support

Bucket filled with gravel sand or rocks

MIH Sand and Gravel Supply, Inc.

greater than 4"

greater than 4"

Scoring:
Trusses will be scored as to how well the second and third objectives are met. The higher the load the truss supports, the higher the score. The less material used in its construction, the higher the score.

The score is calculated as follows:

\[
Score = 100 \times \frac{Failure\ Load}{Cost}
\]

Cost is calculated as follows:

\[
Cost = 2 \times (number\ of\ bolts) + number\ of\ long\ craft\ sticks + 0.75 \times (number\ of\ short\ craft\ sticks)
\]
APPENDIX B
THE ENGINEERING BY DESIGN METHODOLOGY

The pages which follow include the formatted methodology referred to earlier in the dissertation. All references to Engineering By Design refer to this document.
Engineering By Design
a Methodology for Designing Creative Engineering Activities
by Matthew W. Ohland

**Step 1: Establish Goals.**

These may be general. While their success need not be measurable, it should be easily achievable within the time allotted.

Some sample goals are given below:
- To teach a particular concept
- To occupy students in an entertaining, educational after school program
- To educate students about engineering and its role in society
- To develop creative thinking and problem solving skills
- To build interpersonal and communication skills through cooperation

**Step 2: Select a Focus.**

If your objectives are very broad (e.g.: to educate students about engineering), you may need a focus for the activity. In the example above, you might decide to focus on building a bridge. This focus will provide a physical example of the role of all the disciplines of civil engineering.

Depending on your goals, you may have a wide range of choices for a focus. If this is the case, consider the following factors in selecting a focus:
- It is easier to teach something you are interested in.
- Involving current issues helps ground the problem in reality.
  - e.g.: recycling, cost concerns, reference to local concerns
- If your students have particular interests, consider them.
  - e.g.: students in Florida might be interested in hurricanes

Do not be concerned about the details of the activity during this step; in fact, the fewer details specified here, the more successful Step 3 will be.

Some examples of the focus of an activity might be:
- The difference between mass and weight
- How to approximate measurements
- The concept of leverage
- The concept of moment of inertia
- The concept of tributary area
- Analyzing failure modes of common toys
Step 3: Brainstorm for Ideas.

Quantity is more important than quality in this step. Brainstorming should be done in small groups which are as diverse as possible. It may help to do a practice exercise, such as solving an amusing problem. During brainstorming no ideas should be rejected because seemingly odd suggestions can lead to outstanding ideas. There should be no discussion or comment on ideas. During this step, it is helpful to have someone serve as a recorder to write down ideas as they are suggested. The recorder may also encourage participation and ensure that criticism of ideas does not occur during this step.

This step lasts approximately 15-20 minutes, followed immediately by step 4. Divergent thinking can be encouraged by the introduction of odd constraints. Many techniques have been suggested to achieve successful brainstorming if it does not occur on its own. These suggestions include:

- Making outlandish departures from the problem foundation
- Asking "what if" questions to encourage divergent thinking

A handy set of such questions was developed by Alex Osborn:

<table>
<thead>
<tr>
<th>Put to other uses?</th>
<th>New ways to use object as is? Other uses if modified?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adapt?</td>
<td>What else is like this? What other ideas does this suggest? Any idea in the past that could be copied or adapted?</td>
</tr>
<tr>
<td>Modify?</td>
<td>Change meaning, color, motion, sound, odor, taste, form, shape? Other changes? New twist?</td>
</tr>
<tr>
<td>Reverse?</td>
<td>Opposites? Turn it backward? Turn it upside down? Turn it inside out? Mirror-reverse it? Transpose positive and negative?</td>
</tr>
<tr>
<td>Combine?</td>
<td>How about a blend, an assortment, an alloy, an ensemble? Combine purposes? Combine units? Combine ideas? Combine appeals?</td>
</tr>
</tbody>
</table>
Some other suggestions might be:
- Give examples to start off / get common ideas out of the way.
- Find something in nature which resembles your model.
- Have participants draw pictures of their ideas -- the imagery may lead to some very new ideas.
- Write ideas on paper and pass them around, adding new twists.

