Integrating Engineering Education

by Sarah Bush
B.S., Civil and Environmental Engineering (1995)
Brigham Young University

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Signature of Author ....
Sarah Bush
Department of Civil and Environmental Engineering
May 1998

Certified by ....
Herbert H. Einstein
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by ....
Joseph M. Sussman
Chairman, Department Committee on Graduate Students

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Abstract

Integrating engineering education involves connecting subject material among individual classes and building upon prior student experience. Integrative teaching helps students to better synthesize knowledge; facilitates easier access of that knowledge in design; provides motivation for learning; and helps students build a strong foundation for future learning. Tools for integrating engineering education presented and discussed in this thesis include: an integrative framework; the use of computers to augment the development of judgement; integrative "capping" experiences with real-world applications; and group work.

Thesis Supervisor: Herbert H. Einstein
Title: Professor of Civil and Environmental Engineering

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1. Introduction

In my undergraduate experience, engineering classrooms were often lessons in endurance and were to be avoided as much as possible. Unfortunately, I do not think my experience was isolated. Admittedly it is difficult to infuse the sometimes dry engineering science concepts with life. I taught a sophomore level mechanics of materials class during the summer of 1996 and constantly struggled to find new ways to present the material and illustrate the material's relevance to students' lives and careers. Rich Felder, an expert in engineering education, travels the country doing workshops encouraging and instructing engineering educators on how to engage engineering students in the class room. In his seminars, Felder argues for effort on the part of engineering educators to engage not only the minds but also that part of students' psyche that motivates them to want to excel and grapple with the problems of the world around them.

In the past two years, I have had the opportunity to interview most of the MIT civil engineering faculty involved in undergraduate education. I have been impressed with their commitment and desire to provide that impetus for students: to turn on a light in the civil engineering undergraduates. This thesis is a compilation of research and information I have gathered that might aid faculty in sparking student desire for learning.

As I spoke with the faculty, most of their concerns dealt with the tension between the need to teach fundamental science principles and the need to teach students design and provide a "big picture" or systems approach to problem solving.

Some professors felt an understanding of core engineering principles was key. A proponent of this view expressed their viewpoint with the following illustration: how could and why should you teach undergraduates how to design an airplane if they do not understand how individual components operate: particularly when teaching integrated design is so difficult?

Others believed that the current emphasis on fundamentals does not necessarily lend itself to illustrating the current and future problems challenging the civil engineering profession. At a place like MIT, students who are not challenged will go elsewhere. Professors argued that it is design which gives students the drive to understand individual components. They believed the lack of overall system design in the civil engineering curriculum would cause enrollment to decline.

In discussing with MIT faculty curriculum integration and enhancement, I developed a sense from them that the curriculum could be improved in three specific areas: integration of current subject material, computer use, and in the development of a "capping subject". This faculty input has largely shaped the work of this thesis. In it, I not only argue for considering students as the foundation of teaching success, but also for considering the primary goal of teaching to be assisting students in integrating what is being taught with what they already know. I discuss why integration is important; a framework for integrative teaching; the integration of computers in engineering curriculum; the integration of engineering curricula through capping subjects; and finally, group work as an integrative process.

2. Integration

In speaking with MIT professors, several mentioned they think the relevance of material they teach and how it relates to other subjects is intuitive. However, in my experience as a student, neither the importance of new material nor its relation to prior knowledge is intuitive upon first introduction. Just as a structural engineer must have a foundation upon which to build; in teaching, teachers must use the foundation of students' prior knowledge and experience to build new knowledge structures that can survive in students' minds.

For example, according to Brereton (1994), students use experience as their first source of reasoning (their foundation's bedrock). They will more readily attach the term gravity to their experience of watching a ball fall from their hands than with the conceptual equation of F = MA. It is not only easier for students to learn new knowledge through attaching it to prior experience, they derive "great satisfaction" when they are able to link new knowledge to existing knowledge (Brereton, 1994). This linking between new and "old" knowledge will be defined here as integrative learning. In the following sections, the advantages of integrative learning and an integrating teaching framework will be developed.

2.1 Advantages

In education, integrative teaching approaches produce many advantages. They assist students in remembering, in finding relevance, in applying new knowledge, in practicing engineering design, and in developing expertise.

Remembering

Information given to students is not stored in figurative lockers in their brains to be easily retrieved. To retrieve learned knowledge, students have to be able to "reconstruct" that knowledge (Ramirez, 1995). One example of reconstructing knowledge is the common use of mnemonics to artificially connect information for future reconstruction (Ramirez, 1995). For example, I would be hard pressed to remember that the advantages of integrative teaching are **R**emembering, **R**elevance, **A**pplication, **D**esign, and **E**xpertise. However, if I linked those advantages to the following mnemonic device, **R**ed **R**abbits **A**te **D**elightful **E**ggs, those links would help me recall (reconstruct) the advantages at a later date. In trying to reconstruct knowledge, if students have not created links to prior experience or previously integrated knowledge, that new knowledge is easily forgotten. Similarly, if links students make with new knowledge are in only one domain (i.e. only theoretical), those links are fragile and more readily "broken" or forgotten.

Relevance

In addition to helping students remember information, integrative learning also helps students grasp the relevance of new material. For students, relevance can be created through connection to the physical world they are familiar with or reference to what can be done with a concept. A mathematical integral by itself may not mean much to students; but if connected to the area under a curve or internal energy in structural mechanics, these connections lend the mathematical integrals relevance.

Application

The more knowledge is integrated into students' experience, the more likely it is that students will be able to access that information to creatively apply it to new problems. Rote knowledge memorization without context is difficult to later recall and apply to new problems. Therefore, providing an integrative learning context helps students in actually using the information in their future endeavors.

Design

Integrative learning prepares students for design, because it teaches students to connect theory with reality. Design requires this skill: it requires students to identify contexts in which abstract mathematical problem-solving skills can be applied, and it requires constant interplay between the abstract and concrete. If students are prepared for design by previous exposure to this interplay, design will strengthen students' prior knowledge links and further develop links between textbook knowledge and real-world experience.

Expertise

Integration of knowledge is cited as the primary difference between a novice and an expert (Ramirez, 1995). Experts validate problem solving approaches by drawing on links to prior experience and continuously correcting for initial mistakes. In contrast, novices do not have many knowledge links or contexts on which to draw. Through links developed in integrative learning and through rich experience, novices become experts.

Thus teaching students to integrate new knowledge with prior experience aids students in remembering new knowledge, finding relevance, application, design preparation, and acquiring expertise. In summary, according to Brereton (1994), developing students' desire and ability to question, observe, actively use, and link theoretical knowledge to their experience should be the central goal of education: these skills will produce effective lifelong learners who can leverage analytical understanding in the real world.

2.2 Integrative Teaching Framework

The ironic thing about trying to make abstract concepts more concrete through integrative teaching is that *how* a teacher does this seems itself nebulous and abstract. The remainder of this chapter will present recommendations from education experts on the art of facilitating integrative learning in engineering education.

In educational research (Ramirez, 1995), the conctructivist model consists of four steps: the invitation, exploration, explanation, and application. The model and its steps will be discussed here as a possible framework for integrative teaching that could be applied to engineering education.

Invitation

The invitation involves discovering students' prior knowledge and experience, introducing students to new material, and providing students with a reason for why they should be interested in the material.

For teachers to facilitate connections between new concepts and ideas already familiar to and accepted by students, they must draw on students' prior knowledge and experience and look at material from their perspective. Only by learning about their students will teachers be able to find feasible connections between new material and students' prior experience.

In addition to learning about what students already know or have experienced, if teachers try to discover student motivation for learning they might be better prepared to give reasons for why students should be interested in material being taught. Providing motivation might involve illustrations of what students will be able to do with knowledge later on, or how it will help them in better understanding the world. Teachers might also give their own reason for learning the material and share why the material has held their interest for so long.

Exploration

After discovering student perspectives and inviting students to learn, the second step of the integrating framework is the exploration. In the exploration phase, students are provided with alternative perspectives of new material being taught and are given different ways to construct the material or link it to their own understanding.

Teachers, when compared with their students, have developed expertise in interacting with the knowledge they teach. In their careers, professors develop diverse and rich connections with knowledge in their field. These connections are often developed in different contexts: for example, a structural mechanics professor might have used mechanics in their research, in consulting practice, and even in their hobbies (I remember a mechanics professor who would often illustrate a point in class by referring to his hobby of building and flying airplanes). Various contexts can be used to enrich student understanding and expand the number of connections students make with new material.

Teachers may be experts in the material being taught, but they are not experts in what the students already know, how their students learn and why they might want to learn. Students provide the expertise in this area. The framework's exploratory phase could be viewed as a negotiation of experts, students and teacher, to accomplish student learning. In negotiation, active questioning is a key process. However obvious it may seem, teachers should emphatically support student questioning and challenge them to question. Specific ways to support student questioning include: encouraging students to carefully observe the world and whether the world agrees with the concepts being taught; engage students' assumptions through "what if" questions; encourage participation in discussion; and finally, require students to reflect on material in personal journals including observations from outside the class and from other classes. My freshman calculus class required just such a personal journal. The journal forced me to establish connections between my calculus, physics, and even my intensive writing classes.

Explanation/Validation

Explanation/Validation affords students a more in depth interaction with new material. This phase could involve "testing" material with new evidence: for example, after learning about the ductility of aluminum, new evidence could be provided through laboratory testing. Explanation/Validation could involve interacting with material in a new or different environment (for example, a computer simulated environment). Explanation/Validation could also involve a revisiting of students' original motivation for learning the material. For example, after teaching about bolted connections, if students are interested in knowing how to design a steel building, further explanation and validation could be provided through examining connections in local buildings or having students design connections for their final building design project

If students enter a subject with similar prerequisites, they could be required to connect new knowledge to material taught previously or concurrently in other subjects. Integrating homework problems in different classes would facilitate linkages. I recently reviewed the problem sets and design projects assigned in the undergraduate civil engineering curriculum at MIT. The opportunities for establishing connections between the projects and problem sets were innumerable. A few examples are provided in Appendix C.

Application

Finally, the whole process of integrating knowledge arrives at closure with the application of knowledge. Students *have* integrated knowledge if they can use it in a variety of contexts. Ramirez would change Decartes' famous statement, "I think, therefore I am," to "I do, therefore I know." He adds that "those who can enable students to do, teach" (Ramirez, 1995). The application of knowledge is the doing and designing that allows students to strengthen links between theory and practice and make the abstract concrete.

2.3 Supporting the Framework

The framework presented here (the invitation, exploration, explanation, and application) is one model for teaching in an integrated fashion. However, there are two key aspects of engineering classes that hinder the implementation of integrative teaching: the amount of material being taught and the reward structure.

The pace of engineering subjects is often governed by the amount of material that "needs" to be covered and not the amount of material that can be effectively covered (integrated with students' prior knowledge and current experience). Many MIT civil engineering professors feel that because the time allotted to a particular subject is limited, and because there is too much material to cover, they need to focus first on the basics before any attempt at integration is made. Yet it could be argued that if material has not been integrated, students will not be able to effectively use it. Furthermore, if instructors actively point out real world applications and mention connections to other subjects, they can help students realize the scientific knowledge they are learning is relevant and applicable in design.

Students are affected by how they are rewarded (by assessments and grades). For an integrative framework to be successful, the grading structure must support and reward students for questioning and linking knowledge. There are several ways in which this can be done: teachers could require student journals; base a portion of the grade (more than 5%) on in-class participation and questioning; use problem set questions that require students to relate material to other classes, prior experience, or real application problems; base grades on design problems with open-ended questions; require field trips to civil engineering project sites. The options are only limited by the imagination of both the teacher and the students.

In summary, if instructors use an integrative framework in teaching, it helps students to better synthesize knowledge and facilitates easier access of that knowledge in design. In addition, showing students how new material is relevant in real world applications illustrates subject importance and provides students with learning motivation. Finally, in using a integrative approach, teachers help students to build a strong (integrated) foundations for future work and learning.

3. Computer Use

Personal computers and relatively inexpensive software have in recent years replaced the historic drafting table and calculator of the civil engineer. In fact, the computer is increasingly dominating engineering analysis, design and drafting. Likewise, computer modeling and simulation are being used to augment traditional engineering education in experimentation and scientific analysis. There is a wide spectrum of ways computers can be used in education. The gamut runs from completely ignoring the computer to training students in how to input data without critically examining the actual analysis or results. Both of these extremes are unsatisfactory. Computers can and should be used to augment education. However, in order to train students to actually think and engage the program, students must be educated in computer use, not just trained to be technicians of the popular software of the day.

The implementation of computers into engineering curriculum is currently a concern for MIT faculty. My interest in how computers and engineering education could and should be combined began through working on a research team developing a geotechnical tunnel simulator called SIMSUPER. Thinking about the possibilities provided through using this and similar programs in educational contexts produced interest in what educators should consider in using computers for educational purposes. This chapter discusses these issues: the reasons for using computers in engineering education, the dangers of educational computer use, and thoughts on implementation.

3.1 Advantages

In addition to extensive use in industry, there are several reasons for using computers in educational contexts. In an IAP course at MIT on the Design Studio of the Future, there was general consensus that the greatest advantage of computer use in engineering education is the opportunity to free students from the grind of iterative calculations and share with them a glimpse of the big picture. Additional advantages that will be discussed here include: increasing student knowledge and breadth, making education more realistic, increasing understanding, and enhancing student creativity.

Knowledge and Understanding

Computer use expands both the complexity of problems that can be addressed by students and the resulting exposure students gain to different kinds of problems. Computers provide the capacity to demonstrate several scenarios or the response of a system to varied input. In addition to increasing student knowledge through wider exposure, there is great potential for using graphical displays to communicate concepts that might be otherwise difficult to visualize. Graphical displays can rapidly illustrate what-if scenarios and demonstrate trends as input is varied (Baker and Rix, 1992). In this way, graphical displays facilitate student understanding and help students understand why or how a system is behaving the way it is.

Real-world Experience

In addition to illustrating systems graphically, computers are often able to create or simulate situations that would be impossible to otherwise experience in educational settings. Students, while interacting with simulators, can tinker with system behavior; gain immediate feedback; experiment with multiple scenarios; and explore design tradeoffs (i.e. between cost and reliability). In addition, simulators facilitate the use of random variables in design and analysis allowing students to realize that engineering deals with the probabilistic nature of the real world more than the deterministic world of textbooks and controlled experiments.

Creativity

Finally, as computers facilitate student exploration of tradeoffs between design variables like cost, time and reliability, they can also decrease the time costs for students in creating design solutions and exploring design alternatives. The options computers provide for doing design and exploring real-world examples facilitate integrative and creative thinking skills (Vanegas, 1993).

3.2 Dangers

While there are benefits to using computers, those benefits keep company with a large number of dangers. This section will discuss a number of these "dangers" or possible disadvantages.

Illusion of Ease

Because computers and particularly professional software have been made easy to use, the illusion may exist that anyone can run a professional analysis by virtue of the computer's existence. Computer use in introductory engineering classes may promote the myth that understanding how to run a computer program is equivalent to understanding the underlying theoretical basis. Therefore, one danger of computer use is the tendency a student might have to believe understanding is equivalent to being able to run a program.

Intuition

Another challenge in using computers is that of reaping the benefits without sacrificing student development of intuition and judgment. Students who are taught on computers how to input data and read output files may fall into the trap of also relying on the computer for intuition. They may fail to develop for themselves a sense of what a deformed structure *should* look like under a particular set of loads.

Another possible loss associated with computer use is that of an engineer's sense of what the calculations are that the computer performs inside its "black box". Students may neglect learning approximate methods for the purpose of either estimating system behavior before doing extensive analyses or checking post-analysis computer output (Parmelee, 1994).

A director of a large contracting firm holds that there are only a couple engineers on his team whom he can rely on to interpret computer structural 3-D analysis (Brohn, 1996). These engineers may not be particularly skilled at modeling creatively; rather, they can predict how a structure will perform and have a sense of whether or not the output accurately describes structural behavior. Intuitively, they can tell after examining computer output whether or not the initial modeling was done correctly.

Just as the senior generation of engineers can intuitively make sense of computer output from years of experience in design and manual calculation, young engineers will have to be educated in their intuitive knowledge of system behavior. This will either have to be done in the context of ready computer output; or perhaps engineers will need to be taught independence from computer output altogether.

Judgment

In addition to failing to develop intuition, students may come to depend too heavily on computer output and interact with computers as black boxes. Instructors introducing computers in classes have experienced students' manual problem solving skills quickly atrophying, a loss of the ability to remember fundamental principles and suffering exam scores. In fact, some instructors believe the losses in student performance far outweigh the possible benefits of computer use (Meyer, 1995).

Young engineers are often enthusiastic about running programs and dislike verification, while senior engineers are reluctant to use computers and can usually predict outcomes in advance (Hrabok, 1993). This raises concerns about ethics and professional responsibility. The computer software that can make design more simple can also, in the long run, increase exposure to liability. Computer programs and programmers are not liable for any failure. The responsibility lies with the engineer. There is an article entitled "Computer-aided Liability" by Lisa Backman in the June 1993 ASCE Civil Engineering publication about the Hartford Civil Center structural failure which is attributed to inaccurate computer modeling (see Appendix D). The discussion detailed there (or a similar discussion about the risks of compute modeling) should be read by engineering students as a sober reminder not to sacrifice judgement on the alter of computer computations.

Finally, as computers become a more integral part of undergraduate curriculum, their invasion will inevitably force out some engineering concepts that were previously taught. Inevitably, including something new will entail examining what must be removed to provide that space.

3.3 Prerequisites

In order for computers to be used well in a class and have educational advantages, there are several prerequisites that students need before embarking upon computer use. The first prerequisite has been summarized by the president of an engineering firm: "I do not want you to go to the computer until you have obtained an answer to the design assignment by non-computer means. Computer work is a small part of design, but new graduates think it's all there is." (Godfrey, 1987). In general, students should not be exposed to computer use until their manual problem solving skills are adequate and they have sufficiently mastered material to prevent computer use as a crutch.

Another "prerequisite" for student use is basic understanding of the theoretical foundation of a computer program. Students should be taught a computer program's computational theory before using that program (unless the program is being used in concept illustration instead of as an analytical tool). Knowing the underlying theory, students should be able to predict a ballpark range of possible outcomes before performing analyses (Hrabok, 1993).

Finally, students should understand the assumptions (particularly the limiting assumptions) of a computer program and the limitations of the program itself. The danger of computer use for new users is in relating to it as a black box. Teaching students why a program runs and the mathematical relationships it uses can be an attempt to pour light into that black box.

When using computer software in educational contexts, the type of software used will also impact effectiveness. It is generally not a good idea to require students to develop their own software in a design class. According to Fleming (1994), in structural design classes, when students write their own software they end up spending extensive time debugging the code and very little time in learning the fundamental structural relationships embedded in that code. Therefore, instructors should invest time in selecting an application to fit the purposes of a class. Education literature cautions against fully automated design packages that allow student use without much thought (Meyer, 1995). They can be particularly harmful in introductory classes in promoting the black box mentality. Heavily automated software packages may be more appropriate for advanced design classes, or for introduction into the final phase of a design project. Instead of the high-power packages, simple programs like MIT's GROWLTIGER (minus the bugs) which will not allow students to blindly input and extract data might be more appropriate.

One final note for program selection that should also be discussed with students is how a program is developed and by whom. To date, there are no industry standards for developing "black boxes". Often purchasers are not advised of the extent of program testing and validation *or* the level and quality of support that can be expected. Furthermore, developers will rarely (if ever in commercial software) release the source code. Users then are left unsure about the assumptions made in code development and about the program's limitations. Students should be taught to inquire into the background of a program's developer and also to be aware of the liability involved in using any program.

Similarly, students should be taught the extent of documentation which needs to be included with their designs to demonstrate they were not negligent in verifying computer analyses; they should also be taught what preliminary calculations show that as analysts, they understood the model before even starting computer computations. Students must know that in using a computer program, it is they, not the programmer who will be liable for *any* mistakes (programming or otherwise).

3.4 Modeling and Verification

In addition to being taught what is going on inside a computer and being exposed to program liability, the most important aspect of integrating computer analysis into design is teaching students modeling and verification. The last two sections of this chapter discuss these two aspects of using computers in engineering education.

Modeling

With computers, it becomes easy to do mountains of calculations without those calculations having much meaning. Part of educating students in computer use is teaching how to correctly model systems and incorporate boundary conditions and how to plan out analyses instead of wasting time generating useless data.

Teaching students modeling is like teaching a right-brain process because it involves creatively designing a computer analysis. Students are often taught in analysis how to break things up into elements. Computers facilitate this task. Yet as the computational side of design is increasingly performed by computers, students must be taught how to use computer computations and output to enhance their ability to design: how to focus on the big picture of the model and not the intricacies of the required computations (Vanegas, 1993).

Teaching modeling then involves teaching students how to look at a system as a whole and how to question the model they are developing; question if they could better represent reality another way; and question if there is a better way to accommodate the design requirements.

In this process, assigning students to experiment with simple models may be more educational than addressing large and more complicated models. Heinz Isler believes that a small, simple, physical model often gives answer to many more questions than anticipated (Wester, 1996). Another method for teaching model design is exposing students to designs that have been realized or built and the modeling assumptions that were used in analyzing them (Billington, 1996). Still another approach is requiring students to develop models and as they do so, interact with professionals or instructors with modeling experience who would both teach and critique students in the art of modeling.

To help students determine how factors affect models and gain a better understanding of how the model behaves, they should be encouraged to analyze different types of systems under various conditions; perform parametric studies; and to investigate model sensitivities to input parameters, boundary constraints and mathematical assumptions (Fleming, 1994), (Puckett and Hamann, 1996). Students can be taught the reality that solving a problem without any further probing means ignoring the opportunity to understand both system behavior and its sensitivity to the inherent variability of the real world.

Educating students in modeling requires more than teaching data input. It brings up the tension inherent in much of engineering education: that of teaching fundamental theory versus training students in a particular area. Training students on how to use a particular program might allow students to work with little on-the-job lag-time; however, it could be argued that teaching modeling fundamentals (instead of computer software) increases student professional ability to adapt as technology progresses.

Verification

As industry is increasingly realizing the importance of adequate verification and documentation of verification, educators experienced with computers are also lauding the importance of teaching verification. Instructors that have been using computers extensively in their design classes purport that verification is paramount.

According to Puckett and Hamann (1996), software validation is the most important issue in the engineering classroom and it should become a formal part of any computer use in engineering curriculum. All computer output should be checked and verified before being incorporated as results in any student design. In a computer-based structural analysis class, Puckett and Hamann require students to include in all projects global equilibrium checks based on quick manual computations; they deduct 50 to 80% if students fail to include these checks (1996). Incorporating validation in the classroom can teach students to be critical of computer output and refute the idea that computers are infallible. Furthermore, it can help students begin to think about what is sufficient validation in the context of engineering practice and help them to think about liability issues as well (Hrabok, 1993).

As part of the validation process, teach students to first review all input data before doing analysis (Parmelee, 1994). Second, expose students to various methods of verification. These include (but are not limited to) using simplified problems for validating computer code; checking the program against already existing solutions; manually checking computer output, perhaps on simplified problems; and using other computer programs to check or validate a solution (Puckett and Hamann, 1996).

Figure 1 and Figure 2 illustrate how computers were used to cross-check solutions in two subsequent structural design and analysis courses. Finally, teach students approximate methods to verify output. Exposure to "rules of thumb" used by professionals can help students develop a feel for what the computer output *should* be. Other methods of validation include: checking the limiting cases, equilibrium, and continuity checks.

In conclusion, though computers allow students to focus more on design, there are some negative aspects associated with computer use as well. A prominent Boston engineer has seen a tendency among entry engineers to use computer software without understanding the underlying algorithm. He cautions against allowing students to use software in a "garbage in, garbage out" mode. However, if both modeling and verification skills are emphasized when introducing computers into the curriculum, computers can facilitate student creativity, understanding, and design acuity.

1. Use CMETRUSS to verify manual analysis of a determinate truss.
2. Use spreadsheet to perform virtual work analysis of truss deflections.
3. Use CMETRUSS to generate influence lines for an indeterminate truss. Using the force method with a spreadsheet, Solve for the bar forces. Use CMETRUSS to verify force method solution.
4. Use CFRAME to perform an iterative design of a frame structure. Using the slope deflection method with a spreadsheet, verify the CFRAME solution.
5. Using the direct stiffness method and a spreadsheet, solve for the deflections, reactions and bar forces in a truss.

Figure 1 First Course Computer Usage (O'Neill et al, 1995)

1. Using a spreadsheet, Mathcad, DERIVE and HP28S calculator, multiply, invert and transpose matrices. Solve systems of simultaneous, linear equations.
2. Program a spreadsheet macro to create a local element stiffness matrix, the transformation matrix and perform the matrix operations to create the global element stiffness matrix.
3. Use spreadsheet macros (STRUSS, SBEAM and SFRAME) to assemble the structure stiffness matrix for a truss, continuous beam, and frame. Using the direct stiffness method with a spreadsheet, solve for displacements. reactions and member forces in a structure. Use CMETRUSS and/or CFRAME to verify manual calculations.
4. Using Mathcad or DERIVE, perform symbolic calculations to determine the stiffness matrix and fixed end forces for a non-prismatic beam element.
5. Analyze a 29 frame structure using ROBOT V6. Verify results using CFRAME.
6. Using FEMCIVIL, perform a finite element analysis on a simply supported beam. Using ROBOT V6, verify your results and analyze more complex structures.

Figure 2 Second Course Computer Usage (O'Neill et al, 1995)

4. Integrating Subject History at MIT

In the fall of 1997 at MIT, there was general consensus among the faculty that the civil engineering undergraduate program needed the addition of a capping subject to assist students in integrating what they learn during their first three years at MIT and in applying their engineering skills to a real-world engineering project.