**STEP 4: EVALUATE IDEAS.**

Once a large number of ideas have been recorded, there is hopefully a synthesis of those ideas which is clearly preferred by all involved. It is possible that some research is necessary to evaluate which options are most feasible. Once an approach has been agreed upon, proceed to Step 5.

Note that while in step 3 anyone can and should offer productive input, this step is much more selective. In the final selection process, an instructor intending to use the material should be involved. This instructor must make judgements regarding the appropriateness of the material and the feasibility of implementation in the classroom. This is true at any level of instruction.

**STEP 5: ESTABLISH SPECIFIC OBJECTIVES.**

These should be specific, observable and measurable. Some sample objectives are given below:
- Students will work in groups of 3 or 4 with all students participating
- Students will construct a device which launches a ping-pong ball
- Students will evaluate their work and make 3 suggestions to improve it
- If given drawings of a layered structured system, students will be able to indicate the appropriate tributary area for selected members
- Students will be able to list at least 7 fields of engineering and give at least two examples of tasks typical of each.

**STEP 6: FIGURE OUT THE DETAILS.**

Now specific details of the activity must be designed based on the objectives. In doing this, consider that people in general tend to remember:
- 10% of what they read
- 20% of what they hear
- 30% of what they see
- 50% of what they both hear and see
- 70% of what they say
- 90% of what they say and do
In order to get the best learning, we must ensure students are active and talking. The best way to achieve this combination is through a cooperative design. Instructor-formed groups of three or four work best. Minimize the amount of time spent lecturing. For example, only give enough information in a design activity to prevent student confusion.

Keep in mind that constraints on the problem not only keep the problem from becoming too complicated, but can also force students to consider different approaches to a problem. You may consider requiring each student in a group to analyze or comment on a proposed idea.

Also consider that students learn in different ways:

- Students may prefer to learn through sensing or intuition. Any creative design activity will most likely contain both concrete and abstract content. Make sure of this.

- Students may prefer input visually or verbally. Give students both. Use models or drawings. If feasible, illustrate the objectives of the activity using the same materials the students will use.

- Learning generally proceeds from induction to deduction. General principles should proceed from specific observations. Give examples before making general statements.

- Students may learn sequentially or globally. Give the big picture right away, or global thinkers may not be able to even begin. Give enough examples for sequential thinkers to see the pattern.

- Students may process information while doing something or by reflecting. Help out reflective students by asking thoughtful questions and allowing enough time for students to consider the answer. Don’t necessarily acknowledge the correct answer immediately, so that all students will continue thinking. The more active students will generally be fine in design activities such as this methodology is intended to facilitate.

Challenge higher level thinking skills. Any design process should do this. A design activity should at the very least be a work of synthesis - putting components together to form new ideas. Students will also use their evaluation skills in selecting an idea. These skills are at the top of the cognitive ladder. In the process of the activity, students will naturally use the less advanced cognitive skills.
STEP 7: IMPROVE THE ACTIVITY.

Consider the following questions about the activity you have just designed:
Can it be made simpler without sacrificing any of the objectives?
Does it challenge higher level thinking skills?
Are various learning styles being addressed?
Is the problem constrained enough to encourage creativity?
The best way to identify methods of improving the activity is to try it out.
Have students comment on the activity and how it might be better.
The instructor’s observations may be most helpful in suggesting modifications.
APPENDIX C
TRIBUTARY AREA LABORATORY

Contained in this appendix are the lesson materials and data for the Tributary Area Laboratory used to evaluate the Engineering By Design methodology.

Special notes regarding the data are included here; the rationale for the decisions described here are found in the dissertation text.

Student #8 did not complete a survey or take the quiz — as a result, he was eliminated from consideration in any calculations. Answers to statement 11 indicated in bold were not included in the computation of the average or standard deviation. Two computations of the Time/Worth grouping were made -- Time/Worth I includes Q11, but does not include the teams which went first; Time/Worth II does not include Q11, but includes the results from all teams. Answers in bold italics (St28/Q5 and St25/Q18) were blank, and neutral responses were substituted.
Tributary Area Brainstorming Session Output

clothing
tire construction
aluminum siding
mobiles
traffic light
grain storage
sandwich
christmas decorations
banners
counterweight
lasagna noodles
bridge construction
composites
weaving
jet engine lift
liquid storage
ferris wheel
pouring concrete
pavement design
centrifuge
house of cards
blocks
interlocking
toothpick models
popsicle sticks
pickup sticks
legos
erector set
lincoln logs
Jenga (a tower game)

roofing
hung ceiling
ceiling fans
chandelier
cantilever
hanging signs
foundation design
laminate
leaf spring
torsion bar
trees
mudslides
caves
snow avalanche
sinkholes
earthquake
subsidence
pile design
load shifting
catapult
pressure
suction
uplift
soil design
fill design
drainage design
Tributary Area Lab Activity Lesson Plans

Discuss laboratory and homework procedures ........................................... 5 minutes
Introduction .............................................................................................. 5 minutes
Block tower activity .................................................................................. 30 minutes
Group solution of simple load distribution set ........................................ 10 minutes
Discussion of problem set solution .......................................................... 10 minutes
Group solution of complex load distribution set ...................................... 15 minutes
Discussion of problem set solution .......................................................... 10 minutes
Brainstorm live load reduction ............................................................... 10 minutes
Discussion of results of live load brainstorming ..................................... 10 minutes
Formal presentation of LRFD Live Load Reduction .................................. 15 minutes
Live load reduction problem set ............................................................. 30 minutes
Discussion of live load reduction problem set ....................................... 15 minutes

Total laboratory time: ............................................................................... 2.75 hours
Floor Load Distribution Exercise

Discuss in your group how the total load on a floor surface is distributed to the various load carrying members which comprise the floor. Discuss what assumptions you make along the way and write those assumptions down here.

For each of the layouts below, shade the area surrounding members a, b, and c which represents the portion of the total surface area carried by that member. Dotted lines represent the edge of the floor surface. To the right, write down the total floor area which each member carries.

![Diagram of load distribution problem set]

Figure 11 Load Distribution Problem Set
Instructions for Block Tower and Live Load Activities

Block Tower Activity
for the illustration of tributary area

Objective:
Each team will begin with the same configuration of starting blocks and, following the rules of play, attempt to construct the tallest tower before it topples.

Rules of play:
Blocks must be removed from any but the top layer and placed back on the top of the stack one at a time.
Only one hand may be used at a time during the removal or placement of blocks.

Hints:
Discuss your strategy as a team before you begin.
You may wish to elect one of your team members (one with a steady hand) to be the block manipulator.
Don’t be afraid to change your strategy after you begin.
Watch what happens to other towers to improve your own ideas!

Live Load Reduction Brainstorming Activity

Introduction:
Since live loads are movable, they do not occur simultaneously over all parts of a structure. Building designers have argued that this causes load calculations to be too conservative. Your team has been enlisted by the American Institute of Steel Construction to devise a method of reducing live loads which assures safety but is not overly conservative.

Objectives:
Brainstorm in your groups to list as many different approaches to this reduction as possible. Then select one or a combination of those ideas and develop it further. Make sure that the reduction is limited and has clear criteria which define under what circumstances it may be used.
Figure 12 Tributary Area Laboratory Exercise
Tributary Area Laboratory Student Evaluation

Although your name is requested for the purposes of correlation of your responses with your performance, this information is considered confidential. No one other than the instructors will view this information with your name attached.

Name: ________________________________

Were you present for the tributary area laboratory? (If "N," STOP NOW) Y N

Had you been introduced to the subject of tributary area prior to the activity? Y N

If yes, what level of education have you had on the subject?
(Circle the letter for all that apply)
A. I had the concept described to me.
B. A sample problem was done on the board.
C. I did a problem informally by myself or with a group.
D. A problem was assigned for homework and graded.
E. I had a test on it.