The civil engineering department at MIT has a long history with integrating subjects which has involved phases of senior level "capstone" subjects. Given the renewed interest in capping subjects, this chapter will provide a historical overview of these subjects, an examination of why they were taught, and an analysis of why they were eventually "renovated". The material in this chapter is largely drawn from work by Stephen Ehrmann in his Ph.D. thesis entitled "Academic Adaptation: Historical Study of a Civil Engineering Department in a Research-Oriented University."

4.1 Overview

Integrating subjects have been a recurring part of the civil engineering curriculum at MIT since 1945. During the period between 1945 and 1975, many integrating subjects were initiated using a variety of formats. Most of these subjects encountered problems and did not survive more than five years. As the integrating subjects were replaced (or revised), they were shifted from the sophomore year to the senior year and back.

The integrating subjects (whether held during the sophomore or senior years) had several characteristics in common. They were generally unique subjects in the curriculum: no other subjects dealing with integration were offered in tandem. The subjects had multiple objectives which often included the following: teaching about design, the designer's role, professional societies, engineering office economics, creativity, communication skills, and systems problem-solving; providing exposure to what civil engineers actually do; improving student judgement; and illustrating how different specialists interact on design teams. Integrating subjects generally did not involve problem sets, exams or lectures. Most faculty were either unwilling or unqualified to teach the subject; furthermore, faculty personality and experience were extremely important in the success of integrating subjects. Finally, integrating subjects were invariably criticized by both faculty and students as being too shallow.

4.2 History

Professional Problems: 1945-1955

The integrating subject was first introduced into the senior year of MIT's civil engineering undergraduate program in 1945 as *Professional Problems*, a six unit class. It was to integrate segments of the civil engineering curriculum and approach problem solving from a broader perspective than other undergraduate classes. For ten years, the class was initiated, taught and championed by the department head, John Wilbur. During this period, subject lectures addressed the following topics: social, legal, functional, economic, technical and aesthetic aspects of engineering planning; professional engineering roles (engineer, planner, executive, etc.); communication skills; getting along with other people; and professional issues (ethics, licensing, leadership, and professional societies).

Wilbur offered several reasons for offering the subject. He saw a need to emphasize planning, increase curriculum synthesis, and recognize economic and social considerations. In addition, the faculty was divided into clear research areas; and no one would champion a subject that was not illustrative of their expertise. Wilbur saw a need for a class that went beyond individual faculty specialties and egos.

Because Wilbur's integrating subject was unique when compared to other engineering subjects of the period, it was difficult for engineering faculty to teach it. Furthermore, the students were not convinced they needed it and were at times ambivalent. Wilbur remembers several problem with the class: students were asked to participate in class discussions (it is interesting that Wilbur saw this as a problem), and the exams were both difficult to compose and difficult for the students to take.

Civil Engineering Projects I and II: 1955-1960

After teaching *Professional Problems* for ten years, Wilbur, the department head, had acquired a vision of teaching engineering students practical judgement. In 1955 the integrating subject became two sophomore subjects, *Civil Engineering Projects I and II* with a total of sixteen units. *Civil Engineering Projects I and II* became an expansion of Wilbur's vision. He recalled, "I felt I had a mission. I told my wife, I'm either going to put [a curriculum teaching practical judgement] over at [MIT], which will be almost impossible, or I'll resign, raise money, and start a new college."

In addition to Wilbur's expanding vision, there were other reasons for changing the integrating subjects. It was hoped that the new sophomore subjects could attract sophomore students into the department; that the practical orientation of the subjects might spark student interest in their junior and senior science and engineering classes; that students might discover what area of civil engineering they wished to specialize in; and finally, that the subjects would aid students in the process of learning how to discuss and write about engineering issues.

Wilbur remained heavily involved in teaching the subjects. In addition, he hired Scheffer Lang, a junior faculty member of transportation engineering, to run the classes. Other senior faculty members were also peripherally involved. The two subjects together had triple the credits of *Professional Problems*. The subjects addressed a series of three projects, for example: a cross-town vehicular tunnel for New York City or a multi-purpose hydraulic development in Haiti. These large projects were divided into smaller problems involving both analysis and design. The problems had no exact answers and required judgement, creativity, intuition, and synthesis. Students worked on the projects in groups of about ten students which were led by senior faculty members.

Wilbur's enthusiasm for the subjects was matched by the students; however, they were frustrated with the class grading. Comments from students included the following: "I remember being very excited about it"; "the stress was on how you attack a problem"; "I do not remember any effort to teach people to define a problem with the exception of *Civil Engineering Projects*"; "it was a sophomore level course where you were thrown into making decisions"; and "we were asked to use a lot of logic, but that same logic wasn't present in the criticism."

Student criticism of grading was accompanied by other stifling factors which eventually caused the demise of the class. These factors included: perceptions of the class as shallow, faculty workload, faculty incompetence, lack of faculty understanding, conflicting sophomore policy, and curriculum reform pressures.

Of the criticism leveled at the subjects, the most damning seems to have been that they were without depth and came across as being "Mickey Mouse". Many professors felt sophomore students lacked the background to figuratively roll-up their sleeves and dirty their hands with real engineering. According to one professor, expecting sophomores to "do something substantive" was "doomed to fail."

During the 1970 curriculum reform effort, Lang, who had been running *Civil Engineering Projects I and II*, advised abandoning the subjects. His primary argument was that they required too much faculty effort. Each year, faculty had to both prepare new projects and supervise them (i.e. stay one step ahead of the students). In addition, most of the MIT faculty were highly specialized and few felt competent at integrating the different civil engineering disciplines. Lang argued that faculty time costs money (at least a research opportunity cost) that the professors themselves and the department could not afford to spare.

Not only did the faculty feel incompetent, they also did not feel they would be adequately rewarded for teaching the challenging subjects. As one professor stated, "It's the old brownie point problem. The faculty tend not to believe the frequent pronouncements that these are keystones." Furthermore, most of the faculty did not share Wilbur's vision of what *Civil Engineering Projects I and II* should be. One faculty member recalls, "[Wilbur] had these ideas that never really seemed to be sold to other people." Another remembers: "Wilbur was trying to accomplish change but he didn't know for sure what he was trying to do. . . . He knew there were important elements of the education that were missing. . . . He was trying to develop a philosophy of engineering that would be the basis for filling those gaps. . . . He just couldn't articulate its implications in a practical way." One student from that time says, "I have a feeling the course was just tolerated by other faculty."

During this same time period, the dean of engineering was pushing for a sophomore curriculum that would be interchangeable across majors. *Civil Engineering Projects I and II* did not match his vision. Finally, when *Civil Engineering Projects I and II* were initiated, it had been claimed they would raise enrollment. However, sophomore enrollment continued to decline.

Engineering I and II : **1960-1965**

In 1960, the civil engineering curriculum was completely reformed. In the process, all courses addressing design or practical knowledge were eliminated save two nine-unit senior level integrating subjects, *Engineering I and II,* which were meant to be senior versions of *Civil Engineering Projects I and II*. For these subjects, Scheffer Lang had recommended a traditional teaching approach using a lecture format, problems shorter than those used in the previous sophomore subjects, and an emphasis on concrete engineering principles. These new senior level classes were "to provide an explicit, scientific framework for doing engineering, with theory derived largely from mathematics."

However, the professor initially assigned to teach the class, Myle Holley, a professor of structural engineering, was a member of the design faculty and was not well-versed in systems analysis. Furthermore, the curriculum reform had eliminated design from all other subjects making *Engineering I and II* the only refuge for undergraduate design. As a result of both these factors, *Engineering I and II* became senior level versions of the previous subjects, *Civil Engineering Projects I and II,* involving case studies and very few lectures.

The evolution of the subjects' system orientation to a practical design orientation can be followed in the yearly reports of the department head, Charles Miller. Following the first year, Miller reported:

> "In the first offering it was found impractical to introduce the formal systems approach in the manner ultimately contemplated. Our inability to do so is primarily caused by the fact that we have not yet been able to assemble a body of real problems which on the one hand have been effectively handled by a systems approach and on the other hand are of a length suitable for student use."

After the second year, he wrote:

> ". . . The original idea involved an emphasis on formal approaches to engineering problem-solving. Now we find that we can do even better by capitalizing on the extensive engineering experience of our senior faculty and their continuous involvement in significant civil engineering projects. Hence the case study and case project approach. . . . Next year six of the senior faculty will present case projects based on current experience in real engineering situations."

The practical design orientation is further illustrated in a comment by the professor actually running the class:

> "I wanted to sharpen their abilities to look at a problem, break it into its pieces, decide what was needed for a solution, decide what they did know and could apply and what they didn't know and where to find it and to get them to implement all this. . . . I was exposing [the seniors] to things people said they weren't ready for. . . . There were very few lectures and they were by others and had nothing to do with the problems."

Students were divided into three-person teams addressing five or six problems each year. They were reportedly enthusiastic and the class produced impressive work, both in quantity and quality. Attempts were made at having faculty teams present case studies, but attempts at faculty teaming failed. Other difficulties were the multiple, conflicting goals of the class (the conflict between teaching systems analysis and practical skills) and the lack of faculty expertise to teach the class.

Civil Engineering **(Senior Requirement): 1965-1970**

During the mid-sixties, the two senior *Engineering I and II* classes were consolidated into a single-term, senior-level subject with eighteen credits. The class was taught each year by a different senior civil engineering professor: T. William Lambe; John Biggs; Robert Whitman; and Myle Holley. Class educational objectives were: learning more about civil engineering practice and the operation of civil engineering firms; improving communication skills; and practicing the art of design.

The number of projects were reduced eventually to just one which allowed students to invest more time in the project and increase the depth at which they addressed the problem. Furthermore, it gave the faculty more preparation time on that problem. The class was divided into two sections which were organized like civil engineering consulting firms. Each firm was required to negotiate a contract, conduct analyses, and prepare designs. Sample projects from these years included: a parking garage, an airport, a nuclear plant site study, and a stadium. The parking garage project required addressing the foundation design, the structural system, mechanical and electrical equipment, operations policy, design costs, construction and operation, and estimation of financial return. The subject gave students experience in acquiring data and applying what they knew. The new department head, Peter Eagleson wrote in his 1970 annual report, "what is more important is that they learned how quickly they were able to acquire knowledge and develop analytical approaches in a new field of technology."

One professor recalled,

> "Many students felt a lot of frustration with *Civil Engineering*. I do not view that as negative at all. A few of them really got turned on to the whole thing but many felt that they were working on things they didn't understand in the depth they were accustomed to. . . . They didn't have that certainty to fall back on."

Another professor involved in teaching the subject recalled:

> "One approaches it with some misgivings because I hadn't had experience with that kind of teaching. I did enjoy it. I felt more comfortable with traditional modes of teaching and lab, but because the class responded and actually exceeded my expectations in terms of what they did—your final reaction would be very much in terms of what they produced."

Yet another professor in describing the class, indicated,

> "*Civil Engineering* was a substitute for a thesis. It was a major project and very difficult to pick a project because the students were in so many different fields. . . . The students complained; the instructors were unhappy. . . . We canceled it."

In summary, the faculty teaching the class had mixed feelings; it required a lot of work from both faculty and students; and attempts at team teaching failed. Students were unprepared for open-ended and poorly defined problems; however, in their work, the students exceeded faculty expectations.

Civil Engineering (Sophomore Requirement) 1970-1975

In 1970, there was yet another curriculum reform. The reform committee was again concerned with the heavy faculty load required by integrating subjects and the problems that accompany team teaching. In addition, the committee felt the "deductive-analytic structure" of the curriculum did not prepare students for the senior level design subject. Students were not taught that engineering problems are often open-ended and ill defined. The committee reported, "we currently parcel out the core courses to the departmental divisions and then hope that a semblance of integration will result." In general, they reported the students wanted more planning, design, breadth, relevance, and a clearer picture of engineering's relevance in a societal context.

The 1970 reform committee determined to cut the units devoted to integration in half creating a sophomore subject also called *Civil Engineering* with twelve units. It returned to the case study model with the aim of exposing undergraduates to civil engineering practice and the social, political, economic, and technical factors influencing the decision to initiate projects and guide planning, design, construction and management. T. William Lambe, a professor of civil engineering, taught the class using guest lecturers to present several mini-case studies.

Student comments on the class are presented on the following page in Figure 3. They criticized the class for arbitrary grading and wandering case studies, but they found the orientation to the civil engineering profession helpful. Professor Lambe was frustrated because all his attempts to involve other faculty failed. There were no incentives for involvement

1975 - 1991

After thirty years of integrating subjects, in 1975, the faculty voted against retaining an integrating subject. The "no" votes came largely from faculty members in systems, and "yes" votes from faculty members in the applied physical sciences. According to one faculty member, "it was a split between those interested in the traditional designing and building versus those interested in planning and operations." The integrating subject was replaced by three "capping" subjects taught in three different civil engineering divisions: transportation, water resources, and constructed facilities.

1991 - 1994

Fifteen years later, in 1991 there was another attempt at integration. Prior to 1991, structural engineering had been concentrated in two senior level classes: *Steel Structural Analysis* and *Concrete Structural Analysis*. The new effort removed half of the material from both of these classes and combined the remaining material into a new fall term subject: *Design of Structures*. An entirely new subject, *Integrated Engineering Design*, was created and taught during the spring term. The fall term *Design of Structures* was jointly taught by Oral Buyukozturk and Ken Kruckemeyer. The spring term *Integrated Engineering Design* was taught by Shyam Sunder and Ken Kruckemeyer.

The vision was to use lectures and progressively more difficult studio design projects to teach complex, open-ended design. Students were pushed to consider not only the strength and safety of structural design projects, but also the social, political, and environmental forces that shape good design. The criteria used for evaluating projects included: aesthetics, economics, serviceability, constructability, and maintainability. Furthermore, students were taught a decision-making framework for complex-interdisciplinary projects. In addition to integrated problem solving, other topics included: knowledge acquisition within the design context; creativity; multi-disciplinary team skills; engineering ethics; communication skills; and the skill and desire to pursue life-long learning.

- Of all the courses, *Civil Engineering* was one of the sources of controversy. Prof. Lambe was a strong-minded person. . . . A lot of students didn't like Lambe, a lot did. There were strong personal reactions.
- The grading of the papers was arbitrary.
- The case studies tended to wander into areas that Lambe was interested in—I couldn't get worked up about it.
- The design of an oil storage facility was irrelevant to most of us in transportation. . . . We felt we couldn't make a constructive critique; we were producing lengthy reports with little content.
- You get a feeling for how to approach problems.
- I think my ability for qualitative and critical thinking [was] improved.
- [The class] gave me an insight and appreciation for [civil engineering].
- I've sort of discovered what the field of geotechnical engineering is all about . . . as an aspiring structural engineer I realized that both structural engineering and geotechnical engineering must go hand in hand.
- I learned about the engineering process in general
- Now, if asked about the difference between civil engineering and architecture, I can answer!
- I have a far more refined idea of where I am headed as well as a good insight into the options perhaps available to me.
- I learned something about dams, construction projects, how a project is completed.
- I could not tell what the course was supposed to do.
- The guest lectures gave us a feeling where civil engineering might lead us. It was even interesting for those of us who had already made career decisions.
- Each lecturer has valuable personal experiences that he should have shared with me. Most of them didn't.
- I think there should be greater care in the selection of the guest lecturers. A couple were terrible.
- There was little substantive in his lecture. He stressed the philosophy of civil engineering, and I am at the point in my education where I have had my fill of philosophy and would like to listen to a talk on something more practical.
- The value of the course is hard to pin down. I would be hard pressed to give a reasonable answer to the question, "What did you learn?"
- Brown-nosing works. . . . Make it pass-fail; the bull-throwers were rewarded inordinately.

Figure 3 Student Response to *Civil Engineering* (Ehrmann, 1976)

The format of the subjects involved both lecture and studio. *Design of Structures* used lectures to teach fundamental concepts of steel and concrete structural analysis. The studio used team-oriented case studies of existing bridges to expose students to real-world engineering projects and the importance of non-technical issues. In the studio, the instructors hoped to teach students observational and visualization skills; the ability to work together; communication and presentation skills; the ability to critique and develop thinking through peer interaction; and the capacity for self-critique. Students kept notebooks of their observations, analyses and conclusions.

In *Integrated Engineering Design*, students grappled with more complex problems. The lectures exposed students to the process of design. In the studio, students practiced the design process by developing and analyzing designs for actual projects. Projects included: a permanent structure for an Olympic pool at MIT, a temporary weatherproof covering for MIT commencement ceremonies, and a bridge structure housing a museum over Seine in Paris.

Kruckemeyer and Sunder shared the common purpose of integrating structural engineering and architectural concepts. They worked well together and tried to understand the other's perspective; together they sought to communicate their combined perspective to the students. The students responded with excitement to the real world aspects of the class; to the fact that Kruckemeyer was a practicing architect; to the intense faculty interaction; and to the community, aesthetic, and political aspects of the integrating subject. Students believed they caught a glimpse of what it meant to "feel like an engineer."

However, Buyukozturk and Kruckemeyer could never reach consensus on what their purpose should be. Kruckemeyer wanted to pursue integration of non-technical issues; while Buyukozturk felt the fundamentals of structural analysis should not be sacrificed in this pursuit. The students were not impervious to the disagreement. With the faculty unable to integrate their perspectives, the students became frustrated.

Students also struggled with the large design projects: they found the large structures were too complex to fully understand or design in a term; they felt the class emphasized breadth over depth; and they were not clear about the level of depth they needed to master.

A group of students eventually drafted a letter to the department. In it, they requested that *Design of Structures* and *Integrated Engineering Design* be returned to separate steel and concrete subjects. They indicated they would find a "materials class . . . more useful than a design class." Furthermore, they felt the "studio time [was] often wasted and [could] be eliminated from [*Design of Structures*]." From the perspective of these more vocal students, the effort at integration had failed. The 1994 curriculum reflected the request of these students; the senior level structural classes became *Design of Steel Structures* and

Design of Concrete Structures. Since then, there have been no further attempts at senior-level integration in the curriculum.

There were several lessons learned by the instructors. First, they learned it is important to try to explain the non-quantifiable aspects of design in as straight forward, clear, and definitive a manner as possible. The same was even more true of communicating expectations for student work (Kruckemeyer, 1995). Second, when running a studio and lecture concurrently, students are more comfortable when the technical lectures and studio content are synchronized. Third, they learned that one hour a week for a studio is highly inadequate. And finally, during the first two year period, a fabulous teaching assistant with extensive practical experience had helped relieve the students' anxiety with complex, open-ended design problems. When the teaching assistant was not involved during the third year, the class suffered.

4.3 Perceived Benefits of Integrating Subjects

As the previous section has illustrated, MIT has a long, diverse history with integrating subject. During that history, several arguments have been made both for and against the need for an integrating subject in the undergraduate curriculum. The next two sections will elaborate on these arguments. First, the arguments in favor of integrating subjects will be discussed including: teaching students judgement, providing integration among undergraduate classes, creating positive student response to engineering, orientating students in the civil engineering department and profession, appeasing accreditation agencies and the visiting committee, and providing faculty benefits.

Judgment

Integrating subjects teach students judgement through addressing ill-defined problems. Several arguments have been made for teaching judgement to undergraduates (or at least exposing them to the need for judgement as professionals.)

As engineering science developed (and hence the amount of information students needed to absorb as undergraduates), space for teaching judgement in traditional engineering classes disappeared. Yet at the same time, the need for teaching engineering judgement was expanding. Engineering design increasingly involved synthesis and planning, both of which require professional judgement. Furthermore, these engineering problems requiring judgement were growing in importance.

Many complex engineering problems did not have a single, correct answer; and undergraduates schooled in engineering science were often unaware of the open-ended, poorly defined nature of engineering problems. The instructor of *Engineering I and II*, Myle Holley, said of the subject:

> I guess I wanted to sharpen their abilities to look at a problem, break it into its pieces, decide what was needed for a solution, decide what they did know and could apply and what they did not know and where to find it and to get them to implement all this. The problems were designed to get them to think a bit about what they had learned. I think among students who have been educated in a routine textbook situation there is a danger they will be less confident when facing a situation . . . [not in] the textbook, and it's worth some time even in their undergraduate years to overcome this.

Finally, the judgement that helped students deal with complexity, Wilbur argued, trained them to be both better citizens and leaders.

Integration

Some of civil engineering's complexity came from the fact that the field spanned many areas of work and research; the civil engineering curriculum represented this breadth. The integrating subjects not only helped students deal with complexity, it served to knit together the curriculum, helping students make sense of the sum of their discrete classes and the relationships between them.

Student Response

Student response to grappling with integrating and learning judgement in integrating subjects at MIT have spanned a broad range. They have often been enthusiastic about the subjects, particularly their scope and the opportunity for design. An alum said of *Civil Engineering Projects*, "I remember being very excited about it. I came turned on to being a civil engineer and this turned me on even more." Another said, "I enjoyed *Civil Engineering Projects* immensely. I got myself in a lot of hot water with some of the faculty. . . . I enjoyed using my intuition and doing design work."

As classes responded positively to integrating subjects, they exceeded faculty expectations. One professor recalls of *Civil Engineering Projects*, "The students were enthusiastic and came up with good solutions even though they didn't have a good grasp of method. They did a plan of a mining complex with its transportation system for Ghana. . . . a schematic solution that was pretty much the same as that which Bechtel Corporation came up with after much more study." Peter Eagleson, department head at the time of *Civil Engineering*, said regarding integrating subjects, students "learned how quickly they were able to acquire knowledge and develop analytical approaches in a new field of technology."

Orientation

When integrating subjects were taught in the sophomore year, almost all students gave positive feedback regarding the civil engineering orientation received (incidentally, sophomore feedback rarely mentioned design). In general, sophomore subjects were used to attract students; illustrate the relevance of other required subjects and thereby improve student learning in engineering science classes; introduce students to their options in the civil engineering department and profession helping students to pick a civil engineering specialty, and improve student writing and discussion skills.

Accreditation and Visiting Committees

Accreditation bodies have required civil engineering departments to incorporate professional exposure, practical knowledge, and integrated design experience. Recent Accreditation Board for Engineering and Technology (ABET) criteria for civil engineering programs stated:

> "The program is encouraged to developed innovative means of integrating design concepts and methodology throughout the curriculum, which must culminate in a major comprehensive design experience. Since the civil engineering design process generally involves a team approach, team design projects are highly recommended. The final design experience should include practitioner involvement whenever appropriate and possible. Student reports and presentations should be an integrated part of the final design experience" (ABET, 1991).

According to ABET, design in the curriculum should include the following features:

> " . . . development of student creativity, use of open-ended problems, development and use of design methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, and detailed system descriptions. Further, it is desirable to include a variety of realistic constraints such as economic factors, safety, reliability, aesthetics, ethics, and social impact" (ABET, 1991).

ABET's focus on integrated design is not a new phenomenon (Lovas, 1994); and the department's integrating subjects have filled ABET requirements. In addition, professionals have been well represented on departmental visiting committees and have supported practice-oriented subjects. Both of these external regulating agencies have provided departmental incentives for integration.

Perceived Faculty Benefits

Finally, despite the difficulty of teaching integrating subjects, there are some faculty benefits. In the civil engineering department where faculty are highly specialized and compartmentalized in their expertise, an integrating subject allowed the problem of integration to also become specialized and compartmentalized into one subject. The task of integration then belongs to only one faculty member freeing up other faculty members to focus solely on their field of expertise in teaching. Whether or not this is ideal (and I would argue it is not), for faculty whose focus is research, the benefit is real.

4.4 Perceived Challenges of Integrating Subjects

Although there may be many benefits to teaching integrating subjects, there are also many challenges which, at MIT, have led to almost continuous revision of integrating subjects. In this section, I have divided the challenges into three categories: general difficulties, student complaints, and faculty issues.

General Difficulties

The integrating subject increasingly clashed with department trends. The civil engineering department tended to emphasize theory in both the department culture and subject offerings while the integrating subjects focused on practical knowledge instead. In addition, the department became more fragmented in its knowledge base while the integrating subjects tried to piece the fragments back together. Finally, research in the department focused on individual tools applied to specific problems while integrating subjects looked at large, complex engineering systems projects. The integrating subjects have seemingly been running against the departmental tide.

Another general difficulty faculty experienced was finding real problems that were an appropriate size for student use while being suitable to a systems approach. A faculty member involved in teaching *Civil Engineering Projects* said of one of the projects, "I did some calculations recently. Such a case requires many more man hours for a consulting firm to do than the students had. So that was why things had to be superficial and as a result the students weren't learning much." Historically, integrating subjects have been criticized for lacking depth and teaching students to be satisfied with shallow answers. Ironically, in a curriculum dominated by theory, any practical subject is open to being critiqued as shallow.

Integrating subjects have also been difficult because they have forced faculty to grapple with this dichotomy between theory and practice, as well as the definition of civil engineering, the purpose of undergraduate education, and the cultural differences between department divisions. These questions have played out in the actual goals of the integrating subject which have been both multiple and competing: for example, teaching systems at a policy level and exposing students to traditional practice. Another example of conflicting goals is illustrated in the question of the integrating subject's placement: whether it belonged in the sophomore or the senior year. A professor who taught *Civil Engineering Projects I & II* commented on this debate:

> Pedagogically we're torn between an objective and an inescapable requirement which are in conflict. The objective is to demonstrate the integration of a whole stream of material which comes together to produce results. . . . Ideally one can argue that the need for and understanding of how substantive matter get integrated in a decision making process should get laid on students early on so they can understand the issues. The difficulty is that they do not have much in the way of methodological ability because they do not have the tools. Is it more important to get a perspective or is it more important to get some knowledge that they can use to understand the integrating subject? There's no answer really.

The pressure that *has* successfully swayed the department away from the sophomore level integrating subject is the institute's goal of making sophomore experience uniform across departments.

Perceived Student Difficulties

Student response to integrating subjects, whether positive or negative, has generally been more intense than to other subjects. Student difficulties can be traced to some key issues. First grading integrating subjects was always difficult because students often did not understand how they were graded and found it arbitrary. Engineering students familiar with answers that were either correct or incorrect were uncomfortable with more subjective grading when there was no "right" answer. Second, when students were trained in engineering science, they were not prepared for open-ended design problems. One professor who helped teach *Professional Problems* noted,

> We didn't have the right type of student. The students were never happier than when solving things by a detectable series of steps. Given something vague, albeit important, and they were far less comfortable. They eschewed the vague, the conditional type of solutions that can be modified by view.

Perceived Faculty Difficulties

Along with their students, the faculty also struggled with integrating subjects. Most faculty were not qualified or comfortable with teaching an integrating subject. Few faculty had the consulting or design experience to integrate subjects. Furthermore, integrating classes were more difficult to teach. The faculty workload was heavier. The yearly changing projects and the race to keep ahead of the students was time consuming. Lecturing on "practical knowledge", writing exams, and grading were all difficult without the right and wrong answers of engineering science.

Because the subject load was too much for one professor, the logical solution would be team teaching; but at MIT, this proved problematic. Holley, who was in charge of *Engineering I & II* in its early years, said of team teaching attempts in the class:

> MIT is a difficult place to get team action. . . . MIT does not encourage teamwork and the kind of person who comes here does not do it well. . . . I think it's more difficult to do it together: the communication problem, the time problem is such that it is very difficult to get faculty together.

Therefore, integrating subjects were generally taught by one professor without sufficient compensation for the extra work required. Faculty perceived there was talk about reward but no follow-through. The perception was that junior faculty received even less recognition than senior faculty for teaching an integrating subject. Furthermore, "rewards" from students were usually mixed. Spanning a wide range, evaluations often left teachers ambivalent towards the subjects themselves.

In summary, integrating subjects seem to involve an inherent tension with the predominant, theoretical, segregated culture of the department. Ehrmann postulates that because of this, they may be viewed in gestation as either a breath of fresh air offering skills that may not be learned elsewhere or as a mystifying, inconvenient necessity. Faculty optimistically began teaching them focusing on the positive side of that tension. But it seems historically, after teaching the class for a couple of years, the challenges grew heavier and the inherent difficulties became more obvious and enthusiasm faded. Like clockwork, after five years, the integrating subject died and a new subject started or integration became an artifice of the past.

5. Current Engineering Capstone Practice

The MIT civil engineering department is again considering the implementation of a capping subject. The faculty has both motivations for and concerns with developing a new capstone offering. In the subjects that are being taught, professors feel there is already too much material being covered to address integrated design. These subjects provide students with important tools; after acquiring the tools, they feel a capping subject could then help students in integrating their knowledge through design. In addition to providing integration, they feel a capstone subject could be used to provide students with motivation to learn subject material. For example, in the steel design subject, if the students knew they would revisit the material in a capping subject, their desire to master the material might increase.

At MIT, a capping subject would have implications for the whole curriculum, not just the capping subject itself. For example, even with a capping subject, Wooh would not change the design component in steel structural design; he thinks the process involved in the design project is important to learning steel design. However, Culligan-Hensley would like to concentrate on the rudiments of soil mechanics and leave teaching design to the capping subject. The faculty will have to address how the capping subject will affect design components in all the undergraduate civil engineering subjects.

The faculty feel the capstone instructor should be given significant incentives to compensate for the time and energy required by capping subjects; in addition, the instructor would need to have access to incentives in soliciting the involvement of other faculty members as consultants to the subject. One professor thought the department might get someone from industry to teach the class, but others have found that people in industry are often too removed from the fundamentals to teach an undergraduate class. One suggested solution was to have professors involved in the systems group coordinate the capping subject; but like people in industry, these professors have not historically been heavily involved in undergraduate teaching. Another solution might be to solicit the involvement of professors with solid scientific and practical design experience. Yet even with these qualifications, heading up the class would require enthusiasm, commitment, and a lot of work.

Finally, the faculty will have to decide how to effectively structure the capping subject. Culligan-Hensley believes the proximity of the Central Artery Project could be an excellent asset to the capping subject; portions of the capping project might be visited in each subject. Kausel developed this idea: he thinks students might then be able to develop a portfolio of projects from individual subjects throughout their undergraduate career at MIT; the projects could then be synthesized in the capping subject. This would require one professor to track portfolio development throughout the undergraduate subjects. Alternatively, responsibility for the capping subject might be rotated among systems professors. With the rotation would come the responsibility to develop a case study or design project for the class.

It is encouraging that there is general consensus about the need for a capping subject and the importance of addressing integrated design. However, structuring a capping subject will require ironing out logistics. To that end, this chapter will provide a look at the state-of-the-art in capping subjects as depicted in engineering education literature: the arguments for capping subjects, a survey of current capping subjects, and more in-depth look at capstone subject design.

5.1 Incentives for Capstone Implementation

Capping subjects provide many learning opportunities for students. Not only do their open-ended "real world" design problems require students to apply and develop creativity, but also to work across traditional academic discipline boundaries. In an age when information is accessible at the press of a computer key, mastery of small subsets of existing knowledge is not sufficient (Bright, 1994). Students need to be taught to construct meaning from information. These higher order thinking skills like open-ended problem solving abilities and engineering synthesis can be learned through practice on open-ended problems under the guidance of experienced problem-solvers.

In capping subjects, students also learn to appreciate and consider non-technical design factors like ethical, political, aesthetic, environmental, economic, and cultural constraints. They can be given the opportunity to work with professional engineers and develop client relations; to enhance their oral and written communication skills; to become more confident in making estimates, assumptions, evaluations, and decisions; and to learn to conduct wide-ranging independent research.

Another world of advantages lies in the team environment of capping subjects. Requiring students to work in teams helps students to begin to recognize the value of collaboration in achieving high-quality, well designed products. In a competitive environment like MIT, this realization can come through sharing problems, communicating concepts, seeking consensus, and accepting help and criticism. Students can also learn to clarify ideas for others to understand, to move between leading and following, to negotiate common strategies, to argue for new approaches and to give credit to others. The benefits as well as the pitfalls of teamwork will be more fully addressed in Chapter 6.

Though many, the benefits of capping subjects do not *all* belong to the students. Faculty are given the opportunity to interact more closely with the students. In addition, capstone classes can be used by faculty to evaluate student perceptions and knowledge levels, the overall curriculum, and how well students are prepared for engineering design.

5.2 Survey of Current Practice

In 1995, Todd et al published a survey of engineering departments in North America which investigated how capstone subjects are being taught. The authors compiled responses from 360 departments representing 173 schools. They concluded that despite the heavy faculty commitment required, many engineering programs in North America are using capstone courses. Furthermore, when asked how beneficial the capstone experience is to their students in helping them prepare for future endeavors, respondents replied with a rating of 8.6 on a 10 point scale. A significant number of schools involve industrial sponsors in the educational process; and many are using a team-based approach.

Survey Respondents

The survey sampled a broad range of engineering disciplines. The number of respondents in each discipline is shown in Figure 4.

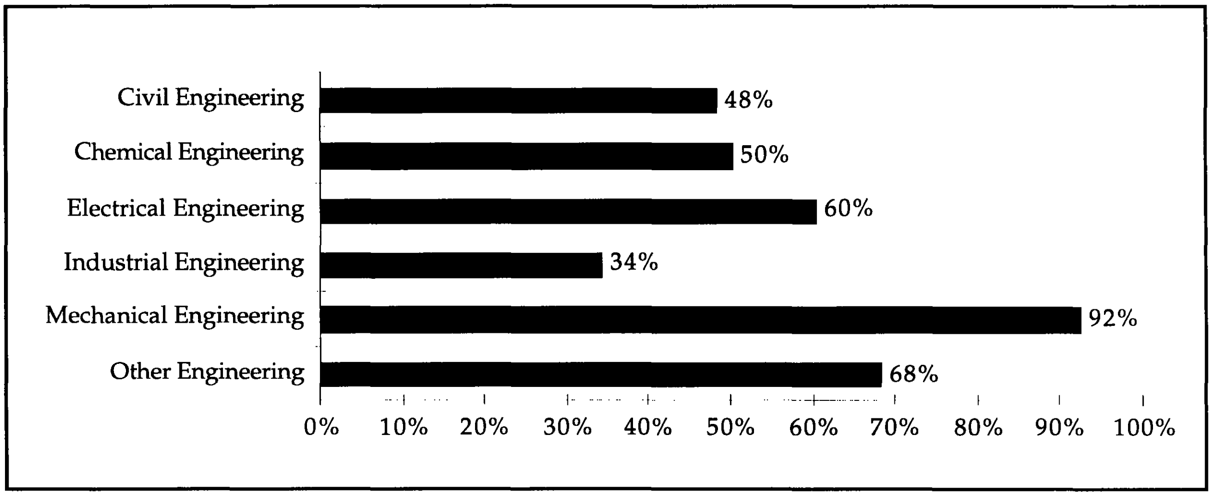

Figure 4 Responding Departments (Todd et al, 1995)

Class Structure

Figure 5 through Figure 13 lend insight into how capstone subjects are structured. As Figure 5 illustrates, most departments indicated they teach students senior level design using team-oriented projects. Because departments may use multiple types of teams, the total in Figure 5 sums to more than 100%. Figure 6 illustrates how classroom instruction and project work were chronologically organized in capstone subjects.

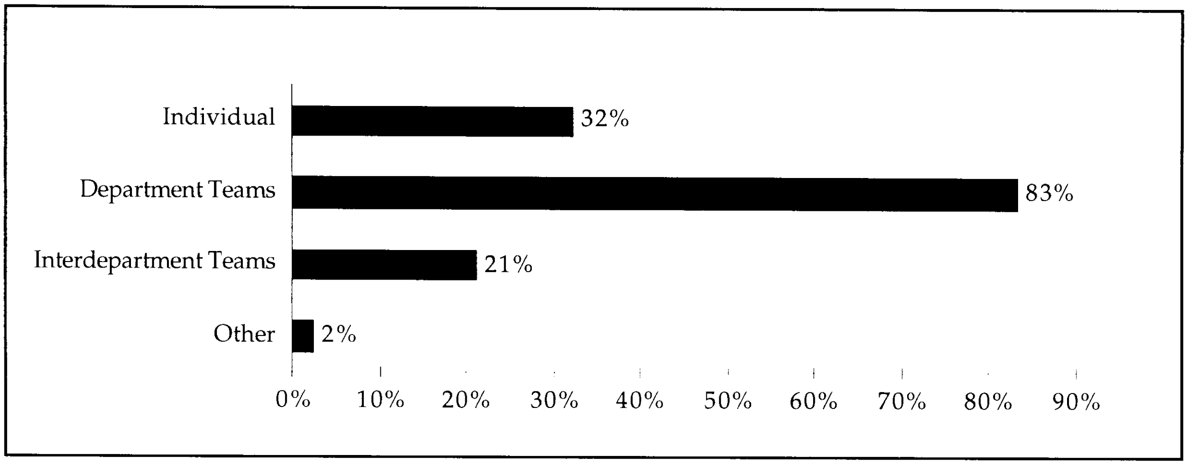

Figure 5 Type of Senior Design Subjects (Todd et al, 1995)

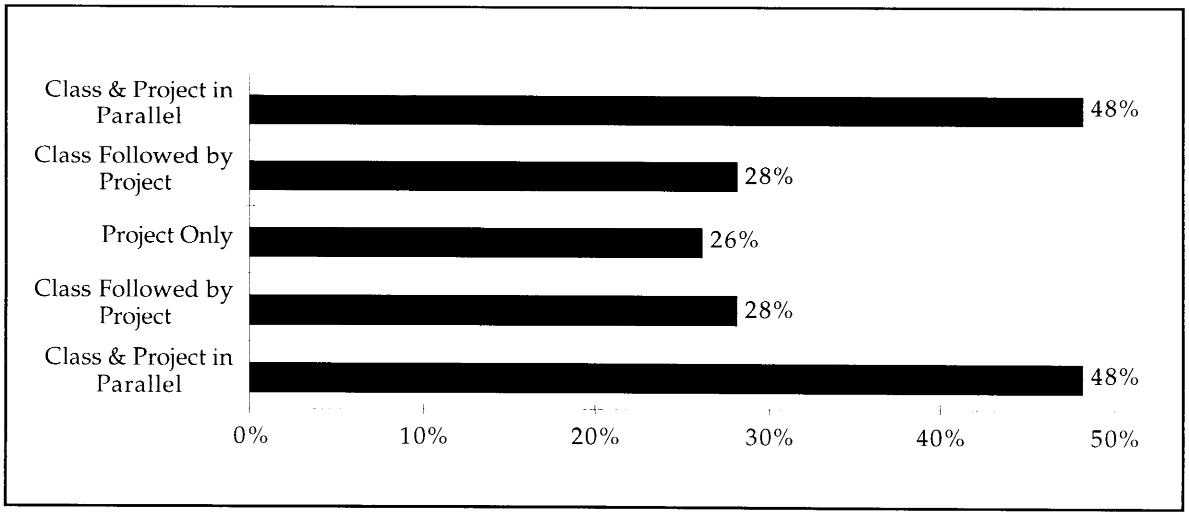

Figure 6 Best Description of Subject (Todd et al, 1995)

Figure 7 illustrates capstone subject duration. Figure 8 deals with classroom instruction hours; the average length per week was 2.9 hours. The "Other" category in Figure 8 represents the respondents that gave formal classroom instruction only during the first few weeks before allowing students to work solely on their projects.

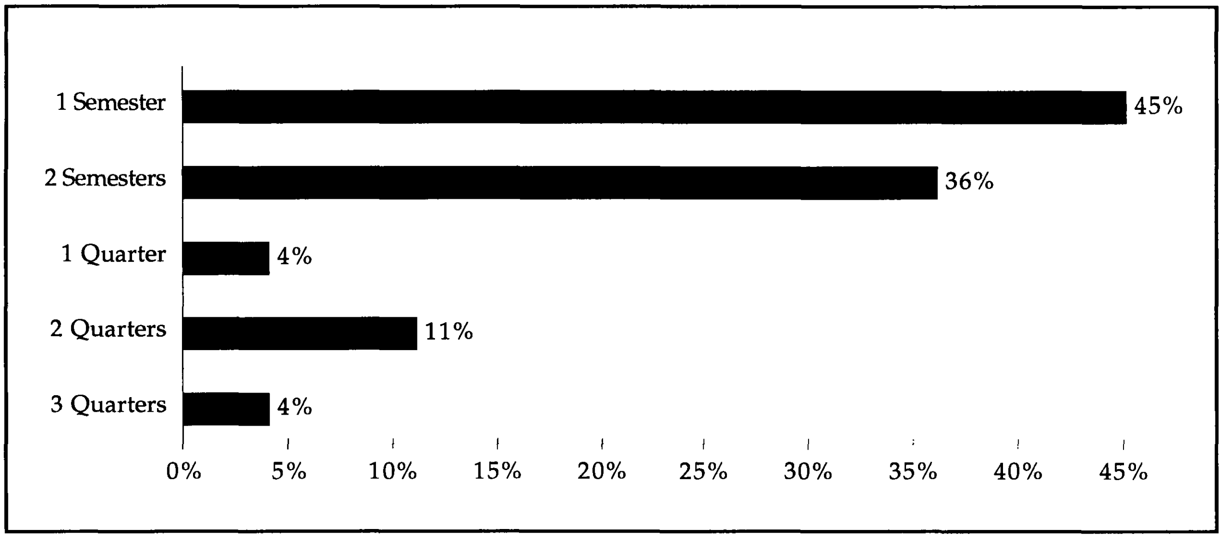

Figure 7 Duration of Capstone Subject and Project (Todd et al, 1995)

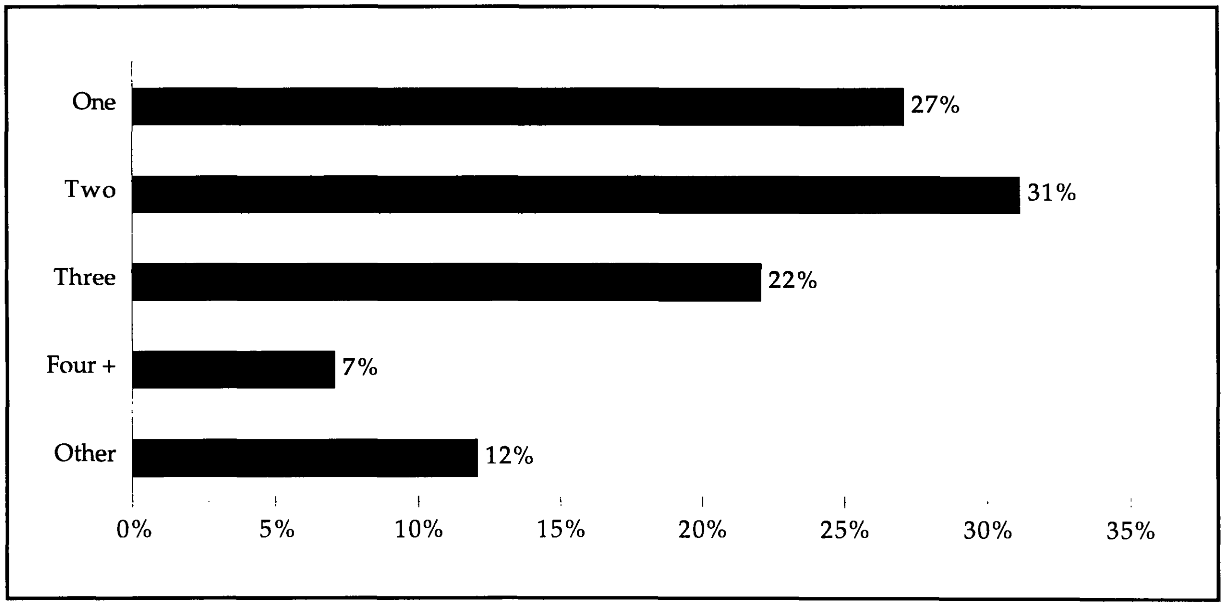

Figure 8 Instruction Hours per Week (Todd et al, 1995)

Figure 9 illustrates the topic variety taught in capstone subjects. Figure 10 indicates the number of projects prepared for students during each cycle of teaching the capping subject.

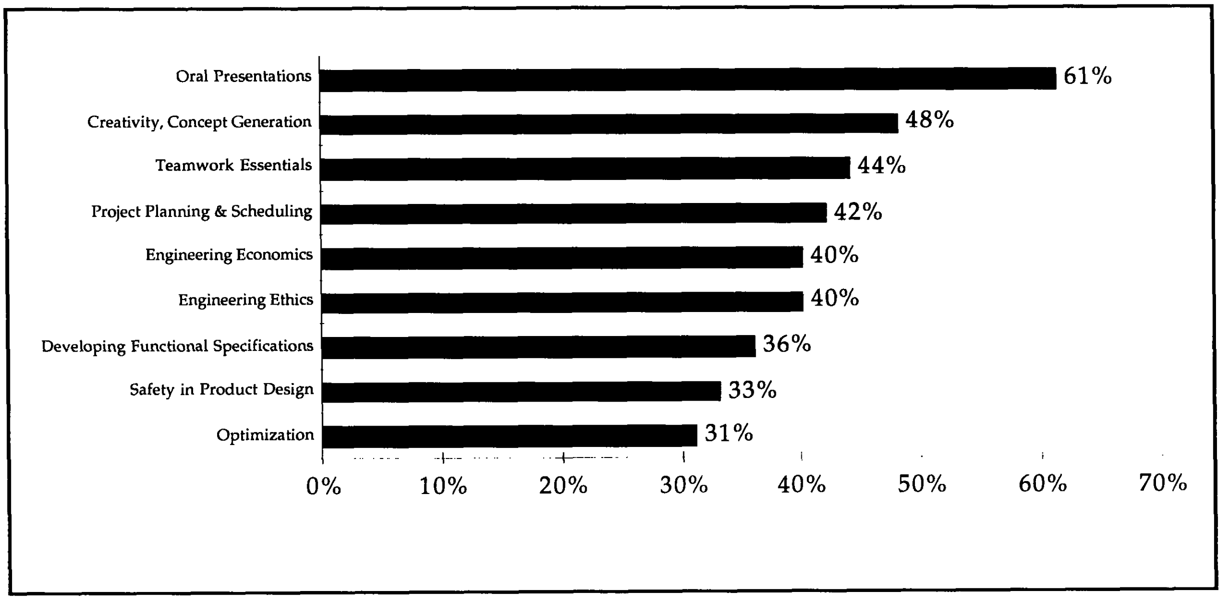

Figure 9 Most Frequently Taught Subjects (Todd et al, 1995)

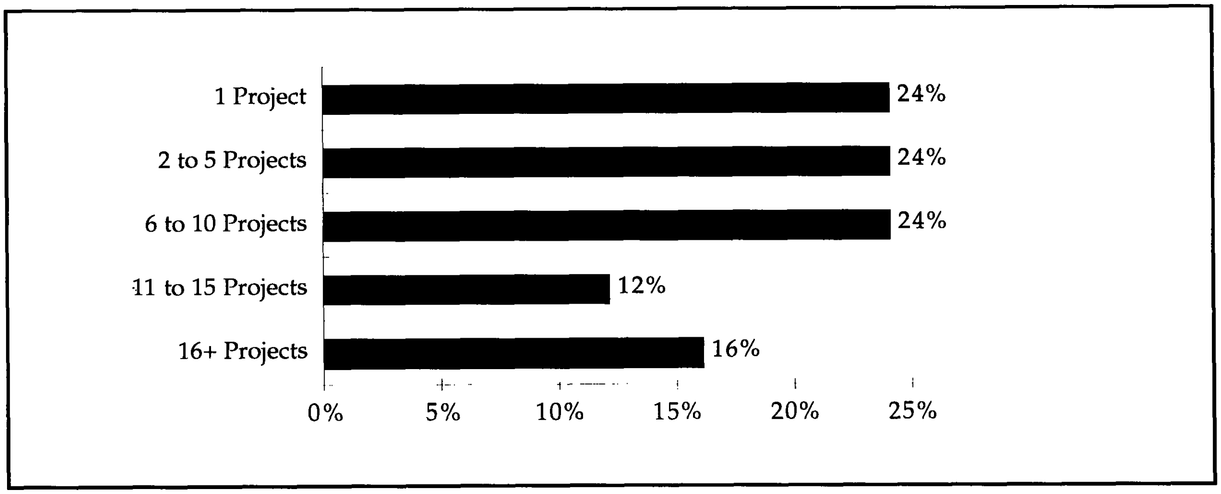

Figure 10 Number of Projects per Course Cycle (Todd et al, 1995)

Figure 11 illustrates the number of teams assigned to each project. 62% of the respondents indicated that each team was given a unique project to solve. Many other departments assigned multiple teams to each project with the teams working competitively to solve the project. Figure 12 illustrates the typical number of students per team.

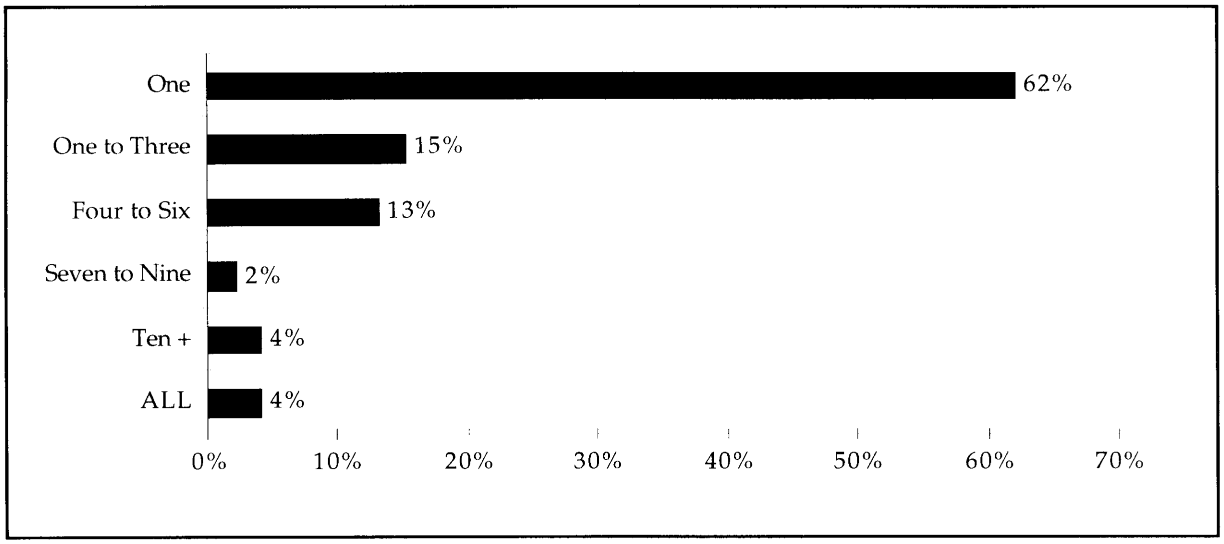

Figure 11 Number of Teams Assigned to Each Project (Todd et al, 1995)

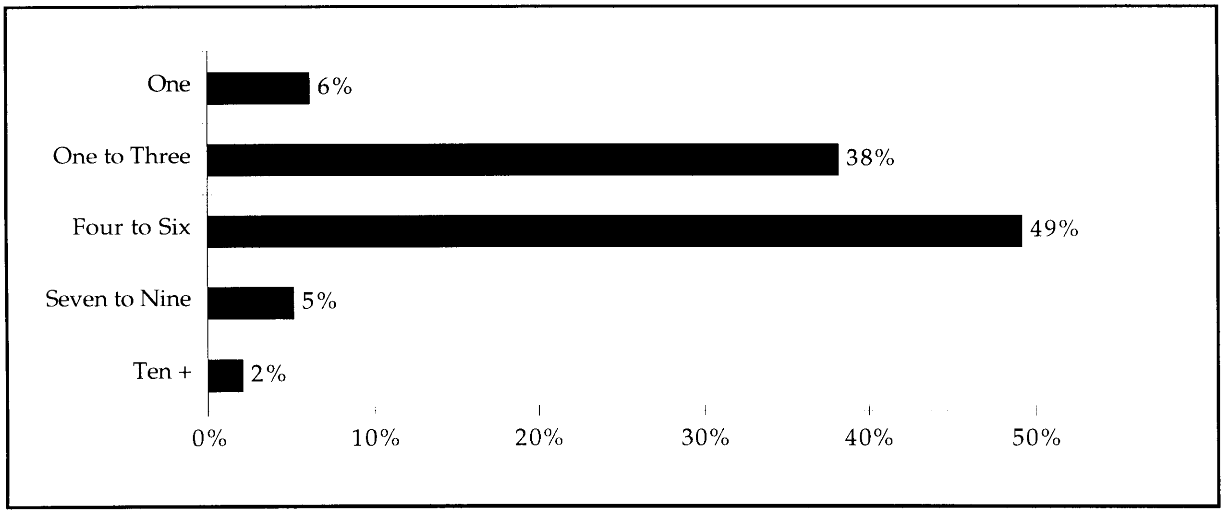

Figure 12 Number of Students per Team (Todd et al, 1995)

Figure 13 illustrates the number of hours allocated for individual or team project work. Many respondents commented that students were expected to finish projects regardless of hours required.