Please indicate your agreement or disagreement with the following statements. The scale goes from 1 to 5, with 1 indicating strong disagreement and 5 indicating strong agreement with the statement.

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
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<td>1</td>
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<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

I prefer working/studying alone. ___
We spent too much time waiting for other teams to finish their towers. ___
I still don't understand tributary area. ___
The block tower activity helped make me alert for the rest of the lab time. ___
I would have done just as well or better individually. ___
I would prefer a formal presentation of the concept of tributary area before attempting problems. ___
It was educational to try to figure out tributary area without being told the method right away. ___
The block tower activity helped me start thinking about how load is distributed. ___
Working in a group is better than working by myself. ___
My team formed a strategy before doing the block tower activity. ___
My team formed a strategy based on the results of other teams. ___
My team's strategy was ineffective because of the limitations of the block tower. ___
Other members in my group helped me see things from a different perspective. ___
Someone else in my group helped me understand something. ___
The block tower activity was a good use of my lab time. ___
The lab was too long. ___
Stretching exercises would have been as good as the block tower activity. ___
Being asked to suggest methods for load reduction made me look more closely at the problem. ___
Trying to guess how live load reduction is accomplished was a waste of my time. ___
We spent more time than usual in the lab, but it was worth it. ___
In the past, I have not enjoyed working in assigned groups. ___

Figure 13 Tributary Area Laboratory Student Evaluation
<table>
<thead>
<tr>
<th>St#</th>
<th>Tm</th>
<th>Exp</th>
<th>S1</th>
<th>S2</th>
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<th>S5</th>
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Significant? Y  Y  Y  Y  N  N  N
Range Max 3.6  4.5  4.5  4.5  5.0  4.2  4.2
Min 1.5  1.8  2.5  1.8  1.0  1.0  1.0
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### Table 16: Survey Responses by Team: Raw Data Averages

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Table 17  Survey Responses by Team: Concept Groupings

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Tributary Area Post-Test

Calculate the tributary area to the beam AB. Sketch it on the plan view. Assume all joists are equally spaced and in contact with the slab. The beams AB, DC, and CE are all at the same elevation but are not in contact with the slab. There is no column at C.

Figure 14 Tributary Area Post-test
Tributary Area Post-Test Grading System

Below is a list of each of the steps established in completing the post-test. Each is assigned equal weight (one point) in the grading system.

1. Joist 1 shares load with the bearing wall
2. Joist 1 contributes to AB
3. Half of Joist 1 rests on the left bearing wall
4. Joist 2 contributes to AB
5. Half of Joist 2 rests on the left bearing wall
6. Beam DC contributes to AB
7. Half of Beam DC rests on the left bearing wall
8. Joist 3 contributes to AB
9. Half of Joist 3 rests on the north bearing wall
10. AB shares load with Joist 3
11. Half of Joist 4 rests on the north bearing wall
12. Joist 4 shares load with the bearing wall
13. Beam CE contributes to AB
14. Half of Beam CE rests on the right bearing wall
15. Joist 5 contributes to AB
16. Half of Joist 5 rests on the right bearing wall
17. Joist 6 contributes to AB
18. Half of Joist 6 rests on the right bearing wall
19. Joist 7 contributes to AB
20. Joist 7 shares load with the bearing wall
21. Half of Joist 7 rests on the right bearing wall

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missed 15 6 3 1 2 1 4 5 9 16 1 3 1 7 0 3 3 3 5 17 2
% corr. 55 82 91 97 94 97 88 85 73 52 97 91 97 79 100 91 91 85 48 94

x=incorrect answer

Avg. 18 Median 18 Std. Dev. 2.56
APPENDIX D
HIGH SCHOOL PHYSICS STATISTICS LESSON

Included in this appendix are the post-test and collected data from a statistics lesson taught High School Physics class as part of the evaluation of Engineering By Design.
CENTRAL TENDENCY AND VARIATION EXAMINATION - grading system in bold.