Faculty Involvement

Figure 14 illustrates the percentage of department faculty involved in the capstone experience; however, the level of involvement particularly with greater than 40% faculty participation is unclear. 27% of the respondents indicated that one professor was employed to run the entire capstone program.

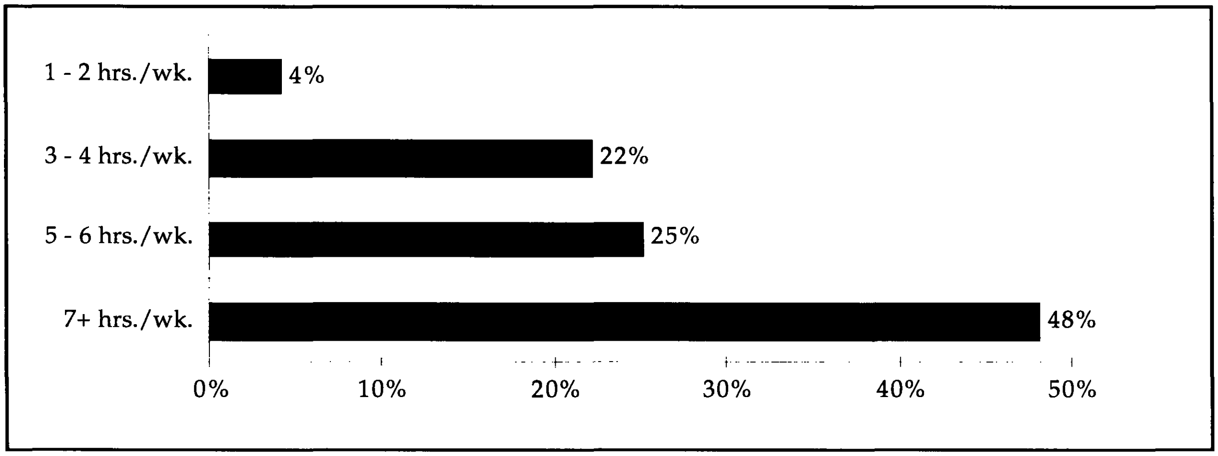

Figure 13 Number of Project Hours Allocated per Week (Todd et al, 1995)

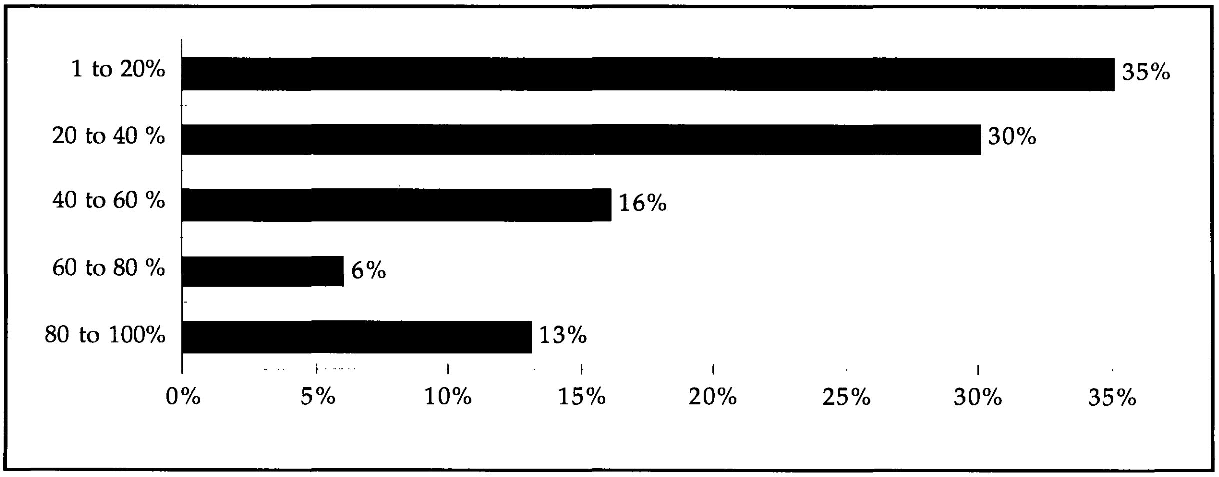

Figure 14 Percent of Faculty Involved in Capstone (Todd et al, 1995)

Figure 15 indicates student-faculty ratios. The survey questions did not distinguish between classroom instruction and project consulting. However, the respondents identified three main models of faculty involvement: one professor supervising a project or team; professors consulting and evaluating teams or projects without being directly responsible; and one or two professors supervising the entire capping subject.

Project Information

In Figure 16 which illustrates project origins, "Internal" sources were projects developed within the department; "Other" sources included scientific journals or sponsored research. Many schools used projects from combined industry and departmental sources.

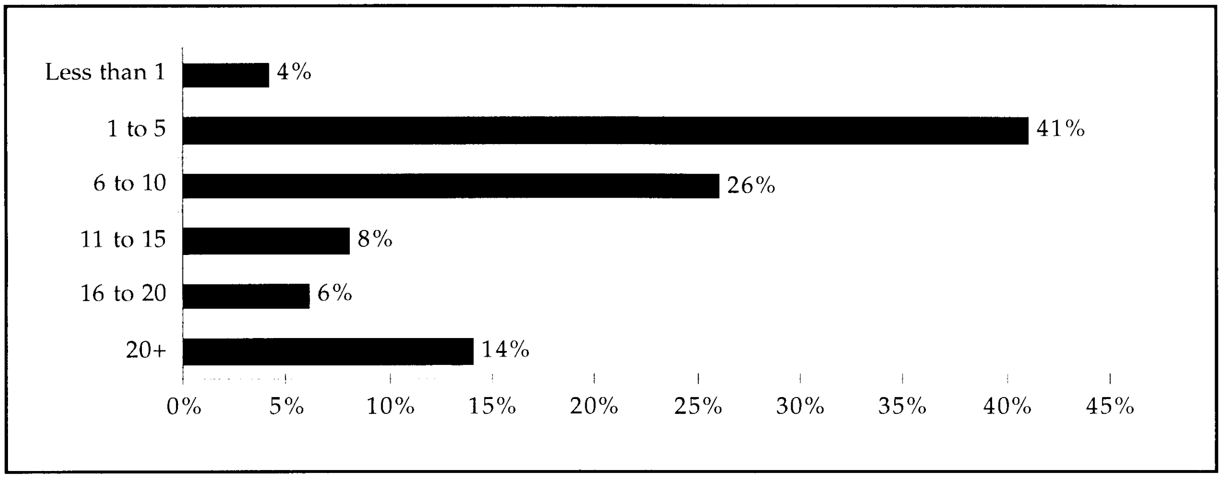

Figure 15 Student-Faculty Ratio (Todd et al, 1995)

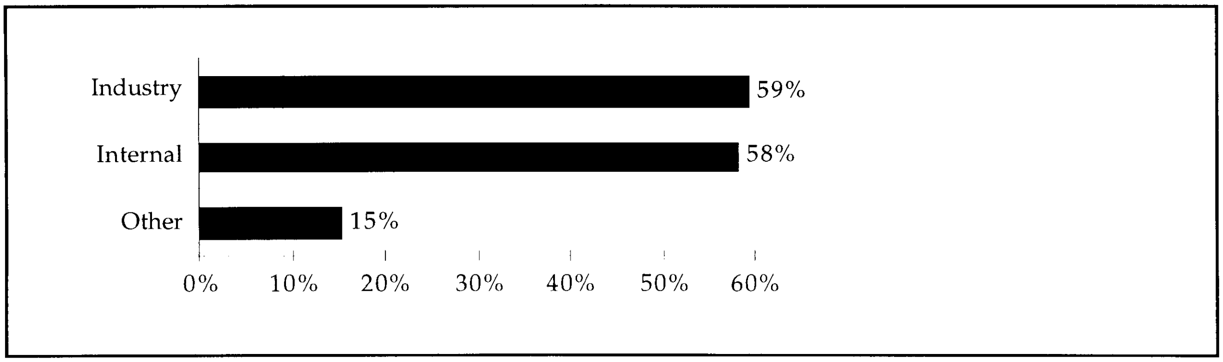

Figure 16 Project Source (Todd et al, 1995)

Figure 17 illustrates project funding sources. Many projects had multiple funding sources. Figure 18 illustrates project requirements. In addition to those listed in Figure 18, almost all departments required written reports and oral presentations.

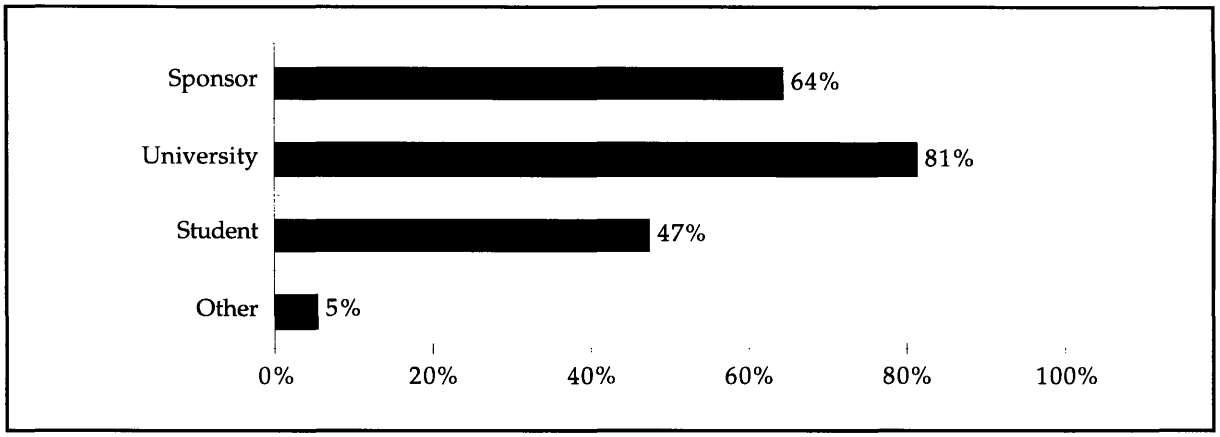

Figure 17 Project Funding Sources (Todd et al, 1995)

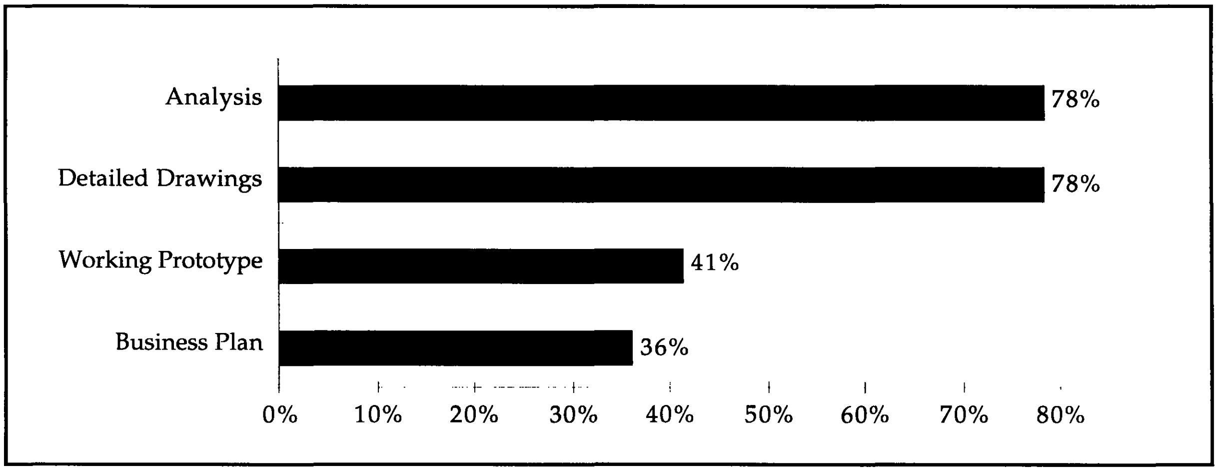

Figure 18 Project Completion Requirements (Todd et al, 1995)

Industry Involvement

64% of all respondents indicated industry involvement. Figure 19 illustrates the frequency of student contact with industry sponsors. Todd et al indicate that higher frequencies of sponsor contact improve project success and student learning. Figure 20 differentiates between industry sponsor types, whether from local industry, industries located in the region, or industries with nation-wide locations. Survey comments suggested that local sponsors were easier to obtain and more successful due to the possibility of increased contact.

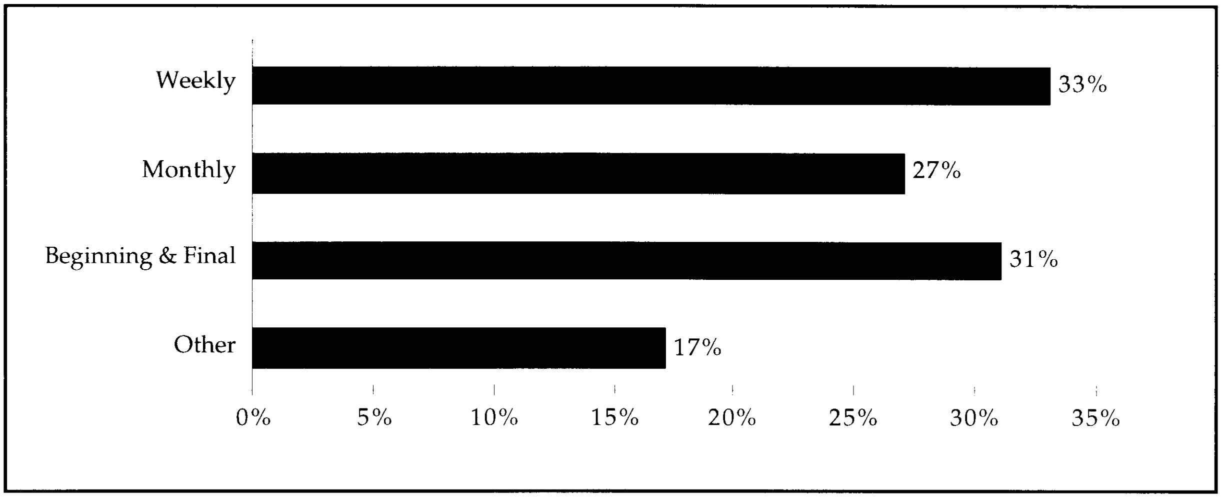

Figure 19 Amount of Sponsor Contact (Todd et al, 1995)

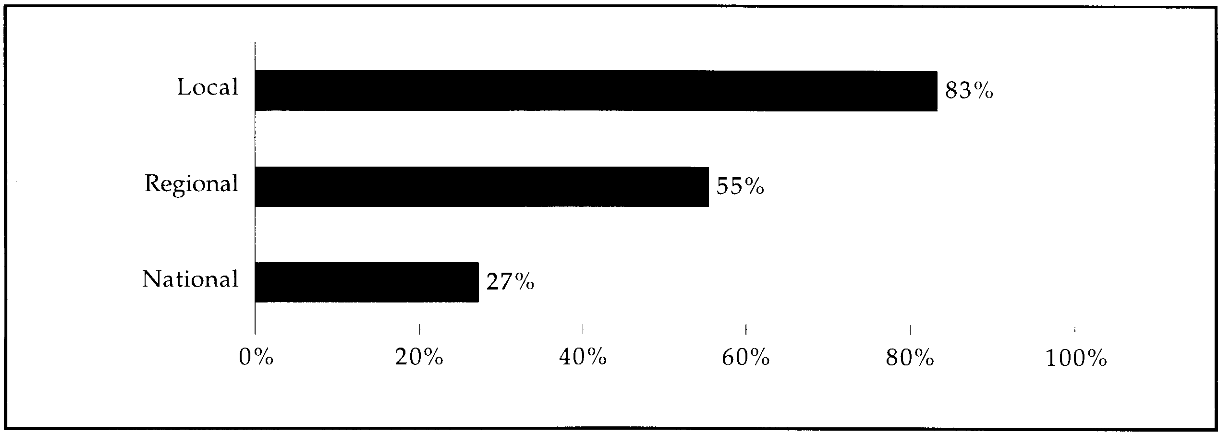

Figure 20 Location of Project Funding (Todd et al, 1995)

In summary, most responding departments were from traditional engineering disciplines. Most capstone subjects involved some form of classroom instruction, lasted four to eight months, and taught a variety of topics. Most respondents favored team-oriented projects with one student team assigned to solve each project. Teams of four to six students were most common. Todd et al suspected that engineering programs were "just scratching the surface" of teaching students how to work successfully in teams. Capping subjects required heavy faculty and student time investment. Project sources and funding largely came from university departments; however more than half the departments solicited industry involvement.

The overview of current practice provided in this section illustrates there is a wide spectrum of alternatives for creating and running a capstone subject Because there are so many alternatives and because the time and energy required by a department offering a capstone course is so great, it seems imperative that departments first define why they are offering a capping subject and the subject objectives; and then examine the alternatives for a best match. The following section offers a more in depth look at capstone classes offered in a variety of civil engineering departments across the nation.

5.3 Design of Civil Engineering Capstone Subjects

There are many ways of designing a capping subject. The following section addresses how faculty around the country are structuring capping subjects. In particular, the following issues are discussed: example projects, faculty involvement, industry involvement, class structure, and grading. Throughout this section, different institutions are often referred to. To avoid using the institution names repeatedly, the following abbreviations will be used:

UMR	University of Missouri-Rolla
UD	University of Delaware
NDSU	North Dakota State University
URI	University of Rhode Island
GIT	Georgia Institute of Technology
MIT	Massachusetts Institute of Technology
CSM	Colorado School of Mines
HMC	Harvey Mudd College
UM	University of Memphis
VU	Villanova University
VMI	Virginia Military Institute
TU	Trinity University
UM	University of Maryland

Example Projects

Each university has its own requirements for project selection. Some requirements include: interdisciplinary nature; technical feasibility; high completion probability; engineering data availability; proximity to campus; opportunity for students to learn technical content; interest to sponsor (if industry is involved); and opportunity for open-ended exploration.

Projects are generally provided by government, practicing engineers, or prior faculty projects. Some schools even allow students to propose their own projects. A list of projects that have been used in capstone subject follows.

Reservoir-dam Complex (URI). Students designed a reservoir-dam complex on a small river located 10 miles from campus which included designs for a water treatment facility, associated highways, parking areas, and a dam spillway bridge. Figure 21 (on the following page) illustrates the project description.

Dam for Water Supply and Flood Control (VU). Project included designs for a concrete spillway, outlet control tower, treatment plant building, pump houses, and treatment basins. Also included are geological studies, highway and railroad removal and location, structure construction cost estimates, and cost-benefit ratios.

New Civil Engineering Building (URI). Students designed a new campus engineering building and investigated road relocation, parking, and the university water distribution system.

Interstate Highway Rest Area/Information Center (NDSU). Project was designed for an actual location for which contour maps, soil data, traffic counts, and water-data were available.

Executive Conference Center (UM). Students designed a conference center for University of Maryland. The project involved transportation, geotechnical, and structural design. It also involved environmental and water resource regulation as well as construction management plans.

Residential Housing Subdivision (UMR). This project required the design engineering for a planned residential community on a plot of land near the university. Project components included: layout of small commercial area with a convenience store, gas station, and residential subdivision; a water-distribution system; an aesthetically pleasing sewage treatment system; hard-surfaced streets; concrete curbs, gutters, and sidewalks.

State Highway Expansion (UMR). For this highway expansion from a two-lane to a 4-lane facility, students were required to assess 3 possible routes for impact on traffic flow, existing commercial development, right-of-way costs, and construction costs. After selecting the optimum route, detailed designs of a highway bypass were completed which addressed environmental concerns and involved the design of a bridge, drainage structures, and pavement.

Golf Course Plan (UMR). Project addressed the flooding problem at a local golf course. Students designed a detention/retention facility, increased the course difficulty, and enhanced the aesthetics of the course. (This project won an award from the city for the design).

REQUEST FOR A PRELIMINARY ENGINEERING DESIGN FOR THE KENT-WASHINGTON COUNTY RESERVOIR AND DAM PROJECT

The South County Water Authority, 1 Upper College Road, Kingston, Rhode Island, 02881, hereinafter referred to as the AUTHORITY requests the development of preliminary site and engineering plans for the design of the Kent-Washington County Reservoir and Dam from CVE Design Teams, Inc., 211 Bliss Hall, Kingston, R.I., 02881, hereinafter referred to as the ENGINEER. The ENGINEER is asked to develop a comprehensive plan and preliminary design drawings for a drinking water reservoir, dam, and treatment facility on the Fisherville Brook in Exeter and West Greenwich, R.I.

A recent study by the AUTHORITY has indicated the need for a reservoir to serve the need of a population of 5000 in the Town of Exeter by the year 2000. The water source is surface runoff from the Fisherville Brook watershed with an area of about 5 square miles. To contain sufficient water, it is anticipated that an earth dam approximately 40 ft high and 2000 ft long will be necessary. Fill material for the dam is to be obtained from local materials on the watershed. The dam design should include a concrete spillway capable of passing a 100-year rainfall event without overtopping.

The water treatment plant should have a design capacity of at least 1 MGD and be designed for the removal of suspended solids, tastes, odors, and colors. Provision for emergency short-term treatment in the event of reservoir contamination must be included. Redundancy in individual unit processes and operations to handle routine maintenance and emergency situations is a requirement.

The AUTHORITY wishes the ENGINEER to evaluate the feasibility of a low-head hydroelectric plant at the site based on a cost-benefit analysis considering the reservoir stage. If feasible, the AUTHORITY will instruct the ENGINEER to proceed with the design.

It is expected that Pardon Joslin Road will be relocated. The ENGINEER should give consideration of locating the roadway on the top of the dam and of crossing the spillway with a bridge. Additional roads, parking areas, and bridge structures for the project are to be included.

The ENGINEER will prepare an environmental impact analysis of the effect of the project on human, wildlife, and plant features at and adjacent to the site.

The ENGINEER will provide the AUTHORITY with written reports on each technical phase of the project as well as a final project report including cost estimates. Preliminary design drawing should be included with the report. In addition the ENGINEER will present an oral presentation for review by the AUTHORITY.

Figure 21 Reservoir and Dam Project Statement (McEwen, 1994)

Nature Center Footbridge (UD). This project involved the design of a foot bridge over an intermittent channel of a major creek to allow pedestrian access to a nature-study area. The pedestrian bridge was not only designed but also built by the students. The students had to convince a licensed engineer of the design competence and had to present designs to the client: the Fair Hill Nature Center. See Figure 22 for the final design.

Olympic Case Studies (GIT)

Although not a design project, researchers at GIT have developed comprehensive interdisciplinary case studies of the actual building projects associated with the Atlanta, Georgia Olympic games. Because the case studies developed by GIT or similar projects could feasibly be used to augment a capstone design experience, I have included a brief description of the GIT project.

The GIT case studies employed a full range of multimedia technologies including: video and audio material, written documents, and computer models. The project tried to capture a comprehensive picture of specific projects and investigated the roles and interactions of owners, architects, civil engineers, contractors, government agencies and financial investors. Project participants were interviewed, construction processes were videotaped, and documents catalogued. The following project elements were also documented: meetings, resolution of conflicting design requirements, development of project goals, interactions with public agencies, and innovative design and construction

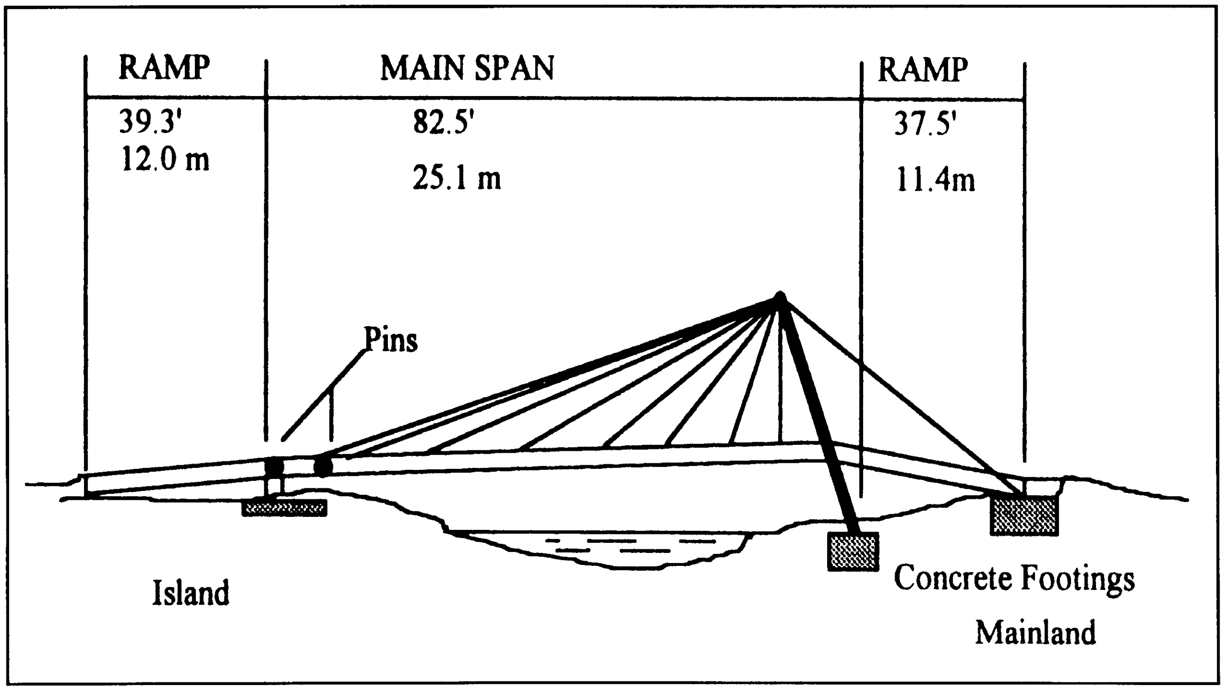

Figure 22 Footbridge Design Elevation

techniques. Also, the design solutions from initial architectural concepts to final as-built implementations were captured.

These and similar interdisciplinary case studies could feasibly be used in lectures and case study analysis to introduce the interdisciplinary reality of the engineering profession, give educational context on critical design decisions, and illustrate the interrelationship between different design decisions. Furthermore, group projects could be assigned students using the case studies as a problem solving resource.

Faculty involvement

There are many options for distributing the teaching load associated with a capping subject. At UD, the capping subject is taught by adjunct faculty drawn from engineers in the community. At UM, the department chair established and taught the capping subject for seven years and then passed it on to another professor. At UMR, the subject is team taught by two principal instructors who have 25 years of combined industry/consulting experience, and the entire faculty participates as expert consultants. A similar approach is taken at VU where three full-time professors serve as faculty supervisors and are credited for a three hour load both semesters; the rest of the faculty is available on an as-need basis during office hours. At MU, P.E. licensed faculty member teaches the capping subject; however, faculty experts are guest lecturers throughout the class. At NDSU, all the faculty are involved, each faculty member serving as an advisor to a project team. Similarly, at HMC each faculty member serves as an advisor to one or two clinic projects each year. In the literature, there is general consensus that more faculty involvement is better as it serves to distribute the work load associated with capping subjects.

Role of Instructors

The primary role of capping subject instructors seems to be that of advisor and mentor offering encouragement, motivation, and a "get-started, try-something, and can-do attitude" (Morris and LaBoube, 1995). Instructors should be willing to teach students how to approach a technical problem, should avoid working out specifics, and should leave management responsibility to the students unless progress stalls. In keeping in the background, faculty allow students to take ownership of their projects.

Though faculty should not be expected to be experts in every facet of the project, they should be able to point students in the direction they can find the expertise they need. Though they need not be experts, UMR instructors believe it is critical that faculty gain student respect and acceptance. They should be able to convey with authority the practice of civil engineering design and must have first-hand field and design experience which will heighten their credibility with students. Finally, HMC faculty think the most important factor in learning the art of advising capping subjects is discussion with other faculty more experienced in this type of advising/teaching role.

Problems Associated with Capstone Teaching

Teaching capping subjects is not for everyone. It requires a greater faculty time commitment than typical undergraduate classes: grading is difficult, particularly when evaluating work outside faculty expertise; and often appropriate teaching credit is not given. These problems if not addressed can lead to low faculty moral and poor student acceptance. Typically administration evaluates faculty by number of student credit hours taught, number of publications, and number of research dollars. This system does not well reflect the time required by capstone subjects. One possible solution might be to recognize a capstone subject as an applied teaching research project and give it the equivalent significance of an average research grant (Morris and LaBoube, 1995).

The faculty at HMC (where the Engineering Clinic has been running for 30 years), believe that the most important component of a capping subject is the dedication of the faculty. Capping subjects require the support of faculty colleagues and administration: a capping subject "will exist only for as long as the faculty wish it to exist" (Bright, 1994).

Industry Involvement

Industry is often recruited to form an education partnership with universities in capstone settings. This enables students to solve real world problems, interact with practicing professionals, gain experience in industry, and increase their job opportunities. In addition, new engineering faculty often have very little design and industry experience for which industry partnership can compensate. Furthermore, working with industry can allow faculty to network for consulting jobs, project grants, capital equipment, computers, etc. However, industry involvement generally does not decrease the amount of time required by faculty to supervise projects. Furthermore, the projects supplied by industry are often either too complex and open-ended or too easy and close-ended for student projects (Uddin et al, 1994).

Advantages and Disadvantages for Industry

Industry can use capping subjects involvement as an effective recruiting tool, an excellent public relations tool, and a method of developing long term relationships with faculty from whose expertise they can often benefit. In providing projects, preliminary feasibility analyses can be done by students saving months of valuable engineering time; and student ideas and work are often very different from internal engineers which can provide a valuable or at least different perspective. In addition, industry often has a philanthropic interest to assist in undergraduate education.

Yet there are risks for industries getting involved in capstone classes: industry typically invests the time of a project coordinator or industry liaison and/or additional funds which may have no return, student outcomes are often crude, and sensitive information may be exposed (Uddin et al, 1994).

Industry Roles

Industry involvement may be as minimal as providing guest speakers, interacting with students on field trips, or judging design projects. One year at URI, the president of Fuss and O'Neill spent a week working with students in a capping subject as an ASCE Practitioner-in-Residence. At VMI, local consulting firms provide design problems, present the problem to the student, and assist in evaluation.

Alternatively, industry involvement may also be extensive. At HMC, industry sponsors pay the college a significant involvement fee. In addition, a company liaison with special interest in project completion spends on average two hours per week with students arranging weekly contact meetings, facilitating access to additional expertise and facilities in the company, conducting design reviews at the company site, and attending presentations at the college. (As an interesting note, when surveyed, 21 of the 27 projects sponsored at HMC during 1992/1993 were rated good to excellent by sponsors.) Once an industry sponsorship is set up, it is critical that an understanding is reached between industry, faculty, and students with regard to project outcome, financial commitments, timetables, and project supervision responsibilities. This is particularly important if any money exchange is involved

Recruiting Industry

Industry recruitment requires a significant time investment from faculty and the development of a solid network foundation with local industries which must be cultivated and maintained. Contacts can be found in industries that employ graduates, alumni, companies that ask for faculty consultations, friends and acquaintances, members of a departmental industrial board of advisors, and professional organizations. Faculty should become familiar with potential industrial sponsors through exchanging industry and departmental visits. Often industry will have "back burner" labor intensive, low risk projects to offer as senior design projects.

Class Structure

This section describes four different approaches to capstone design: conventional, integrated, intensive, and clinic approaches. Each approach is described using illustrations of how capstone programs are run at different universities. The following issues are discussed: how capstone classes are fit into the curriculum, what class time is used for, lecture topics covered, how teams are grouped, and what students actually produce.

Conventional Approach

Probably the most common approach (most often cited in capstone literature) is a class taught during one or two semesters in which a design problem is introduced and a team approach is taken to design. Four civil engineering departments that take this approach are at CSM, VU, UMR, and NDSU.

Colorado School of Mines

CSM has been teaching a capstone subject since 1990. The subject is a two semester (six credit hour) sequence. In a typical week, the class meets together for one common lecture and/or discussion session; the students also meet in design teams with their assigned faculty member; and they are expected to invest an additional eight hours of individual or team effort into the project. During the fall semester, lectures cover topics listed in Figure 23. The spring semester lectures cover topic in Figure 24.

- Project team organization
- Problem formulation and self-education
- Time management and effective meeting strategies
- Quality concepts
- Professional oral, written, and graphic communications
- Engineering design processes
- Engineering analysis and strategies
- Proposal preparation

Figure 23 Fall Semester Lecture Topics (Miller and Olds, 1994)

- Review of engineering design processes
- Engineering synthesis strategies
- Liability and safety issues
- Personal and professional ethics
- Sexual harassment and discrimination in the professional environment
- Patent disclosure issues in engineering design
- Final oral and written report preparation
- Public demonstration of team designs

Figure 24 Spring Semester Lecture Topics (Miller and Olds, 1994)

Concurrently, during the fall semester, students produce several written and oral progress reports, a comprehensive written summary of the design team's proposed solution including a detailed work statement, a proposed budget, and a project completion schedule with intermediate milestones. This proposal is presented not only to faculty but also to the project client in written and oral form for critique. During the spring term, design teams implement their proposed solutions performing analysis, synthesis evaluation, and finishing necessary field work. The capstone culminates in a written and oral presentation of results. Throughout the capstone experience, students are required to document their formal and informal design activities in a bound design notebook including a log of time spent for each activity.

Villanova University

VU capstone classes usually involve up to 45 students in a two semester sequence. The class meets Tuesdays for one hour for formal lectures and two hours on Friday afternoons for student oral presentations, question and answer sessions, guest speakers, and field trips. The Friday class is unpopular, but it helps in scheduling trips and outside speakers. In addition, teams meet biweekly with assigned faculty supervisors.

During the first semester, lecture topics include: design process, managing technical personnel, cost and benefit estimation, and project specialty areas. Students are assigned to teams of four with members from structures, environment, and water specialty areas. Teams elect one leader at the beginning of the semester and another at midterm. Groups prepare a written feasibility study and time and cost estimates for engineering services.

During the second semester, teams of five tackle the more technically intensive tasks. Guest lecturers from government and private industry are brought in to cover ethics, professional liability, environmental impact assessment, regulatory issues and project management. In addition, design specialty lectures are held concurrently for the three different specialty areas which include question and answer sessions. Teams each send representatives to the sessions for each area. By the end of the year, students complete a feasibility study, project siting and sizing, local geologic and hydrologic and water quality investigations, and cost-benefit ratio analysis. They produce an extensive design report with calculations, plans, and specifications and present a forty minute oral presentation to faculty, students and interested public.

University of Missouri-Rolla

The capstone class at UMR has been taught since 1989 and involves an outside "client". The class of 17-34 students is organized like a consulting firm with a pyramid structure. The two faculty instructors are the firm principals. The students are surveyed to identify preferred engineering disciplines, and this information is used to make "staffing" decisions. The class is divided into three primary design teams (water, geotechnics, and structures) and teams are subdivided by design task. A project coordinator and team coordinators are selected by the class from class members interested in management and willing to serve.

The two principals serve the function of overall engineering managers and financial and marketing supervisors. They are responsible for ensuring the project is successfully finished, offering guidance, and protecting against questionable design practice. The project coordinator coordinates activities between teams, serves as the client contact, chairs weekly project-review sessions, chairs all client meetings, and coordinates the development of oral and written project documents. The team coordinators coordinate design team activities including development of team presentations; in addition, they represent the team at client meetings and weekly project review meetings. The team members are responsible for specific design components and for both oral and written communication of their design.

In the weekly project review meetings, project status is reported against a predetermined schedule with penalties assessed. At the end of the term, each team member is required to present and defend their work to the principals and team representatives give a formal presentation to the client and civil engineering faculty. In addition, each student submits a written report with project specifications, design calculations and cost estimates. The teams develop schedules that are integrated with other teams to ensure a successful product. The suggested scheduling tasks listed in Figure 25 are given students to help alleviate uneasiness in the scheduling process. The technical phases of the project are summarized in Figure 26.

University of Maryland

At MU, the final undergraduate semester involves a capstone class. Students meet for lecture once a week. Although the class is run by one professor, different professors participate in the class as lecturers and consultants for their area of expertise (i.e. structures, construction management, etc.). In addition to lectures, there are two-hour labs held twice each week. Students work in groups of six or seven and prepare technical reports and presentations for each major aspect of the project. In addition, students deliver a final one hour presentation emphasizing their technical design.

North Dakota State University

The capstone subject at NDSU is a two quarter, three credit sequence (one credit the first quarter, and two the second). During the first quarter, faculty members in particular areas of expertise make presentations to the class during the weekly lecture period. During the second quarter, the lectures each week are used for

- Identify aspects of the design where safety, economics, or health are of prime importance.
- Identify theoretical concepts required for the design.
- Identify types of expertise required.
- Outline the end products required and prepare an expanded "scope of work" statement.
- Establish project management needs.
- Separate the design problem into sequential phases and identify and list the objectives of each phase.
- Identify major tasks associated with each phase.
- Establish critical dates to aid in schedule preparation.
- Organize and staff tasks by phase, and prepare an organizational chart showing task assignments.
- Prepare job planning sheets to schedule personnel and evaluate manpower loads.
- Estimate manpower resources needed for project design.
- Establish project files that contain a thorough set of records, to include correspondence, design assumptions, and so on.

Figure 25 Suggested Scheduling Tasks (Morris and LaBoube, 1995)

- Information collection. The objective of this study phase is to gather the necessary data to adequately define the problem and develop preliminary solutions. This may consist of site inventories or interviews with the client and other potential users of the facility to be designed. During this phase of the project all pertinent design codes and standards should be identified and obtained. To identify appropriate design requirements, the student may be required to visit local or state building officials.
- Generation of alternative solutions. Based on the goals and objectives of the designed facility, design alternatives must be identified.
- Preliminary evaluation. Design alternatives are compared with an emphasis on identifying the best and worst features of each alternative. From this activity, recommendation must be made on the most optimal design alternative.
- Analysis. Where design begins to take shape is the detail design phase, which usually involves sizing or determining dimensions, selecting members, selecting equipment, and so on.
- Synthesis. It is during this activity that the various components or elements of the facility are identified and incorporated in the design.
- Evaluation. An evaluation of the functionality of the design is considered in this phase of the study. Of particular importance are the perceived likes and dislikes of the client and public toward this proposed design. Does the design address the desired goals of the completed facility?
- Implementation. To bring any project to its fruition requires project specifications, bidding procedures, necessary permits and approvals.
- Project completion. Although primarily a management activity, it is key to a successful product. Final reports are written, project costs are developed, and project design files are assembled.

Figure 26 Project Technical Phases (Morris and LaBoube, 1995) general announcements and several guest speakers with experience on related projects. Faculty advisors also meet informally with groups to monitor progress and schedule activities. Groups of four are randomly selected to work together. During the first quarter, groups collect data and develop project completion strategies which they present to the faculty in ten minute oral presentations. In the second quarter, groups complete their design producing written documentation and an oral presentation with accompanying written reports, design calculations, plans and specifications. Groups are required to keep a daily diary and log of project activities noting which individuals worked on each phase.

Integrated Approach

University of Rhode Island

Since 1990, the URI capstone experience has been integrated throughout the entire undergraduate experience. The theme design project is introduced in a one credit professional practice subject taught first semester junior year. This class serves as a mini-planning course for the design project with introductory lectures on the project, field trips to the site and similar projects under construction. Students in teams of three or four submit a report and preliminary plans. A class schedule is illustrated in Figure 28.

After the initial one credit seminar introducing the theme design project, design modules related to that project are incorporated into most of the junior and senior level classes. The design modules consist of lectures, example problems, homework, and problem data applicable to the theme project and last anywhere from two or three lectures to four weeks in duration.

During the first semester of senior year, students have a one credit professional practice class in which outside speakers of general civil engineering interest speak. In the last two class meetings, the design requirements of the capstone design course are given (Figure 27 illustrates a sample set of design task requirements); and the class is divided into design teams of four or five members. Note that though the design task requirements are extensive, much work has been completed already in the design modules.

The team selection process at URI is noteworthy. Project managers for each design team are selected by the faculty course coordinator from a list of students who apply. The project managers then meet together to select their design teams. The criteria for selection include students' professional interests and completed electives, and the aim of creating well-balanced teams.

During the culminating capstone course, the class meets two times (for a total of eight hours) each week. The project manager is responsible for completion of work assignments, progress reports, the final project report and oral presentation. Each student is the project engineer for one technical phase of the project and is responsible for the associated written report and engineering plans. The final product of the capstone course is judged by two practicing engineers and a faculty member not directly involved in the subject. The team with the highest grade receives a monetary reward from the department.

Recycling Facility Design

The ultimate objective of any design project is a set of plans, specifications, and reports from which the project can be constructed. The following tasks define the scope of the project:

1. Conduct a Market Research Study
    - a) Determine population of the area and percentage which is urban, suburban, and rural.
    - b) Determine the quantity and composition of solid waste; daily tonnage, average monthly tonnage, seasonal variation and annual tonnage of potential recyclable items.
    - c) Survey potential buyers in the Northeastern region for type, specification, and quantity of desirable products. What is demand cycle and possibility of a long term contract?
    - d) Finalize the quantity and type of recyclable items, number of days of operation per year, average daily delivery, maximum daily delivery, and number of shifts per day.
2. Design of Recycling Processes
    - a) Determine the flow pattern and number of process lines for each material (including spare lines).
    - b) Select suitable equipment for processing each material, number of picking stations, space requirements for equipment, and working areas.
    - c) Determining space requirements for stockpiling, changing area for vehicle unloading, process system loading, storage area for recyclable products, and shipping vehicle loading area.
    - d) Determine number of scales and capacity, space requirements for tipping hall, vehicle delivery, maneuver area, and exit area.
    - e) Determine space requirements for administration and maintenance areas, e.g., offices, conference rooms, and machine shop.
    - f) Determine if land fill is required; if so, include estimated cost under cost estimating.
3. Site Planning
    - a) An initial site reconnaissance taking notes, photographs, etc. To get a "feel" for the location.
    - b) A review of the site topographic survey. Supplemental field measurements may be necessary to confirm critical site elevations.
    - c) Preparation of a base map of the area to include survey details and other pertinent features. This will include location of buildings, utilities, streets and sidewalks, drainage structures, large trees, and plantings.
    - d) Research area utilities for details, including exact locations and capacities. Make plans for connections for new construction.
    - e) Using the foregoing information, review several alternatives for recycling facility, road, and operational area siting and select the one which is viewed as the most feasible. (See also highway design)
    - f) Expected products:
        1. A plan cover sheet, which identifies the project and includes an area location map.
        2. A topographic map sheet, which details the specific site characteristics with the superimposed "foot prints" of the building.
        3. A sheet, which shows location of existing and planned utilities (water, sewer, storm drains, electric, oil tanks, gas lines) relative tot he planned facilities.

A sheet, which shows the designed roadways, parking and truck and trailer maneuver areas and drainage.

Figure 27 Example Project Design Tasks (McEwen, 1994)

Intensive Approach

University of Delaware

At UD, a five week, three credit intensive design class was offered during their 7 week winter break. The class designed a pedestrian bridge for a nature center which the ASCE chapter subsequently built. The class of sophomores, juniors, and seniors met three to four hours, five days a week. The course was divided into three segments.

In the first segment, students were introduced to conceptual design development, materials selection, construction methods, and project management. During the second, the students were given an accelerated introduction to timber design. And in the final section, the students were divided into design teams to produce the final designs. The professor was available during class hours to meet with groups as often as needed and assist in coordination among groups. In addition, teams made periodic presentations to summarize and explain their designs to the other groups. The six working groups were assigned to the following areas: surveying and mapping, permit application, overall design and load analysis, deck design, tower and cable design, and foundation design. The students developed design concepts, calculations and specifications, hydrology and environmental loadings; prepared a soil erosions permit application, and a joint State of Maryland-Corps of engineers construction permit application. A retired professional engineer from Maryland reviewed student work and sealed the final drawings.

Date	**Planned activity**	**Guest**
September 6	Introduction to design program	—
September 13	Introduction to solid waste recycling project, organization of design teams	—
September 20	Economic analysis of solid waste recycling	Prof. Calvin Poon
September 27	Field trip to R.I. Solid Waste Recycling Facility	—
October 4	Guest speaker	Mr. Thomas Wright, Executive Director, R.I. Solid Waste Management Corp.
October 11	Guest speaker	Mr. Victor Bell, Director, Planning and Development RIDEM
October 18	Field trip to project site	—
October 25	Collection of environmental, geological, and soils data	Prof. Daniel Urish
November 1	Environmental impact study	Prof. John Kupa
November 8	Work session	—
November 15	Work session	—
November 20	Work session	—
December 6	Work session	—

Figure 28 Junior-year Professional Practice Schedule (McEwen, 1994)

Engineering Clinic Approach

Harvey Mudd College

The Engineering Clinic program at HMC has been run successfully for over thirty years, and each year it involves about thirty industry-sponsored projects. The required clinic is a three semester sequence of the second junior semester and both senior semesters. At the start of the junior academic year, students read project descriptions and express their project preference in a closed ballot selection process. The students are then assigned to four or five member teams and each team is given a faculty advisor. The teams choose a team leader, meet with their industry liaison, and commence work on their projects. Design reviews are held at company (industry) location, and each semester teams give a 20 minute oral presentation to faculty, students, and guests. Upon project completion, teams present their results to an audience of project sponsors, prospective sponsors, faculty, and visitors at the student Project Day.

Massachusetts Institute of Technology

In the environmental engineering clinic program at MIT, students are assigned to an industry project and the industry sponsor provides a student supervisor. In addition, each student is given a faculty advisor. Students work on the industry project for one term and produce a short written proposal, two interim written reports, and a final written report. Oral reports accompany each written report. The clinic has experimented with group projects and discovered the following advantages: students are exposed to group leadership; the experience is more typical of the real world; there is less administrative load; and the group work is encouraged by ABET. However, individual work is the norm which encourages independent work; reduces possibility of team "followers" who put in less effort; and leads to more vicarious learning because as more projects are run concurrently, students learn from each others' projects.

Recommendations for Class Structure

The faculty involved in teaching the capstone classes described above often expressed the same concerns and desires for improvement. Their suggestions future capstone practice include: professional involvement from the engineering community both in lectures at the beginning of capstone subjects and in final design critiques; equitable information transfer to groups and facilitation of inter-group communication; and multiple formal progress reports. Faculty involved in teaching open-ended design indicate it is imperative that instructors use every opportunity possible to encourage students to have a can-do attitude when exposed to the uncertainty of open-ended design.

Grading

There is general consensus that grading capping subjects is extremely difficult and very time consuming. In grading team efforts, most instructors choose to assign a team grade and then adjust that grade using peer and self-evaluations, attendance, and professional conduct. An element of competition is often introduced to increase student incentive: putting the outstanding capstone design on a plaque outside the department office, or giving the winning group a letter grade increment, or offering a monetary reward. Instructors at UMR recommend using a pass-fail grading scheme if possible.

Student Response

Overall, student response to capstone subjects published in the literature seems to be very positive. Students struggle with the ambiguity of design, but generally realize the value of a capping subject. Reported student responses to programs at various universities are summarized in the following paragraphs.

University of Delaware

In five weeks, inexperienced engineering students (there were four sophomores in the class with only a basic statics course for background) successfully completed a comprehensive and sophisticated design project and gained the confidence that comes in completing a project far beyond their perceived capabilities.

Colorado School of Mines

Student response to the capping subject is consistently positive. They rate highly the special class sessions devoted to discussions of ethics and whistle-blowing, sexual harassment, liability and safety, and patent disclosure. Overall, ninety percent of course comments are positive, and approximately twice as many students apply as the program can accommodate (other students do individual research projects to fulfill the same requirement). Students are selected on the basis of GPA, interest, motivation, and project "fit."

University of Rhode Island

Student response is excellent and they exhibit more interest than in the traditional courses with is reflected in the quality of the final reports. Students often invest over thirty hours of work per week outside of class. The most common responses from students include: "the capstone course was a very valuable experience"; "it was a tremendous amount of work"; "I didn't like the uncertainties of not knowing what the correct answer was or where to find all the data I needed"; and "before I took this course, I was concerned about undertaking a new problem and where to find answers to my questions, but now I am confident that I can approach similar situations."

Harvey Mudd College

Fifteen of eighteen students enjoy the clinic experience at HMC more than any other course and put more time into the clinic than the average course. Team leaders say learning management skills was the most beneficial part of the course.

In general, students would like better defined objectives at the start of the year from the company liaisons; and clearer goals, expectations and more help in technical aspects from the faculty. They struggle with not being given explicit directions for completing their tasks and are reluctant to assume responsibility for their own design decisions.

With respect to team work, one student indicated, "as much as I hate to say it, and not that I would have enjoyed it or gone to it had it been optional, instruction on project management, group behavior, working with others, etc., general information that would help organize the team and make it communicate better would have been very helpful and is a big part of the clinic experience."

University of Missouri-Rolla

In educational value, *all* students at UMR rated the capping subject average or above. Common students comments include: "good learning experience"; "very practical course"; "gives student the chance to go out and learn on their own"; "it is reality and it is up to the student to finish in time and with accuracy in their design"; "practical application of class material that was previously taught"; and "it is definitely a valuable course since it brings everything we have learned in the past four to five years together."

For students, the class is a major time commitment. Because students are used to solving defined equations, open-ended design is intimidating. The course weaknesses they cite include excessive work and vagueness of instructor expectations. They get frustrated by the ill-defined nature of the design process. UMR instructors feel, "what [the students] fail to understand at this juncture of their career is that practicing design professionals share similar frustrations, but that is the nature of the design process" (Morris and LaBoube, 1995).

5.4 Conclusions

To summarize the lessons learned both from the MIT integrating history and from capping experience elsewhere, this section will draw multiple conclusions and outline a set of brief guidelines for structuring a capping subject.