1. Why are deviations from the mean *squared* in computing standard deviation?
   2 pts. To include both positive and negative / both sides of the mean, etc.

2. Of mean, median, and mode, which is the least reliable measure of central tendency? Why?
   1 pt. Mode
   2 pts. Any reason higher frequency does not guarantee central tendency

3. Of mean, median, and mode, which is most affected by extremely high or low measurements?
   2 pts. Mean

4. The ABC test has a mean of 50 and a standard deviation of 10. If only students with an “A” average were permitted to take the test, would the mean increase or decrease?
   1 pt. Increase
   1 pt. Because the remaining students will have a higher set of scores

   Would the standard deviation increase or decrease? Why?
   1 pt. Decrease
   2 pts. Any description of restriction of range / variation

5. Scores on an exam range from 10 to 70 with a mean of 40 and standard deviation of 10. 100 students took the exam. 20 points will be added to each of the scores to avoid causing shock among students. (without sacrificing the educational standard)

   What is the mean of the new set of scores?
   2 pts. 60

   What is the standard deviation of the new set of scores?
   3 pts. 10

6. Considering that household income has a lower limit but no upper limit, speculate as to what the distribution of household income would look like in the United States.
   2 pts. Distribution as drawn has positive skew
   1 pt. Distribution as drawn has non-zero frequency at low income

   What measure of central tendency is best used for this distribution?
   2 pts. Median (reliable, but less affected by extreme scores)
   1 pt. Mode (less reliable, but still unaffected by extreme scores)
   1 pt. Mean, if distribution as drawn was normal

7. An exam is given, and the mean score is 50 points out of 100. The standard deviation is 1.
   Draw a sketch of this distribution and speculate as to what events might have caused it.
   2 pts. If distribution as drawn is tight / clustered
   3 pts. Any range restriction -- cheating / limited, comprehensive knowledge

*Figure 15 Statistics Post-test, Page 1*
8. A bolt manufacturer requires that 95% of the bolts it sells must be able to carry 1000 Kg. A single bolt is tested and is found to carry 750 Kg. Sue, the plant manager, has contacted you and asked you to suggest a procedure to assess whether the manufacturing process meets company requirements. Describe a procedure below, including any additional measurements or assumptions you make.

2 pts. Test more bolts
1 pt. Establishing a criterion (after testing bolts, 5% or fewer fail)
3 pts. For considering the role variation plays in estimating reliability


2 pts. Distribution as drawn has positive skew
1 pt. Distribution as drawn has non-zero frequency at zero children
1 pt. Mean drawn toward extreme scores
1 pt. Mode drawn at high point of distribution as drawn

Is mean a good measure of central tendency for this distribution? Why or why not?
1 pt. No
2 pts. Extreme scores - families with many children will affect the mean

10. Would the distribution from #9 be different for the number of baby bunnies born to rabbit "households"? Why or why not?

3 pts. Yes -- rabbits do not have choice / economic factors affecting breeding

If so, sketch the new distribution.

2 pts. Distribution as drawn is essentially normal
1 pt. Distribution as drawn tends toward zero at left end

11. Amy (A) and Bob (B) are trying out for the rifle team. Their shots are shown below. You are the coach and have to choose one of them for the team. Discuss what each must do to improve their shooting. Who is the best choice for the team and why?