Teaching

The most important component of a capping subject is having a dedicated faculty, not only among those actually teaching the subject, but also a committed department chair and supportive faculty willing to step in and assist those actually teaching the subject. History would indicate that a capping "vision" at MIT has been both difficult to create and sustain. Furthermore, MIT's civil engineering department has struggled to maintain commitment while capping subjects were being taught.

Faculty personality and experience are also critical in the capping subject success. Faculty should have first-hand field and design experience, not only to guide students through an intensive design experience, but also to gain their respect and acceptance. This combination is difficult to find in research-oriented universities. However, the consulting experience of senior faculty members may often be capitalized upon.

The work required in teaching a capping class is too much for one professor and should be distributed among the faculty. Team teaching and involvement of as much departmental faculty as possible would be the logical solution to help lessen the time load required from any individual faculty member. However, at MIT this has historically been difficult. When it has worked, it has required not only coordination, but faculty mindfulness in trying to both understand and respect other's opinions, perspectives, and approaches to teaching.

Regardless of how a capping subject is taught and how many instructors are involved, it is important for the teaching effort to be rewarded adequately. Faculty tend not to believe frequent pronouncements regarding the importance of capping subjects; and the reward structure of research universities is inherently not set up to credit the time required by good teaching. Therefore, teaching capping subjects requires notable incentives, not only for primary instructors, but also incentives for other faculty members to become involved.

When exposing students to the uncertainty of open-ended design, faculty should serve more as advisors and mentors with a "you-can-do-it" attitude than as teachers in the traditional sense of information providers. This helps students to find new and unique solutions to design problems. Teaching assistants with extensive practical experience are invaluable in relieving student anxiety with open-ended design. In assuming the mentor/advisor role, discussion with and advice from seasoned capping instructors is the most helpful preparation. This may require talking with professors from other universities.

Design

It seems inherently difficult for undergraduate students to become comfortable with design. Therefore, a large part of successful capstone teaching is related to helping students with the design process, both prior to the capping subject and within the subject itself.

The idea that design can be successfully taught in one class is risky; curricula that are primarily "deductive-analytic" do not facilitate an easy or successful design exposure process, particularly if design is *first* introduced in the capping subject. Therefore, it is highly recommended that design be integrated throughout the entire curriculum avoiding a the fire-hose model often used to describe the MIT undergraduate experience.

Within the capping subject, initially well-defined objectives and straightforward explanations of design's non-quantifiable aspects will help alleviate student frustration. This is particularly true with respect to expectations for student work and the grading structure. In capping subjects, students often do not understand how they are graded and experience it as being either completely subjective or arbitrary. Some recommend a pass-fail grading scheme as a solution to the grading problem and using competition as a means of otherwise providing student incentive.

Because design is a vague, ill-defined process, it is helpful to require from students multiple formal progress reports or other intermediate milestones. Time logs and diaries are another measure to help students maintain focus.

Finally, students are more comfortable when lectures roughly follow or complement their design process. Studio time (or recitation time) should be an integral part of capping subjects to allow question and answer periods and easy access to faculty or expert advise.

Groups

Group process can be the source of project failure or success. Therefore, if group work is involved in the capping class (which is almost invariably the case due the workload and inter-disciplinary nature of capping subjects), students should be given as much guidance as possible on how to function effectively in groups. Guidance should include group dynamics, communication, organization, and project management (see Chapter 6). With multiple groups, inter-group communication and equitable information transfer to groups also become important issues to monitor.

Projects

The projects chosen for capping subjects are critical to success as well. In general, projects should be complex, open-ended, and require students to gather information on an as needed basis. Furthermore, to avoid unnecessary student frustration, they should be an appropriate size (technically feasible with a high completion probability) and engineering data should be available. Finally, projects that are based on real problems that are physically in close proximity to the campus are helpful in stimulating student interest. If a sponsor is involved, it is critical that the sponsor also be invested in the project.

Industry

Industry sponsorship can be particularly helpful if faculty have little design experience for which professional engineers can compensate. Furthermore, industry involvement provides students with real world problems, interaction with practicing professionals, industry experience, and increased job opportunities. Even if industry involvement is minimal, it can be particularly helpful in lectures at the beginning of the capstone process and in final design critiques. Local sponsors are easiest to obtain and generally more successful. Finally, it is critical that industry, faculty, and students initially agree on project outcomes, financial commitments, timetables, and supervision responsibilities.

In conclusion, it should be noted that there is increasing emphasis on introducing open-ended problem solving, communication, and team processes in freshman and sophomore level classes. This trend recognizes the fact that students often do not enjoy their first experience swimming in the shocking cold of real world ambiguity and through the maze of team work subtleties. However with experience, the learning process associated with design and group work becomes easier as students gain confidence in making and justifying assumptions and in collaborating with others.

As students are exposed to design, they should be encouraged to not only consider project outcomes and deliverables, but also investigate how they interact with the activity of design and the associated learning process. When students become aware of these different levels of engagement, they will be more likely to enjoy the experience of design.

6. Group Work

Each year the solar electric vehicle team at MIT, in preparing for the Sunrayce, a national 1,150 mile race from Indiana to Colorado, designs and builds a vehicle requiring technical expertise, fund raising, headache, and daunting time commitment. Kim Vandiver, the faculty advisor for the team, says that of all the problems the team runs into each year, the most challenging concern is team dynamics: operating as a team, respecting each other, and supporting individual talent.

My own experience mirrors Vandiver's. As an undergraduate on the first day of class, whenever group work was part of a class syllabus, my spirit sunk. As an instructor for an undergraduate mechanics of materials class, implementing group work in the class was the most difficult concept to sell students: as comfortable as fingernails screeching down the blackboard.

In preparation for teaching that mechanics class, I knew I wanted to implement group work, but wasn't certain how. In educational settings, I had not seen group work integrated into teaching in a way that could be characterized as supportive of a first exposure to group work. This final chapter is a summary of my attempt to look at group work in the context of undergraduate engineering education and address the following questions: why group work is, in my experience, so difficult for engineers; why should engineering educators bother with group work; and how could group work be implemented to maximize potential benefits and minimize pitfalls?

6.1 The Challenge and Reward

There are challenges and rewards to doing group work from both from the perspective of an engineering student and the perspective of an engineering instructor. In this section, I will discuss primarily the challenge and reward of group work from the student's perspective. The challenge of implementing group work from an instructor's perspective will be addressed. To the extent instructors are committed to student growth, they will derive satisfaction from the rewards students gain from group work.

As I refer to group work in this paper, I realize group work does mean different things to different people. Therefore, I will define group work as two (preferably three) or more students working together on a task: whether a term design project or an in-class brainstorming session or a collaborative writing assignment or a mechanics of materials problem set. Because there are many different tasks or assignments in an engineering education context that could involve group work, in this paper, I will always refer to a group task, however large or small, as a group project.

The Challenge

When examined, it is not surprising that engineering students initially have such high aversion to group work. According to my thinking, they have three things against them.

First, engineers are not commonly lauded for being socially adept. In fact, they are better known for befriending computers than people. Though degrees of being people-friendly vary widely among engineers, I do not think the stereotype is completely mythical. Engineers traditionally have spent more time working on their own than with other people; and engineering education has also been traditionally focused on individual work involving intensive analysis and calculation. Neither of these activities fosters group skills. However, there are skills that can be learned about working with people, just as there are skills that can be learned to become computer-literate.

Second, given that engineering students usually do not have much experience working in groups, to be thrown into a group situation without much supervision or support can greatly magnify fear and distaste for groups. The few times I was exposed to group work as an undergraduate, whether in engineering or humanities, I was never given any instructions or "how to's". Admittedly the "how to's" for group work are less easily stated and less easily followed than the "how to's" for creating computer code, but I am convinced that some rudimentary guidelines or even conversations about what it means to work in a group can be beneficial. Again, given that engineers may be less people-oriented, dropping engineers into group work without support may be comparable to throwing students who can not swim into a swimming pool's deep-end without first giving them instructions on how to swim.

Finally, engineers are often trained to be more product rather than process oriented. They work on specific projects with certain specifications and are rewarded for getting the project built, the specifications met, the deadlines satisfied. In contrast, group work involves tending process. I have been involved in some intense group work with a community dedicated to building and understanding group dynamics. Having met weekly in this group for a number of months, I have learned that reaping the benefits of group work requires shifting focus from deadlines and finished products to group process: slowing down (something not taught at MIT), respecting one another, acquiring the input of everyone involved. Educational literature supports this perception (Hensey, 1992; Katzenbach, 1993; Ward, 1994). Common sense supports it as well: getting three or four people to move in the same direction can be much more cumbersome than moving an individual. If an individual is oriented towards completing the product as quickly as possible regardless of means or the learning involved or resulting quality, group process can be excruciating. This, in my opinion, is the crux of an engineer's headache with group work.

The Reward

Given that engineering students have historically not been praised for social skills, are often not given much support doing group work (which magnifies anti-group prejudices), and are usually not process oriented, why bother with group work? In a time when industry is using group work increasingly and looking for employees that will fit into their teams (Aller, 1993; Nicholson, 1994; Simpson, 1994), maybe we can safely ask the contrary. How can we afford not to bother? But even if the Western World weren't moving in the direction of groups and requiring group proficiency, many inherent qualities of group work are advantageous in educational settings. In fact, "during the past 90 years, nearly 600 experimental and over 100 correlational studies have compared the effectiveness of cooperative, competitive, and individualistic efforts" (Smith, 1995). These studies indicate that "the more students work in cooperative learning groups the more they will learn, the better they will understand what they are learning, the easier it will be to remember what they learn, and the better they will feel about themselves, the class, and their classmates" (Smith, 1995).

In my own personal research, I have found three overriding reasons for the comparative advantage of group work which will be discussed in depth in the following sections. Group work provides more opportunity for students to learn from each other; it dramatically improves the learning climate and teaches students important social skills; and it results in students producing better work.

Educational Advantages

Each student brings unique history and skill to a classroom. Group work capitalizes on these histories. It gives students the opportunity to learn technical, communication, and practical skills from each other. Perhaps even more valuable, through exposure to professional lives and experiences different from their own, students are also exposed to alternative problem-solving strategies and perspectives which they may use in their educational or professional careers. This exposure not only enriches student experience, but it teaches that colleagues are not merely competitors to beat on the final exam; rather, they are invaluable assets both inside and outside the classroom.

As students are interacting with each other and gaining windows into each other's lives, they will also be engaging new learning material. Group work requires students to teach each other what they are learning, review what they have learned, and reach consensus on any points of disagreement. This process (called cognitive rehearsal) increases information retention dramatically, calls for higher-level thinking skills and improves critical thinking. Simply put, students, like professors, learn best what they teach. As students verbalize what they are learning and put it into their own words, not only do they learn the material better, they also begin the process of making an engineering discipline's language their own.

Social Advantages

It is myopic to think that education is solely about teaching technical skills. Particularly in today's world, much technical knowledge can be found on the Internet at the touch of a key. Because much of life involves other people, education is also about encouraging students to build relationships with their colleagues, to create support networks and professional contacts, and to learn from each other in school and beyond. Most would agree that contacts and friends are as helpful as technical expertise in solving a problem, gathering information, or finding a job.

Group work teaches students necessary and even crucial communication skills, teamwork skills, and interpersonal skills that can not be learned out of a textbook. Myron Tribus (Smith, 1995) maintains the group project is the educator's tool for teaching students wisdom and character. Experiences with group activities require groups to exhibit honesty, integrity, perseverance, creativity and cooperation.

Finally, relationships fostered through group work help to create a supportive environment for students. Research shows the highest indicator of failure in higher education is associated with alienation and isolation (Light, 1990). Cooperative environments reduce anxiety students feel with respect to a subject, improve morale, and better students' attitudes towards a subject; in class, attendance increases, there is more and better question generation, and less hesitancy among students (Felder, 1996).

Product Advantages

Not only does group process result in increased learning, enhanced social skills, and supportive environments; a group of students working together will produce better quality work than those same students working independently (Hensey, 1992). Engineers analyze complex, often interdisciplinary design problems. Groups are better at analyzing these problems for several reasons. First, members provide each other with ongoing critical review which reduces the probability of errors. Through this process, groups arrive at more realistic solutions to difficult problems (Free, 1993). Second, with combined experience, groups bring more technical expertise to a design problem. Third, in idea generation, three or four minds are always better than one. Groups produce a richer collection of ideas in quantity, quality, and diversity as members build upon the ideas of each other. In addition, group members will push each other to clarify their ideas and reduce idea ambiguity. Fourth, groups are high-powered vehicles for motivating students to learn skills they didn't previously have. In essence, they jump-start and support student drive that would otherwise fizzle.

Finally, research shows that group work reduces absentee-ism, encourages students to work harder, keeps members more committed to completion of a task (Hensey, 1992). The expectations of group members are more tangible than the expectations of a removed professor and are more motivating than a distant end-of-the-term grade. Groups have the unique capacity to create an esprit de corps phenomenon, synergistically transcending individual limits and displaying "enhanced creativity, collective wisdom, stronger productivity, deeper commitment and greater resourcefulness" (Hensey, 1992).

Summary

Some might argue that all the benefits of group work, whether educational, social, or product based, can happen spontaneously. Students find friends, work together on homework, and support each other naturally. This does happen, but I think it is the exception, not the rule. I am personally amazed at the number of undergraduate engineering classes I was able to navigate without conversing with a classmate or the instructor about more than the weather much less the material I was engaged in learning. Furthermore, as a graduate student at MIT, of the twelve classes I have taken, only three required even minimal group interaction. While I have personally made an effort to get to know my classmates and their histories, I have not been pushed to grapple with them about differing opinions or to discuss the subject material at hand. In hindsight, I experience this as a huge loss, due in part to my own lack of engagement, and also my perception that I could not learn from fellow classmates. Educators could help students become more engaged with each other and with learning; they could ensure everyone, not just the outgoing student, has the opportunity to build relationships, support each other, and learn more.

Finally, to sum up the argument for group work in the words of W. Edwards Deming (Deming, 1993):

> We have grown up in a climate of competition between people, teams, departments, divisions, pupils, schools, universities. We have been taught by economists that competition will solve our problems. Actually, competition, we see now, is destructive. It would be better if everyone would work together as a system, with the aim for everybody to win. What we need is cooperation and transformation to a new style of management. . . . Competition leads to loss. People pulling in opposite directions on a rope only exhaust themselves: they go nowhere. . . . Every example of cooperation is one of benefit and gains to them that cooperate. Cooperation is especially productive in a system well managed.

6.2 How To Guide

The benefits of group work are substantial, however, achieving the benefits requires effort. Instructors have to establish a group compatible grading structure, organize groups, and do initial and follow up work on group process. In this implementation, there are many things that need to be considered: how to reduce the likelihood and impact of shirking or solo-working members, chronically late (or absent) members, overly aggressive (or excessively meek) members, etc. The remainder of this chapter provides organizing tips to minimize these and other group pitfalls and maximize group benefits. These methods are not fool-proof nor are they the only solution to facilitating group effectiveness. All have been tried and proven by group work experts in industry or education. At best, they are ready-made organizational blueprints for educators to tinker with as they develop their own group style and strategies.

Because instructors are likely to encounter initial resistance to group work (particularly in undergraduate engineering courses), it is imperative to explain carefully how group work will fit into the class and what the students can expect to gain from participating in the group experience. It is also a good idea to continue this dialogue periodically throughout an entire term. In group work, an ounce of prevention is always better than a pound of regret: structuring groups effectively will not only dramatically increase group success, it will also save an instructor much headache.

Group Formation

Groups will perform their educational functions best when the instructor configures the groups instead of allowing haphazard group formation (Felder, 1996). To form groups of students, on the first day of class, require the students to write down and submit answers to the following questions: sex, gender, race, times not available for group work, GPA, and comfort or competence with skills pertinent to class group work (i.e. experience with C programming). Place students in groups using the following guidelines: three to four members of heterogeneous ability, ensure a female or minority is not alone on a team (place two or more females or minority members on a team), and check for time slots when groups will be able to meet together.

Class Structure

Second to group formation in importance, educators should foster both positive interdependence among students and personal accountability.

Positive Interdependence

Positive interdependence means students cannot succeed by themselves: they need their group and the individual members of their group to do well. For positive interdependence, students should be rewarded for helping each other and for being concerned about the welfare of their groups. Accordingly, grades should not be curved but should reference static criteria to help alleviate the all too common competitive environment in engineering classrooms. Groups, not individual members of a group, should be assigned project grades.

Another idea for increasing interdependence is to assign each member of a group to a different focus area. Students, separated by focus area, are then given special training and handouts. After receiving expert training, students return to their groups and must to rely on each other for information taught in focus areas different than their own. Felder, an expert in engineering education, calls this method the jigsaw puzzle. Group members are individually given puzzle pieces, which requires them to work cooperatively to put the puzzle together (Felder, 1996).

Finally, one additional interdependence grading incentive is while testing individually, offer groups a 5% bonus on exams if everyone in their group scores over 80 % . According to those that have used this practice, rarely (if ever) does a group get the 5% bonus, but many come close. It encourages groups to support each other in their respective studying throughout the term and even in crunch times before exams.

Personal Accountability

In trying to support interdependence in a classroom, instructors will continually come up against the individualistic milieu of higher education. For example, in the grading structure instructors are required to evaluate students as individuals, not as groups. Yet it could be argued that individual accountability is necessary for groups to function: a group will not function well if a student is relying on other group members to do all the work. Several methods have been developed to assist an instructor in evaluating individual performance and in encouraging students to pull their own weight.

Individual testing is one way of assessing and encouraging individual comprehension of class material. Individual progress and comprehension can also be assessed through active questioning both inside and outside the classroom. In assessing individual participation and involvement in group projects, instructors can also use students, the groups themselves, as a resource.

One method for allowing the group members to evaluate each other is to require the group to rotate the role of team leader among group members (i.e. each member takes turns at being the team leader for small projects or for different phases of larger projects). The team leader is then responsible to submit performance "grades" for each member of the group which the instructor can then use in assigning individual grades. Another method is to have group members rate each other's overall performance. Brown (1995) has developed an elaborate method in which a group's project grade (assigned by the instructor) is weighted for each individual group member to reflect the group's assessment of his/her contribution to the project.

Both students and instructors may be uncomfortable with student involvement in the grading process. Students, because grading *is* uncomfortable. Instructors because it is they who ultimately assign individual grades. Instructors should encourage students to be honest and should trust students' ability to evaluate each other. Having worked closely together in a group, students will probably evaluate each other more accurately than an instructor could, having been largely removed from the actual work. If an instructor is concerned about *how* individuals contributed (i.e. in the realm of ideas or information gathering or number of hours spent), these questions can be asked allowing students to respond.

Individual accountability may also become an issue if a project involves many different aspects, whether writing or analysis or research. If an instructor is concerned that students develop their abilities in multiple areas, students can be assigned these roles on a rotating basis during multiple phases of a project or consecutive smaller projects. The issue of assigning roles is further addressed in a following section. These various strategies: individual testing, group grading and evaluation, and role assignation can assist an instructor in maintaining individual motivation.

Team Building

Just as it might be ludicrous to give a construction team the task to build without plans, inexperienced (and even experienced) team players will perform better and more efficiently if they are given plans and support in the building process. An educator can do several things to facilitate team building.

When groups are forming, their first meeting with each other is the most important. Therefore, it is a good idea to provide class time for this first meeting, perhaps after a session on groups, their importance, and what students have to gain from working with each other. Another helpful idea is to require group-building activities. Students, particularly those technically oriented, may label such activities "warm and fuzzy" and be disinclined to take them seriously. Therefore, it might be good to allow groups to function on their own for a week or two (allowing possible and inevitable differences to arise) before hitting the groups with group-building advice and activities. The optimal scenario might be a combination of the two.

In the following sections, several suggestions for helping groups to coalesce into teams are given. These suggestions include requiring both a goal statement and a social contract, providing meeting guidelines, a description of what good team work looks like, and potential team roles. The final section provides suggestions for ongoing group support throughout a term.

Goal Statement

Many (if not most) group dynamics experts cite creating a mission (or goal) statement as the most important thing a group can do to ensure success (Dyson, 1996; Hensey, 1992; Katzenbach, 1993; Free, 1993). A goal statement is a list of goals students commit to as a group; for example, getting a particular grade, or setting and achieving a target schedule for large projects.

The process of stating group goals requires group members to discuss their varied motives for taking a class (to meet graduation requirements, for learning, to pass, or gain exposure to material). A goal statement forces students to at least consider what as a group they can commit to doing together and for each other.

Goal statements are beneficial in other ways as well. If the goal statement includes specific benchmarks or tangible goals, they can assist a group in maintaining both focus and motivation throughout a term. When conflict or communication problems arise, a goal statement provides a framework for dealing with difficult issues. Given a conflict, if discussion revolves around how to accomplish previously stated common goals instead of current differences, it is more likely to reach resolution. In addition, a goal statement can help create equality within a group because it shifts focus from the individual to the group or the task at hand. Individual members then become important as they support the group and not in fostering their individual egos. In summary, experts agree that the more time you give students to initially set goals and then allow and encourage them to continue exploring where they are going, why they are together, and what their purpose is, the better they will work together (Katzenbach, 1993).

Social Contract

In support of a group's goal statement, it is helpful for groups to establish clear rules about how they plan to function collectively. This in essence could be seen as a social contract among the group members providing structure and support for the work they do together. In the social contract, groups should establish expectations regarding scheduled meetings (preparation, notification of absence, etc.), the roles each member will hold, the decision-making and modification process, and any other issue that is of concern to a group member. In addition to establishing expectations, the group should also discuss and come to consensus about consequences of not keeping the contract: how continuing membership in the group is earned. In helping groups take both their social contract and goal statements seriously, instructors can require group members to sign these two "documents" making copies for themselves and submitting one to the instructor.

Meetings

An important component of the social contract is a discussion of how meetings will be held. Group meetings are the time when group members will probably spend the most time together and are a formal situation in which instructors can intervene with meeting guidelines. From a review of literature on group work, I developed a set of guidelines that could be given to students about how to hold effective meetings. These guidelines are illustrated in Figure 29. These meeting rules, if implemented, will help students maximize the use of time spent together in meetings.

Roles

Another method that helps facilitate group process (particularly when members have little group experience) is assigning roles to each group member. There are several models for group roles depending on the forum in which they are used (i.e. roles assigned for meetings would be different from project roles). If group projects were routine problem sets, group roles might consist of: supervisor, writer, and reviewer. The supervisor's responsibility could involve responsibility for the problem set and assigning involvement grades to group members. Another model for meetings might include the roles of scribe (to record meeting progress and individual input), discussion leader (to keep the meeting on task), and initiator (to prepare and distribute the meeting agenda beforehand) (Hilliard, 1993). Whatever model(s) is used, it is important that group roles are rotated throughout the term (particularly if one role involves assigning credit) to maximize the input of each individual.

Interpersonal Skills

Experts suggest instructors should give students guidelines on interpersonal skills. Hensey (1992), in his ASCE book *Collective Excellence*, has surveyed management teams looking for indicators of successful teamwork. The result of his study is the most appealing list of interpersonal skills I have found; and it has the added impact of being a practical list from industry. Hensey's list is given in Figure 30.

In addition to handing out guidelines, an informal discussion in which students create their own guidelines will also help students internalize the importance of interpersonal skills and perhaps also remember them at three a.m. the night before a project is due.

Beginning

- Start meetings on time and hold them in a place where the group won't be distracted or interrupted.
- Come to meetings prepared.
- Assign someone in the group to prepare an agenda before each meeting to be finalized and agreed upon in the first few minutes of the meeting.

Speaking

- In speaking, the most important thing to aim for is balance. Try to balance the input of each member.
- To maximize the group's collective wisdom, seek to hear from everyone.
- As a group, appoint a leader during each meeting to notice who is speaking and who is not and to invite the comments of those who are silent.
- Encourage each other to speak for no more than 2 minutes at a time unless a group member has a report to give.
- Individually try to find a place where you are not monopolizing nor withdrawing from the conversation at hand.
- When you do speak, try to be honest, courteous, and to the point regarding your own work and the work and ideas of others.
- Avoid interrupting and side conversations; one conversation at a time is plenty, while three or four concurrent conversations make it impossible to go anywhere collectively.
- Stories whether about basketball games or political farce, should probably be saved for other forums.

Listening

- View listening as more important than speaking.
- Listen well enough to be able to paraphrase what is said.

Giving/Receiving Feedback

- Give feedback to each other in non-threatening supportive ways (a good way to do this is to focus on the group goals and how a particular issue assists group objectives without attacking any group member).
- Seek feedback from each other, because it is most often useful even if disconcerting.
- Expect to disagree with each other.
- Do not personalize disagreement; instead, try to learn from it.
- Acknowledge as a group that wisdom and information can come from many different sources: facts, feelings, hunches, opinions, ideas, mistakes, and even silence.
- Seek to maximize the information you obtain from each other in your meetings through asking questions.

Decision-making

- Be careful with the decision-making process. Once a decision has been made, it is very difficult and painful to backtrack.
- Be patient with the process of shaping consensus; make sure everyone agrees with a decision before moving on. One member's disagreement is a liability to group effectiveness.
- Make sure you hear and address all sides of an issue.
- If necessary, go through several iterations of analyzing alternatives, eliminating the most obvious, re-analyzing, eliminating, etc.
- If the decision-making process is not handled with care, a decision will probably have to be rethought at a later date after unneeded headache and work.

Ending

- End meetings on time.
- Make significant progress towards the goal of a meeting before ending.
- Whenever these two objectives conflict, be sure to discuss why significant progress was not achieved and whether to continue or meet another time.
- Summarize what the meeting accomplished
- Set the date and time of your next meeting, the possible agenda, and any necessary preparations or tasks.

Figure 29 Student Guidelines for Effective Meetings (Bush, 1998)

Group Facilitating

There are several activities which, if spaced throughout a term, smooth group functioning. This final section discusses these activities. The most important thing an instructor can do is too consistently take group work seriously; believe the groups will succeed; and infuse student, group, and class interactions with this belief. This might involve relating to groups as a whole and individuals as part of their respective groups; and in discussion with a student or a group, bringing up how groups are functioning and what if any changes need to be made.

- Obtaining the opinions and involvement of other group members in issues that concern them before making final decisions
- Being willing to help team members even when inconvenient or requires extra effort
- Voluntarily offering relevant experiences, ideas, and findings to team members
- Making timely contribution to someone else's action plan or project when requested
- Acknowledging a colleague's contribution to a project when working with a client or senior manager, sharing the credit
- Being non-defensive and receptive to the suggestions, ideas, opinions, and needs of colleagues; making effort to understand before criticizing
- Considering impact your plans and actions will have on others
- Being unwilling to criticize third party who is not present, not gossiping
- Coming prepared to present or participate when you have a role to play in meetings
- Expressing appreciation for teamwork extended to you and your people that was helpful
- Identifying and helping to pick up loose ends even though they may not be in your area of responsibility
- Keeping people advised of changes and developments and new information on a task or project
- Being supportive of team's objectives once they are set, rather than sabotaging, fault-finding, or being negative behind the scenes
- Pitching in when the whole team needs help in meeting a deadline or solving a problem, even if it's "not your job"
- Trusting the team to develop consensus on an issue, even if it takes a little more time

Figure 30 Indicators of Successful Teamwork in Industry (Hensey, 1992)

To reduce unnecessary (and potentially explosive) tension, take care that group projects, particularly if defined by groups themselves, are reasonable and achievable in the allotted time. Similarly, instructors support functioning groups when they make sure needed resources (learning materials, data, etc. needed to complete group projects) are accessible.

Another helpful measure is to periodically require students to turn in questionnaires or short memos addressing group progress, individual roles or contributions made, and any conflicts or concerns. Group evaluations are also a good option: give groups in-class time to collectively evaluate how they are doing as a team. This evaluation could be as simple as asking each group bi-weekly for one thing they doing well (or one way in which they are benefiting from the group) and one thing that needs improvement. Another method is to have groups reach consensus (perhaps on a scale of one to five) regarding how well they are doing with respect to specific team performance criteria. The more time students are given to stop and evaluate where they are and how they are doing, the better they will function and the more they will accomplish.

Summary

In summary, instructors support group work as they relate to and believe in student groups, safeguard against groups getting in over their heads, and allow for group and individual self-evaluation. In class structure, positive interdependence, personal accountability and instructor group formation work for group success. Team building activities (goal statement and social contract creation, meeting and interpersonal skill guidelines, and rotating roles) help groups coalesce and move constructively through a term.

As students and teachers and people, we do our jobs, interact with each other, negotiate, question. We require some competency in these skills for survival, but can always do better. The Indigo Girls in a popular song suggest the "simplest things are the hardest to learn." These simple things (giving and requiring support, seeking resolution, asking better questions, growing more) are the hardest skills to learns. As the history of the human race and our current social fabric illustrate, we have not mastered them yet; furthermore, these skills are perhaps the most important thing to teach and to learn ourselves. The absence or deficiency of these skills are both highlighted and taught in group work. The challenge is to include group work in our classes. The reward is to reap its educational and social benefits.

6.3 Conclusions

Group or team work not only enhances the educational experience; it leads to better products. However, successful group work is not something that happens by virtue of a number of people working together. This chapter has shown what problems have to be overcome, how a team can benefit most from collaboration, and what teachers can do to monitor and guide the process.

7. Conclusion

Integrative teaching helps students to better synthesize knowledge; facilitates easier access of that knowledge in design; provides motivation for learning; and helps students build a strong foundation for future endeavors. Careful integration of engineering education is a challenge. It involves integrating subject material and building upon prior student experience. Both of these endeavors require faculty interest and commitment.

Each chapter of this thesis has examined a tool that could be used in integrating education. They addressed the following: an integrative framework; using computers in a way to augment development of student judgement; integrative "capping" experiences containing real-world applications; and group work.

My hope is that teachers of today and the future will use this thesis, and more importantly the integrative methods it describes, to expose students to the ambiguous and subtle world of design; to help students gain confidence in making and justifying assumptions; and to create student excitement for the complex, inter-disciplinary, challenging, and rewarding problems awaiting them in their chosen careers.

8. Appendices

8.1 MIT Civil Engineering Curriculum

The following classes are currently required for 1-C graduation:

14.01	Principles of Microeconomics
18.03	Differential Equations
1.00	Introduction to Computers and Engineering Problem Solving
1.03	Introduction to Probability and Statistics for Engineers
1.04	Solid Mechanics
1.05	Fluid Mechanics
1.105	Structural Engineering Laboratory
1.12	Computer Models of Physical and Engineering Systems
1.30	Introduction to Geotechnical Engineering
1.50	Structural Engineering
1.51	Design of Steel Structures
1.52	Design of Concrete Structures
1.53	Constructed Facilities Project Laboratory
1.59	Mechanics of Construction Materials

These classes and a brief list of topics covered are listed in this section.

14.01 Principles of Microeconomics

- Consumer Theory
- Firm and Individual Behavior
- Competition
- Monopoly
- Market Equilibrium
- Government Regulation
- Investment
- Welfare Economics

18.03 Differential Equations

- First-order Equation Solution Methods
- Higher-order Forced Linear Equations
- Complex Numbers
- Laplace Transform
- Matrix Methods
- Non-linear Systems
- Phase-plane Analysis
- Series Solutions

1.00 Introduction to Computers and Engineering Problem Solving

- C Programming
- Numerical Analysis
- Graphics
- Data Structures
- Searching and Sorting
- Matrix Methods
- Simulation
- Engineering and Scientific Application

1.03 Introduction to Probability and Statistics for Engineers

- Estimation
- Prediction
- Probability
- Random Variables & Vectors
- Univariate & Multivariate Distributions
- Reliability Analyses
- Distribution Parameters & Estimation
- Linear Regression

1.04 Solid Mechanics

- Statics
- Truss Analysis
- Material Stress and Strain
- Torsion
- Beam Stresses
- Beam Deflections

1.05 Fluid Mechanics

- Water Properties
- Static Pressures
- Flow Pressure Differences
- Head Losses
- Flow Characteristics
- Elementary Hydrology

1.105 Structural Engineering Laboratory

- Steel Wire Stress and Strain
- Cable Uses
- Column and Beam Behavior

1.12 Computer Models of Physical and Engineering Systems

- Object Orientation
- C++ Programming
- Functional Analysis
- System and Object Design
- Curve-fitting
- Fractals
- Chaos Theory

1.30 Introduction to Geotechnical Engineering

- Geostatic Stresses
- Friction Angles
- Rankine and Coulomb Earth Pressures
- Effective Stress
- Darcy's Law
- Heads
- Seepage Force
- Flow Nets
- Compression and Swell of Clays
- Consolidation and Settlement
- Drained and Undrained Strength of Simple Clay

1.50 Structural Engineering

- Truss, Beam, and Frame Analysis
- Method of Sections
- Conjugate Beam Method
- Moment Distribution
- Member Force Determination
- Virtual Work Method
- Matrix Methods
- Structural Deformations
- Structural Stability

1.51 Design of Steel Structures

- Conventional Design Practices
- Load and Resistance Factor Design
- Structural Members
- Joints and Connections
- Structural Systems

1.52 Design of Concrete Structures

- Conventional Design Practices
- Ultimate Load Design Concept
- Reinforced Concrete Members
- Prestressed Concrete Members
- Structural Systems

1.53 Constructed Facilities Project Laboratory

- Techniques for Material Property Measurements
- Testing Error Approximation

1.59 Mechanics of Construction Materials

- Elastic and Plastic Behavior
- Creep
- Failure mechanisms and Criteria
- Environmental Conditions
- Material Selection
- Cementitious Materials
- Timber
- Polymers
- Pavement Materials
- Composites

8.2 Design Project Integration

Engineering educators have difficulty deciding exactly what design is and what role it should play in undergraduate education. However, ABET gives several criteria for effective design projects and design education literature supports these criteria. Design projects should be open-ended requiring task definition and should have practical application to the real world. In addition, they should require the following activities from the students: creative thinking, analysis, iterative evaluation, construction, testing, and synthesis.

The following required Course 1-C subjects involve major design projects:

1.04 Solid Mechanics
1.105 Structural Engineering Laboratory
1.05 Fluid Mechanics
1.30 Introduction to Geotechnical Engineering
1.51 Design of Steel Structures
1.52 Design of Concrete Structures

Though instructors of design subjects might not agree on the importance of individual design criteria listed above and may emphasize one over another; enhancing any one of these components in a design project should also enhance a student's learning experience.

In the remainder of this appendix, I have included a brief description of these design projects and possibilities for including or augmenting the design criteria listed above. Admittedly these are just a few suggestions and amount to a drop in the ocean of possibility.

Finally, the current 1-C program has a "minor deficiency" in the area of a "major integrating design experience" according to ABET standards. Therefore, in addition to enhancing the individual projects through synthesis, attempts at synthesis might also get the ball rolling towards better fulfillment of the ABET integrating design requirement.

1.04 Solid Mechanics

Project I: Bentley Pedestrian Bridge

Project Description
In this project, students in groups of 3 or 4 are asked to design a pedestrian bridge for Bentley college. The truss bridge is to span 63.5 feet and be 10 feet wide with a 12% camber. A36 steel is required and AASHTO standards are specified though wind and seismic loads are to be neglected. Each group should investigate 3 designs then narrow their focus to one final design evaluating its performance in depth.

Design Component Enhancement
- To make more open-ended, bending members could be allowed
- Seismic and Wind Loading could also be included
- Project could require an economic analysis of design
- Analytical computer software used in more advanced classes (steel and concrete design) could be introduced to allow for more sophisticated analyses later on
- Advantages of steel compared to other materials could be discussed
- Project could be related to other bridge design projects by using the same site or later expansion of this design

1.105 Structural Engineering Laboratory

Project I: 30" Span Structure

Project Description
This group project requires students to build a 30 inch span truss and/or cable structure. The structure is to be less than 3 inches wide and 10 inches high and should fail under a centrally applied load of exactly 100 lb. (No less or more). Deflections are to be less that 1/2" per 100 lb. Weight is to be optimized. Material selection is left to the students.

Design Component Enhancement
- The project could involve a model for a specific bridge site
- Use of 1.04 analysis software could be encouraged
- Value of models in civil engineering practice could be addressed

Project II: Cantilevered Enclosure

Project Description
In this group project, students design a cantilevered space enclosure to enclose a specified volume. The enclosure is to fit on a 3 by 3 feet plywood board and be no more than 15 inches high. It is evaluated on its maximum load capacity (250 lb. required), stiffness (deflect limited to 1 inch), weight, and aesthetics. In testing, the structure is loaded using a whiffle tree which distributes load over the roof of structure.

Design Component Enhancement
- A specific place, function, and scale could be specified to add a practical component
- Project could be modified to model a structure design in steel or concrete subjects
- The importance of connections in structural design could be emphasized and expanded in 1.51 and 1.52
- Requirements for constructing a rigid vs. a pinned frame could be addressed and related to real structural projects

1.05 Fluid Mechanics

Project I: Edgarton Pond

Project Description
This group project addresses the hydrology of the Edgarton pond, a saltwater pond separated from the ocean by a barrier beach. As water drains into this pond, the water level rises and the salinity decreases. Currently, when the water level reaches 1 meter above sea level, an artificial breach is created to lower the water level and increase the salinity. In this design project, groups are to estimate the physical pond parameters, analyze the current method of salinity control and develop cost effective alternatives.

Design Component Enhancement
- Might include statistical analysis of real rainfall data and fresh water inflow

1.30 Introduction to Geotechnical Engineering

Project I: Highway Retaining Wall

Project Description
This group project involves designing a retaining wall for a highway embankment. Each group is to investigate 3 designs: a gravity wall, a cantilever wall, and a sheet pile wall with tie-backs. In this process, they are to come up with total costs and a final design recommendation.

Design Component Enhancement

- Allow students to work through and develop methods of building retaining walls and set their own time scale
- Connect project to a specific site in Boston or elsewhere to give it more tangible practical application
- Encourage students to develop or propose a new idea or unconventional method of retaining wall design
- Construct scale model of final design (Note: the effectiveness of scale models is questioned in design literature)
- Use project as a hypothetical retaining wall for construction of one of the structural design projects
- Investigate spatial variability in soil properties at a specific site (calculate mean and variation)
- Explore the use of unconventional materials considering economic implications
- Include structural analyses of retaining wall members.

Project II: Cofferdam

Project Description
This group project requires analysis of a sheet pile wall cofferdam design as well as the development of other cofferdam design alternatives. For specific design tolerances, groups are to use flow nets to determine minimum sheet pile embedment; check wall stability for rotational failure, and design the foundation block. Economic analyses are to be conducted for each design.

Design Component Enhancement

- The project could be associated with a real construction project
- Costs could be calculated from construction cost estimate handbooks
- Perhaps the structural analysis program used in 1.04 could be used to analyze the cofferdam structure (deflections, etc.)
- Advantages of different materials could be explored

Project III: Highway Embankment

Project Description
This group project addresses a highway embankment design considering undrained slope stability, settlement, cost-effectiveness, and construction sequence. They are to investigate the use of preloading with additional fill, and vertical drain installation.

Design Component Enhancement

- Instead of a highway, the project could model a preloading situation for any of the structural design project buildings, or an approach to one of the bridge design projects
- Project could be more open-ended by allowing students to arrive at the drain and fill method themselves
- Real soil data from a specific site could be used
- Uncertainty in the soil property data could require students to estimate soil parameters

1.51 Design of Steel Structures

Project I: Steel Structural System

Project Description

This group project investigates the design of a simple, framed, steel structure. Each group of four is required to design one of the following structures: a light industrial building with traveling hoist, a tier building, a stiffleg derrick, or the Boston Citco sign. The overall dimensions are given; students determine the structural system, develop loading combinations, and design structural members.

Design Component Enhancement

- Include design optimization using economic and/or aesthetic criteria
- Investigate possibility of using different (high strength) materials
- Locate building site in high seismicity zone; give local seismic data and evaluate probability of seismic loading of building to failure with given factor of safety
- Include the possibility of differential foundation settlement in all the projects
- Discuss advantages of using steel instead of concrete for building design
- Solutions might be "tested" through student evaluation of other group designs in the course of the design process
- Consider availability and costs of real steel members in Boston
- Consider welding vs. bolt connections and associated probabilities of failure

1.52 Design of Concrete Structures

Project I: MIT Biology Building

Project Description

Teams of 4 students are required to develop a feasible girder/column/slab system for an MIT biology building. The shape and configuration of the frame system is given; the project requires load determination, approximate analysis, computer analysis, and final dimensioning of members. Students are asked to consider mechanical and aesthetic as well as structural considerations.

Design Component Enhancement

- Students could be given more leeway in the shape and arrangement of the frame
- More emphasis could be placed on optimization
- Students could perhaps build and test 1 member; or visit the construction site of a concrete monolithic structure
- Effects of differential settlement (resultant stressing of members) could be addressed
- Foundation members could also be designed
- Probability of wind and seismic loading to failure could be evaluated
- Material efficiency might be addressed in relation to steel or high strength materials
- Possible advantages to using prestressed concrete could be considered

Project II: Stevens Brook Bridge

Project Description

Pairs of students are to investigate the design of a replacement bridge that has deteriorated due to environmental damage. Students are given the bridge's current structural system; they are required to determine loading conditions and develop the design of an alternative system consisting of precast girders and a cast in place slab deck.

Design Component Enhancement

- The project would be more open-ended without the specified spans and foundations
- Students could be asked to develop ways to protect structure against concrete corrosion
- Students might be asked to consider differences between a prestressed vs. conventional bridge design
- Perhaps students could be shown how prestressing is actually done
- The project might also involve a market investigation of prestressed members

8.3 Homework Integration

A large number of the current homework assignments are non-design in nature requiring linear thought processes to arrive at one correct answer. For these non-design assignments, I have suggested ways connect them to a broader framework through referencing another subjects, home problems, design projects, or real-world situations.

1.04 Solid Mechanics

Problem Set #1: Statics

Problem Descriptions
1. resultant force determination
2. resultant force determination
3. resultant force determination
4. cable forces
5. spring forces and deformation
6. cable and reaction forces
7. beam reactions

Integration Possibilities
- Problem No. 4 could model a cable system for the steel stiffleg derrick design project
- Deflections for the cable/frame system in Problem No. 6 could be calculated in 1.50
- Cable deformations in Problem No. 6 could be analyzed later in the course
- Problem No. 7 could be phrased in terms of a cantilevered overhang for a specific building
- Problem No. 7 could mention deflections for a similar beam to be calculated in 1.50

Problem Set #2: Trusses

Problem Descriptions
1. truss member forces using joint method
2. zero force truss members
3. truss member force determination
4. truss member force determination
5. sectioning method truss member force determination

Integration Possibilities
- Trusses in Problem No. 1 could be possible designs for the 30" Span Structure or the pedestrian bridge design projects
- Problem No. 2 could ask why zero force truss members might be included in future truss bridge design projects if the goal is optimization of material use
- Truss loading in Problem No. 3 might be the placement of two pedestrians on a pedestrian bridge to model a possible loading situation for the pedestrian bridge design projects
- Deflections for Problem Nos. 4 and 5 could be calculated in 1.50 and referenced by these problems

Problem Set #3 Stress and Strain

Problem Descriptions

1. bar stresses
2. strut and cable assembly normal stresses and strains
3. cable stress/strain behavior
4. plastic material stress/strain diagram and material properties
5. steel bar stress/strain behavior
6. modulus of elasticity
7. aluminum bar stress/strain behavior
8. steel pipe strain from poissons ratio
9. wheel axle shear stress
10. elastomer shear modulus of elasticity

Integration Possibilities

- Problem No. 1 could consider a member in one of the truss bridge design projects
- Problem No. 2 could reference strains measured in Course 1.105
- A practical application for Problem No. 2 could be the support for a hanging MIT sign or a student hanging from a bungee cord or the steel wire in the next problem
- Problem No. 3 might include a reason for hanging a steel cable off the side of a ship, like a hypothetical geotechnical site investigation
- Problem No. 4 could use 1.105 test data
- Problem No. 5 might use 1.105 data from testing a 30" Span Structure member to yielding
- The wire in Problem No. 6 could be the same wire used in Problem No. 3
- The aluminum bar in Problem No. 7 could be a member from the 30" Span Structure Design Project
- The steel pipe in Problem No. 8 could be a possible member from the pedestrian bridge design project
- Problem No. 8 could investigate the advantages of using hollow members for bridge design
- The moving crane in Problem No. 9 could be a crane from construction of the pedestrian bridge design project
- The materials in Problem No. 10 could be changed to concrete and steel to tie into 1.51 and 1.52

Problem Set #4: Axial Loading

Problem Descriptions

1. non-prismatic bar elongation
2. non-prismatic bar elongation
3. aluminum pipe thermal expansion
4. welded railroad track thermal expansion
5. truss strain energy and joint displacement
6. stress element shear strain
7. volumetric strain equation
8. volumetric strain and bulk modulus equations

Integration Possibilities

- The bar in Problem No. 1 could be a hypothetical member for the 30" Span Structure Design Project
- Problem No. 3 could address the use of two materials in the 30" Span Structure
- Problem No. 4 could model thermal expansion in a bridge with welded members.
- Problem No. 5 could use strain energy to evaluated a truss from earlier in the course
- The shear element in Problem No. 6 could be related to one of the design projects simulating a specific loading situation

Problem Set #5: Bar Stresses

Problem Descriptions

1. steel pipe factor of safety and yield stress
2. pressure cylinder allowable stress bolt requirements
3. spliced bar and rivet connection allowable load
4. steel drill rod torque and shear stress
5. hollow shaft torque and shear stress variation
6. stepped shaft shear stress and rotation angle
7. prismatic bar angle of rotation formula

Integration Possibilities

- The steel pipe in Problem No. 1 could reference a member from a pedestrian bridge design project or the 30" Span Structure
- Problem No. 2 could describe a situation where such a cylinder might be used
- The pressure in Problem No. 2 could be from an incompressible fluid and reference 1.05
- Problem No. 3 could model a connection for the pedestrian bridge or the 30" Span Structure
- Problem No. 3 could mention that connections often cause failure of the 30" Span Structures
- The torque in Problem No. 4 could model a member of the 30" Span Structure subjected to a very eccentric loading condition
- Perhaps Problem Nos. 6 and 7 could be tied to the torque shaft in a real machine, like a geotechnical drilling rig

Problem Set #6: Torsion

Problem Descriptions

1. shaft power transmission at maximum shear stress
2. hollow shaft dimensions for power requirement, allowable shear stress
3. shaft dimensions for power requirement, allowable shear stress, and angle of twist

Integration Possibilities

- Problem Nos. 1, 2, and 3 could be related to a water pump from the Edgarton Pond Design Project

Problem Set #7: Shear and Moment Diagrams

Problem Descriptions

1. bending moment equation and maximum moment
2. shear and moment diagrams for uniformly loaded cantilever beam
3. beam and bracket shear and moment diagrams
4. shear and moment diagrams for cantilever beam with linearly varying load
5. overhanging beam support locations to minimize moment
6. shear and moment diagrams for beam with linearly varying load

Integration Possibilities

- The cantilever beam in Problem No. 2 could represent an overhang with a partial snow or live load condition
- The cantilever in Problem No. 4 could represent a load configuration for a cantilevered sheet pile retaining wall
- Problem No. 5 could refer to the optimization of a roof overhang length
- Problem Nos. 1, 3, and 6 could be used in 1.50 deflection calculations

Problem Set #8: Beam Stresses

Problem Descriptions

1. beam radius of curvature and vertical deflection
2. circular copper strip bending stresses
3. simple beam maximum bending stress
4. overhanging steel I-beam maximum bending stress
5. small dam (simply supported beam) maximum bending stress
6. simply supported beam maximum tensile and compressive stresses

Integration Possibilities

- Vertical loading might be added to Problem No. 1 to connect it to the shear and moment diagram Problem Set
- Problem No. 2 could be altered to model the previous considered steel cable if hung from a pulley system
- Problem No. 3 could model any beam in a wood structure
- Problem No. 4 might model a more conventional beam in a steel-frame building
- The small dam in Problem No. 5 could be used in 1.30 for flow net construction or be modified as a propped excavation brace
- Problem No. 6 could represent a person walking over a small footbridge

Problem Set #9: More Beam Stresses

Problem Descriptions

1. maximum tensile stress formulas for triangular, semi-circular, and trapezoidal sections
2. required cantilever beam section modulus
3. fiberglass bracket minimum diameter for concentrated load
4. weight ratios for rectangular, square, and circular beam sections with same stresses
5. maximum shear and bending stress for simply supported wood beam
6. laminated plastic beam maximum load for allowable shear and bending stress
7. steel W-beam flange shear stress
8. T-beam web maximum shear stress

Integration Possibilities

- Problem No. 1 could ask which cross-section(s) might be best suited for the Pedestrian Bridge or 30" Span Structure Design Projects
- Problem No. 2 could use the same loading configuration as a previous cantilever problem and compare material requirements for rectangular and W section beams
- The fiberglass bracket in Problem No. 3 could model a plant hanger or similar device
- The results of manipulation in Problem No. 4 could be referenced in the design project as a starting point for choosing cross-sectional shapes for the bridge design projects
- Problem No. 5 could develop Problem No. 3 from the previous Problem Set investigating whether bending or shear stresses are critical.
- Problem No. 6 could mention how common laminated beams are used in wood construction due to size limits of natural materials
- Problem No. 7 could use a loading condition from a previous problem for comparison of cross-sections
- Problem No. 8 could reference the T cross-section in Problem No. 8 from the previous Problem Set

1.105 Structural Engineering Laboratory

Lab #1 Stress Strain Relationships

Lab Tasks
1. load cell calibration
2. stress-strain measurements for steel wire
3. stress-strain data reduction
4. evaluation and application

Integration Possibilities
- The lab could indicate if practicing engineers are usually involved in material testing
- The lab could also indicate if engineers analyze similar data
- Students might be asked what value of stress they would use if the tested wire were to be used in the 1.04 Problem Sets

Lab #2 Cable Structures

Lab Tasks
1. cable shape geometry with varying loads
2. cable forces with varying symmetrical and non-symmetrical loads
3. dead load pre-tensioning
4. cable pre-tensioning against second cable

Integration Possibilities
- The lab could ask for advantages and disadvantages of using cables in the 30″ Span Structure or the Cantilevered Enclosure
- The lab could ask how cables might be used in these projects
- Perhaps the lab could incorporate the concept of using pretensioned cables in concrete beams

Lab #3 Concentrically Loaded Columns and Elastic Stability

Lab Tasks
1. Euler buckling formula verification
2. higher mode shape induction and verification

Integration Possibilities
- Examples could be given of real columns that have buckled due to insufficient support
- Relevance could be added by mentioning the use of bracing to prevent column buckling in the design projects
- The lab could also indicate that Euler's column buckling formula will be revisited in 1.51 and 1.52

Lab #4 Span Structure Design Project

(see design section)

Lab #5 Linear Elastic Beam Behavior

Lab Tasks
1. calculated and measured beam deflection and strain for mid-span and eccentric loading
2. bending moment diagram for midspan and eccentric loading

Integration Possibilities
- This lab could mention that 1.50 will develop the principle of calculating deflections from moment diagrams
- Real situations could be cited where bending or deflection are critical
- The lab could also indicate how deflections are measured or controlled in the field

Lab #6 Beam Behavior and Strength

Lab Tasks
1. steel beam behavior; modulus of elasticity; yield stress
2. reinforced concrete beam behavior; modulus of elasticity; yield stress
3. wood beam behavior; modulus of elasticity; yield stress

Integration Possibilities
- The lab might include real world costs of using steel, concrete, or wood
- Reasons for using each of these materials could be mentioned
- Advantages to using steel, concrete, or wood in class design projects could also be discussed

Lab #7 Space Enclosure Design Project

(see design portion)

1.05 Fluid Mechanics

This course is not taken solely by 1-C course, so many students taking the course do not have any exposure to geotechnical or structural engineering. The best way to integrate this material will probably be to use it in the 1-C classes rather than integrating the 1-C classes into the course. Therefore, I have just listed the homework assignments. Efforts to make each problem as practical as possible by referring to specific examples would be beneficial for every student enrolled in the course.