2 pts. Amy is precise but not accurate -- adjust her sights or her aim.
2 pts. Bob is more accurate, but not precise. Bob must be more consistent.
3 pts. Amy is likely the better choice, because she already has precision.
| ID | Group | Q1 | Q2a | Q2b | Q3 | Q4a | Q4b | Q5a | Q5b | Q6a | Q6b | Q7a | Q8 | Q9a | Q9b | Q10a | Q10b | Q11a | Q11b | Total |
|----|-------|----|-----|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| S1 | ctrl  | 1  | 2   | 2   | 1  | 1   | 2   | 3   | 2   | 1   | 2   | 3   | 4   | 1   | 2   | 4   | 2   | 4   | 32    |
| S2 | ctrl  | 1  | 2   | 2   | 2  | 2   | 1   | 3   | 2   | 1   | 2   | 3   | 4   | 1   | 2   | 4   | 2   | 4   | 11    |
| S3 | ctrl  | 1  | 2   | 2   | 2  | 3   | 1   | 2   | 3   | 3   | 4   | 3   | 3   | 3   | 3   | 4   | 3   | 18    |
| S4 | ctrl  | 2  | 1   | 2   | 2  | 2   | 3   | 2   | 3   | 2   | 2   | 2   | 3   | 3   | 2   | 3   | 1   | 18    |
| S5 | ctrl  | 2  | 1   | 2   | 2  | 2   | 2   | 1   | 2   | 3   | 3   | 4   | 3   | 4   | 3   | 4   | 1   | 15    |
| S6 | ctrl  | 1  | 2   | 2   | 2  | 2   | 3   | 3   | 2   | 3   | 1   | 4   | 3   | 2   | 4   | 3   | 31    |
| S7 | ctrl  | 2  | 1   | 2   | 2  | 2   | 2   | 3   | 2   | 3   | 2   | 3   | 2   | 1   | 2   | 4   | 3   | 31    |
| S8 | ctrl  | 2  | 2   | 2   | 2  | 2   | 2   | 1   | 2   | 3   | 1   | 4   | 3   | 14   |
| S9 | exp   | 1  | 1   | 2   | 2  | 2   | 3   | 2   | 3   | 2   | 2   | 3   | 4   | 1   | 3   | 3   | 4   | 31    |
| S10| exp   | 2  | 3   | 2   | 2  | 1   | 1   | 1   | 1   | 3   | 3   | 3   | 4   | 3   | 15   |
| S11| exp   | 2  | 1   | 2   | 2  | 2   | 2   | 3   | 3   | 2   | 2   | 1   | 3   | 3   | 4   | 3   | 38    |
| S12| exp   | 1  | 2   | 2   | 2  | 2   | 2   | 2   | 2   | 2   | 1   | 4   | 15   |
| S13| exp   | 2  | 1   | 2   | 2  | 2   | 2   | 3   | 3   | 2   | 2   | 1   | 4   | 28   |
| S14| exp   | 1  | 2   | 2   | 2  | 2   | 1   | 2   | 2   | 2   | 1   | 4   | 3   | 16   |
| S15| exp   | 2  | 1   | 2   | 2  | 2   | 2   | 3   | 3   | 1   | 2   | 1   | 3   | 4   | 3   | 28    |
| S16| exp   | 2  | 2   | 3   | 1   | 2   | 3   | 3   | 3   | 1   | 2   | 3   | 19   |

# rec'd.  8  13  13  13  14  8  12  8  4  3  7  2  9  5  5  10  7  16  14

some credit

**Averages**

- Control Group  23.5
- Experimental Group  25

Difference not physically significant, standard deviation not computed.
Table 20 Statistics Post-Test Score Summary

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BIOGRAPHICAL SKETCH

Matthew Ohland focused on educational research after coming to the University of Florida under Dr. Marc Hoit. In addition to his Ph.D. in civil engineering, he is pursuing a graduate minor in education. Mr. Ohland has a long record of interdisciplinary work, holding degrees in engineering (B.S., 1989) and religion (B.A., 1989) from Swarthmore College and in mechanical engineering (M.S., 1991) and materials engineering (M.S., 1992) from Rensselaer Polytechnic Institute.

Mr. Ohland intends to continue research in engineering education, dedicating his career to the improvement of the profession.
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Marc I. Hoit, Chair
Associate Professor of
Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Charles R. Giaccia, Cochair
Assistant Professor of
Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Duane S. Ellifritt
Professor of
Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Clifford O. Hays
Professor of
Civil Engineering
I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Mary Grace Kantowski
Professor of
Instruction and Curriculum

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 1996

Winfred M. Phillips
Dean, College of Engineering

Karen A. Holbrook
Dean, Graduate School