Problem Set #1

Problem Descriptions
1. pressure difference equation for artery blockage
2. specific weight, density, specific gravity
3. Newtonian fluid flow shearing stress
4. sliding block terminal velocity on lubricated inclined surface
5. water column surface tension

Problem Set #2

Problem Descriptions

1. micromanometer readings; effects of fluid specific weight and area ratios
2. critical water depth behind concrete dam
3. water pressure distribution on cylindrical gate
4. pressure forces acting on partially submerged diving bell
5. gage and absolute pressures in fluid system

Problem Set #3

Problem Descriptions

1. vertical flow bend pressure distribution
2. Bernoulli's effect; pressure difference in prairie dog burrow
3. drag force of variable mesh screen
4. flow rate through vertical pipe contraction
5. conservation of mass and momentum in hydraulic jump

Problem Set #4

Problem Descriptions

1. converging elbow anchoring forces
2. nozzle anchoring force
3. average velocity of tank exit flow
4. average fluid exit velocity due to closing hinged plate
5. tidal velocity variation equation, maximum tidal velocity and energy flow

Problem Set #5

Problem Descriptions

1. free water stream height
2. oil flow through pipe constriction
3. flow rate over spillway and resulting horizontal force
4. air flow rate for air cushioned vehicle support
5. sprinkler system jet velocity and discharge; hose flow, pressure and velocity

Problem Set #6

Problem Descriptions

1. head loss and flow in cast iron pipe
2. reservoir water elevation difference; connecting pipe hydraulic and energy grade lines
3. fluid flow shear stress, Darcy-Weisbach friction factor, roughness
4. maximum sewer discharge to prevent basement flooding
5. reservoir system flow in connecting pipes; frictional and singular head losses

Problem Set #7

Problem Descriptions

1. pressure drop relationship for blood flow in small tube
2. critical velocity for particle transport
3. buoyant force, drag force, and fluid velocity effect on submerged plastic sphere
4. terminal velocity of falling raindrop
5. manometer reading, fluid forces, and side wall shear forces on obstructing cylinder

Problem Set #8

Problem Descriptions

1. head increase from centrifugal pump
2. fluid temperature and density effects on pump efficiency
3. pipe flow rate considering minor and friction head losses
4. head, friction losses, and exit temperature of hydroelectric power plant
5. flow depth and Froude number in concrete channel

1.30 Introduction to Geotechnical Engineering

Problem Set #1

Problem Descriptions

1. soil property equation verification
2. soil saturation, void ratio, porosity, water content
3. water content
4. bulk density, unit weight, void ratio, saturation
5. soil classification
6. plasticity index
7. particle size distribution curve, soil classification

Integration Possibilities

- This problem set could be centered around a soil sample from a particular site
- A site description could be included and students might predict soil properties before performing routine calculations in Problem Nos. 2, 3, 4, 5, 6, and 7
- Soil samples from the hypothetical site of any of the design projects could be used

Problem Set #2

Problem Descriptions

1. principal stress determination
2. vertical and horizontal soil stress profiles
3. vertical stress determination
4. stress path and resulting stress state
5. principle stresses, soil friction angle, failure plane inclination
6. failure envelope and principle stress
7. Mohr and p-q diagrams; internal friction angle

Integration Possibilities

- Problem No. 1 could reference similar concept development in 1.04
- Problem No. 2 might use an actual site description and share a site with Problem No. 1

- Problem No. 2 might ask where you might find a soil profile without a water table extending 15 meters
- An actual structure (or design project) could provide the loading for Problem No. 4
- The soil mass for Problem Nos. 5, 6, & 7 might be attached to a specific site and later referenced by design projects
- Students could be asked to consider the implications of soil profiles for structural design

Problem Set #3

Problem Descriptions

1. oedometer test stress path; lateral stress ratio
2. active and passive p-q diagrams
3. gravity wall stability; bearing capacity failure
4. normal and shear stresses beneath slope

Integration Possibilities

- Problem No. 1 might illustrate advantages of running oedometer tests by using a specific case study
- Problem No. 1 could also ask what other tests could provide similar information
- Problem Nos. 2 & 3 could use a real site, or one of the 1.30 design projects, or a foundation support for one of the structural design projects
- An actual construction excavation or soil berm from the Staged Excavation Design Project could be used to provide integration and application to Problem No. 4

Problem Set #4

Problem Descriptions

1. retaining wall passive, active, shear and normal forces
2. retaining wall overturning and sliding factors of safety
3. retaining wall bending moment; maximum soil stresses
4. cantilever wall embedment depth
5. required anchor force for embedded wall

Integration Possibilities

- This Problem Set could be modified to facilitate comparisons between granular and cohesive backfills
- The problems could ask for specific incidents when it might be advantageous to use one soil type over another

Problem Set #5

Problem Descriptions

1. allowable footing load
2. required strip footing width
3. sand settlement under circular tank

Integration Possibilities

- Problem No. 1 could reference a specific circular footing use
- Problem No. 1 could be the footing for one of the 1.51 or 1.52 design projects (probably modified to a square or rectangle)

- The strip footing in Problem No. 2 could model a bridge pier foundation or a wall foundation from one of the design projects
- Problem No. 2 could indicate what average footing widths are used in practice
- The foundation in Problem No. 3 might be modified to have application to one of the design problems

Problem Set #6

Problem Descriptions

1. soil profile pore pressures & total and effective stress
2. soil profile hydraulic gradient and critical hydraulic gradient
3. submerged retaining wall active and passive thrusts

Integration Possibilities

- The soil profile in Problem No. 1 could reference an actual site and be incorporated into lab samples and design projects
- Problem No. 2 could ask for reasons for possible causes of increased pore pressures in underlying gravel
- Implications of the critical hydraulic gradient in Problem No. 3 could be illustrated with an example of the critical hydraulic gradient being reached at a real site (i.e. downstream from a dam)
- Problem No. 3 might reference the Cofferdam Design Project or the side foundations of a bridge in one of the other design projects

Problem Set #7

Problem Descriptions

1. concrete weir flow net, seepage, hydraulic gradient, uplift pressure
2. sand hydraulic conductivity
3. soil system vertical flow and pore pressures

Integration Possibilities

- An actual concrete weir could be used for Problem No. 1
- Problem No. 1 could give reasons for using a concrete weir
- The critical hydraulic gradient in the previous Problem Set could be referenced
- Problem No. 1 could also ask the required height of retained water to reach the critical uplift pressure
- For Problem No. 2, actual test data from a particular site could be used
- Problem No. 3 could indicate when knowing the hydraulic conductivity is critical in practice
- Problem No. 3 could analyze the granular filter used in the Cofferdam Design Project

Problem Set #8

Problem Descriptions

1. oedometer text compression index
2. clay swelling index, overconsolidation ratio
3. change in void ratio due to vertical load application
4. vertical settlement
5. vertical settlement estimate

Integration Possibilities

- The soil profiles for each problem in this Problem Set could reference a particular site or design project
- For Problem No. 5, students might apply their knowledge of statistics to develop an estimate of settlement given two similar soil profiles and the occurrence of each profile in the bore hole data

Problem Set #9

Problem Descriptions

1. retaining wall pore pressure, vertical and horizontal stress distributions
2. infinite slope with seepage factor of safety

Integration Possibilities

- For Problem No. 1, a specific example of a wall with similar backfill (overconsolidated clay) could be given
- Problem No. 1 could incorporate methods to facilitate drainage
- The infinite slope in Problem No. 2 could reference an actual slope with seepage
- Effects of seepage could be investigated by using the Problem Set #3 slope and comparing slope angles with the same factor of safety

Problem Set #10

Problem Descriptions

1. clay consolidation times
2. clay vertical effective stress profile variance with loading
3. clay layer settlement and swelling with fill placement and removal
4. slope failure factor of safety

Integration Possibilities

- Problem No. 1 could indicate how consolidation data obtained from small samples transfers to large scale consolidation problems
- Problem Nos. 2 & 3 could refer to an actual dry fill, or consolidation beneath one of the design project structures.
- Problem No. 4 could reference the slopes in the previous Problem Set as well as the slope in the Cofferdam Design Project.

Lab #1

This lab involves the classification of several soil types using the following methods:

- particle size distribution
- fine grained "quick tests"
- liquid and plastic limit tests

Lab #2

This lab introduces the direct shear test

Lab Integration Possibilities

- Labs could be used to run tests on soil samples from real soil profiles
- Lab tests could be referenced in problem sets and in design projects
- Lab reports produced in industry could be provided to show applicability of testing
- Real world costs of running tests could also be provided

1.50 Structural Engineering

Problem Set #1

Problem Descriptions
1. structure classification
2. determinate truss forces
3. simple beam reactions

Integration Possibilities
- Real structures could be used for Problem No. 1
- Trusses in Problem No. 2 might be tied to trusses analyzed in 1.04
- A real beam example from 1.105, 1.51 or 1.52 design projects could be used in Problem No. 3

Problem Set #2

Problem Descriptions
1. shear and moment diagrams
2. shear and moment diagrams

Integration Possibilities
- The problems in this homework set could be tied to 1.51 and 1.52 by referencing the importance of being able to do quick shear and moment diagrams in design work.
- Real beams from the steel building design projects or the MIT Biology Building Design Project would also give the problems a practical grounding

Problem Set #3

Problem Descriptions
1. beam and frame reactions and internal forces
2. conjugate beam for continuous beam
3. support reactions, rotation, and deflections using conjugate beam method
4. simple frame moment diagram analysis

Integration Possibilities
- The frame in Problem No. 1 could be tied to a structural bay of the steel design projects or MIT Biology Building design project
- The problem might address the realistic limitations of constructing a "rigid" frame
- Problem No. 2 might indicate advantages of using continuous beams in design
- A real conjugate beam example could be used from one of the 1.51 or 1.52 design projects or from another source.
- Problem No. 3 might illustrate the importance of deflections and rotations in beam design and use real examples
- Problem No. 4 could ask what type of loading condition might produce the moment diagram in this problem

Problem Set #4

Problem Descriptions

1. moment of inertia and maximum moment determination
2. beam deflection and rotation using conjugate beam method

Integration Possibilities

- The L-shape used in Problem No. 1 could be tied to the L-shape used in Problem Set #1 of 1.51
- Problem No. 1 could be connected to 1.04 moment of inertia determinations
- Real world applications of L-shaped connectors could be included
- Problem No. 1 could include a practical application for a similar beam
- Advantages to using the hinges in this problem could also be included with reference to the design projects.

Problem Set #5

Problem Descriptions

1. frame moment diagram and reactions using moment distribution
2. continuous beam moment diagram and reactions by moment distribution

Integration Possibilities

- A more realistic problem could be developed for Problem No. 1 using design projects in 1.51 or 1.52.
- Problem No. 2 could build on Problem No. 2 in Problem Set #3
- A real example could be used to illustrate the advantages of using conjugate beams in later design projects

Problem Set #6

Problem Descriptions

1. frame moment diagram using moment distribution
2. truss horizontal displacement using virtual force method

Integration Possibilities

- Perhaps a more practical frame could be used in Problem No. 1.
- Problem No. 2 could also be altered slightly to resemble trusses analyzed in 1.04 or a truss from one of the bridge design projects.

Problem Set #7

Problem Descriptions

1. truss node horizontal deflection using virtual force method
2. internal force determination of internally indeterminate frame using virtual force method

Integration Possibilities

- Problem No. 1 could be tied to any of the bridge design projects
- The frame in Problem No. 2 could be connected to either the steel design or MIT Biology building design projects

Problem Set #8

Problem Descriptions
1. spring system stiffness matrix, displacements, and reactions
2. truss node displacement using matrix method and virtual force method

Integration Possibilities
- The spring system in Problem No. 1 could be connected to the spring problem in 1.04
- Problem No. 2 could be altered include the effects of the support settling
- Real world examples could also be used

1.51 Design of Steel Structures

Problem Set #1 Tension Members

Problem Descriptions
1. building column strength requirements
2. short connecting member design capacity
3. bolt-hole arrangement and connecting member design capacity
4. L-angle effective area, yield and fracture tension capacity, maximum length

Integration Possibilities
- Problem No. 1 could develop the strength requirements for one of the steel design project columns
- Problem No. 2 could refer to often encountered difficulties in 30" Span Structure Design Project connections
- The connection in Problem No. 2 could be from the 30″ Span Structure or one of the other design projects
- Problem No. 3 is similar to Problem No. 2 with a different bolt configuration; students could be asked to design an optimal bolt configuration to maximize member capacity
- The problem could also discuss standard practice for designing connecting members
- Problem No. 4 could indicate where L-angles are commonly used

Problem Set #2 Columns

Problem Descriptions
1. elastic column slenderness parameter, critical compressive strength
2. lightest section for column compression load
3. lightest W12 section for column load using LRFD and column tables
4. frame interior column design

Integration Possibilities
- Problem No. 1 could reference the development of Euler's buckling equation in 1.105
- Problem Nos. 2 & 3 could use an actual column from the Citgo sign or another design project
- Different ways to increase column capacity could be developed considering Euler's critical buckling stress
- The problems could also include common bracing methods used in practice
- A frame from one of the steel design projects could be used for Problem No. 4
- Problem No. 4 could also ask how differential settling of the column foundations might affect column and connection design

Problem Set #3

Problem Descriptions

1. theoretical beam mid-span load at yielding and for plastic hinge
2. lightest beam size for specified load, span, and supports
3. lightest beam size for specified load, span, and supports
4. nominal beam loads using virtual work method
5. optimum W14 section using plastic design

Integration Possibilities

- Each of the beams in this problem set could reference an actual beam or a design project member
- The problem set could also bring up the issue of supply and demand; i.e. when it might be cost-effective to go with larger sizes than needed
- It would be interesting to discover how large typical order volumes are for a rolling mill and what typical beam sizes are used in the Boston area

Problem Set #4

Problem Descriptions

1. lightest beam section using c_b
2. lightest beam W-section considering various support conditions

Integration Possibilities

- Problem No. 1 could give an example of a real beam that failed in lateral torsion
- A real beam from the design projects could be used
- Problem No. 2 could also illustrate detailing of beam supports

Problem Set #5

Problem Descriptions

1. tension member adequacy with additional bending moment
2. beam-column design using lightest W14 section
3. beam-column design assuming no joint translation

Integration Possibilities

- Problem No. 1 could indicate when tension members might be loaded in tension and bending.
- Problem Nos. 2 & 3 could model specific columns from the design projects
- Examples of similar critical loading condition, and occurrence in the Boston area, could be used

Project #1

Project Description

For this project, students are divided into 4 groups. Each group researches one of the following topics: Specifications and Standards, Issues of Safety in Structural Design, Structural Systems, and the Design Process. The groups are responsible for writing a report on the topic and presenting the topic to the rest of the class.

Integration Possibilities

- Students might be asked to compare how these issues differ when considering concrete structures
- The project could require students to talk with practicing engineers about common practice in the Boston area
- The implications of computers in these processes could be addressed

Project #2

Project Description

This project requires students to determine loading conditions for a building structure.

Integration Possibilities

- Students could examine the loading conditions for their final group projects
- Project could revisit the 1.04 pedestrian bridge design to investigate loading conditions
- Stresses resulting from differential settlements could also be addressed

1.52 Design of Concrete Structures

Problem Set #1

Problem Descriptions

1. factor of safety, concrete and steel stresses, hairline cracks
2. moment producing cracking, maximum moment, flexural strength
3. precast T-beam design moment capacity and uniform service live load limit

Integration Possibilities

- Problem No. 3 refers to "a bridge over a small roadway"; to make this whole problem set more applicable, perhaps Problem Nos. 1 & 2 could also be members of this same bridge
- The Stevens Brook Bridge Design Project might be used to make the "bridge over a small roadway" even more applicable
- For any of these problems, a comparable beam in steel might be provided to investigate cost and performance differences
- Problem No. 3 might also include advantages of using T-beams and examples of use in practice

Problem Set #2

Problem Descriptions

1. rectangular beam theoretical web reinforcement
2. maximum vertical shear; diagonal tension reinforcement

Integration Possibilities

- Problem No. 1 could model an actual structural beam from the MIT Biology building or a beam from in the classroom
- The 22 ft span beam in Problem No. 2 could also be an actual beam
- Students could be asked how much a Problem Set span could be safely lengthened

Problem Set #3 & 4

Problem Descriptions

1. reinforcement detailing, embedded length, support requirements, practicality
2. steel stress; maximum crack width; suitability in moist air
3. continuous beam immediate and long-term deflections; increment of life load deflection.

Integration Possibilities

- An actual example would increase the practical aspects of all these Problems
- One building, structure, or design project could be used to illustrate all of the Problem Sets
- Problem No. 1 asks the student to comment on the practicality of the proposed design; perhaps it could also ask students to come up with possible alternatives
- Problem No. 2 could be integrated with 1.59 by asking what material or kinds of concrete might perform better in a moist environment.
- Examples might be shown of beams exceeding the maximum crack width or illustrating the effects of moist environment.
- Problem No. 3 could refer to the continuous beam in 1.50
- Problem No. 3 might also ask for measures to reduce deflections
- Deflections of a comparable steel beam might be given to provide a sense of relative performance.

Problem Set #5

Problem Descriptions

1. column axial and flexural strength interaction diagram
2. design strength curve; tie steel detailing; allowable load and eccentricity

Integration Possibilities

- Perhaps a foundation pile could be modeled as a slender column
- Students might also be asked what problems would arise from pouring concrete in the ground considering quality control and corrosion

Problem Set #6

Problem Descriptions

1. interior panel slab thickness and reinforcement using ACI Direct Design Method

Integration Possibilities

- This problem could refer to an actual floor structure
- The costs associated with a concrete vs. a steel floor system might be considered

Problem Set #7

Problem Descriptions

1. parabolic tendon forces, shear, and moment curves; dead load and prestress shear and moment curves
2. allowable uniform service load; end stresses

Integration Possibilities

- Beams with similar outer dimensions as an earlier problems could be used to compare capacity and costs between different beam types
- A practical application could increase students' vision of possible application

8.4 Computer Aided Liability Article

The following article reproduced here was written by Lisa Backman and entitled "Computer-aided Liability." It was published by the ASCE *Civil Engineering* Publication June 1993 (Vol. 63, No. 6).

As engineers increasingly rely on computer software to help them design and analyze structures, their liability risk grows. Many computer users would like to see software developers share financial responsibility if use of defective software results in design problems, but the law allows developers to limit their own liability.

Just a few short hours after 5,000 basketball fans left the Hartford (Conn.) Civic Center in January 1978, the 21/2 acre space-frame roof of the arena collapsed under 4 in. of snow and ice. Analysis revealed that the two engineers who designed the structure were so confident of the computer-generated results of their model of the roof that they did not verify the calculations when informed during construction that the roof sagged.

The engineers were held fully accountable for the damage, but should the developer of the software used, which generated an oversimplified model, bear some financial responsibility for the collapse?

The question of developer liability becomes more important as engineers rely more on computers. Computers have allowed civil engineers, especially structural engineers, to streamline design, raise productivity and cut costs. Greater reliance on computers for everything from business activities to complex design and analysis, however, has led to increased exposure to liability for failures.

Problems with software can be undetectable. In one incident, described in the book To Engineer is Human by Henry Petroski, chairman of the department of civil and environmental engineering at Duke University, an incorrect sign in one of the instructions to a structural analysis program caused the computer to subtract stresses when it should have added. During seismic analysis of several nuclear power plants, the program r& ported values that were lower than they would have been during an earthquake. The plants were declared earthquake-proof based on the faulty analysis, and they had to be reanalyzed.

Such an error is arguably hard for the engineer to detect. Could the software developer have been legally required to pay part of the cost of reanalyzing the structures, which took so long that the Nuclear Regulatory Commission threatened to shut them down if safety was not demonstrated in a reasonable time?

Probably not, says Paul M. Lurie, a partner at Chicago based law firm Schiff, Hardin & Waite.

Most commercial software that engineering firms use is mass-marketed, such as Autodesk Inc.'s AutoCAD and Intergraph Corp.'s MicroStation. Mass-marketed software has been, with some debate, classified as a good and subjected to the same laws as other goods. This means that remedies for software defects that cause economic loss are limited to the contract between the software developer and the engineering firm, says Lurie. Most often, this contract is nothing more than the license printed on the envelope the software comes in, which usually limits remedies to the cost of replacing the software. Purchasers agree to the license when the seal is broken.

Engineers' ability to sue is also limited by the lower professional status of developers. "Engineers who design bridges or high-rise buildings, the collapse of which could cost lives, are licensed and regulated. But thus far, there are no similar requirements for programmers in the United States," reported Newsweek in 1990. Since they do not qualify as professionals, developers are held to a lower standard of care than engineers in legal disputes and are therefore not required to assume the same degree of liability.

In a dispute involving a faulty design that may have resulted from defective software, even in cases where injury or death has occurred, the courts place the burden of proof on engineers to show that developer error, not user error, is responsible for the bad design. A contractor sued Lotus Development Corp., Cambridge, Mass., alleging that a bug in its Symphony spreadsheet software caused the contractor to underbid a project by $245,000. The court found that user error was the cause and dismissed the case.

What the Law Says

The software license is the key to whether a computer user can recover damages from a software developer. A contract is automatically created when the software is sold even though nothing has been signed. The license presents the terms of this contract, and under contract law, all remedies for economic losses are subject to the terms agreed on in the contract.

This contract is governed by the Uniform Commercial Code (ucc), says Lurie. Section 2 of the ucc states that goods sold I are subject to the warranties of the ucc, which are either express or implied.

An express warranty promises that a particular program will perform as described when it was purchased. Any statement of fact that the developer makes in product brochures, advertisements, manuals or demonstration versions of the program is an express warranty. A statement of opinion, such as a developer's claim that its software is the best in the field, does not constitute an express warranty. Developers rarely create express warranties.

Implied warranties, however, are created automatically when the software is sold. Under the ucc, the developers guarantee that the program will perform normally for this type of program. The ucc also assumes that the buyer can rely on the judgment of the seller that the software sold will fit the purpose for which the buyer intends it.

If the engineer buys defective software, in limited circumstances he or she can recover losses from the software developer for breach of those implied warranties. The circumstances are limited because the ucc lets developers modify or disclaim implied warranties. "Most sophisticated companies will disclaim the warranties," says Lurie. Developers cannot disclaim express warranties, but they can limit the remedy available to purchasers. Most limit that remedy to the cost of replacing the software.

What this means to engineers is that developers are usually protected from suits brought by engineers. "An engineer might be able to sue and at best get his or her money back," says Peter Brown, founding partner of Brown Raysman & Millstein, a computer law firm in New York, unless they can prove fraud-cases where the developer has knowingly said that software can do something it cannot do.

By using software, therefore, the liability burden of engineering firms increases. "Computers will create problems for engineers," says Lurie.

In cases where only economic loss occurred, the engineer's clients or other third parties are also barred from suing the software developer. The Economic Loss Doctrine, which has been adopted by most states, holds that the injured party can only seek remedy with the person with whom they have a contract with or did business with, says Lurie. The client will generally only have a contract with the engineering firm.

In cases where personal injury or death results from structural failure, engineers or their clients are not limited by the terms of the contract. They can sue for negligence, strict liability, malpractice or misrepresentation (fraud). Engineers will find it difficult, however, to recover in such cases, because the engineer must prove that his or her own professional judgment was sound. Third parties, such as clients or injured parties, may have a better chance.

In Chatlos Systems vs. National Cash Register Corp., the plaintiff asserted the theory of computer malpractice in a post-trial memorandum. The court dismissed the malpractice claim in a footnote:

"The novel concept of a new tort called 'computer malpractice' is premised upon the theory of elevated responsibility on the part of those who render computer sales and services. Plaintiff equates ... [these] ... with established theories of professional malpractice. Simply because an activity is technically complex and important to the business community does not mean that a greater potential liability must attach. In the absence of precedential authority, the court declines the invitation to create a new tort."

To guard against these kinds of claims, Computers & Structures Inc. (CSI) of Berkeley, Calif., which develops SAP90, SAFE and ETABS, keeps thorough records of what quality testing was done and the results, says president Ashraf Habibullah. CSI also releases notices about known bugs and updates of the software to correct problems. Proving gross negligence or malpractice would be difficult under these circumstances.

Caveat Emptors

Trying to sue a developer for liability is not impossible, but so far it is unlikely the engineer would win. There have been cases against developers of engineering software, but they never made it to trial and the records were sealed. This leaves engineers, developers and lawyers with few guidelines.

For engineers who use computers, the best policy is caveat emptor-let the buyer beware, says Barry Milliken, systems director for Parsons Brinkerhoff Quade & Douglas (PRQD) in New York. Firms should establish guidelines by which to test software and check out the developers behind the software.

David Friedlander, independent programming consultant and president of the New York chapter of Computer Programmers for Social Responsibility, advises engineers to be wary of software with a small user base, because often the developer does not have the resources to test it as thoroughly as developers of well-known products. Richard Parmelee, chief structural engineer at Alfred Benesch & Co. in Chicago, agrees. His company prefers to deal only with tried and true developers. "Much software is written by people in their basements," he says.

Friedlander also says engineers should never depend too much on version 1.0 of anything. Only after the software has been tested by the market can engineers have some confidence in it.

To avoid failures such as the Hartford Civic Center collapse, engineers should not relax their professional judgment or skepticism when they use computers. Software, especially complex structural or analysis software, often comprises thousands of lines of code and errors are inevitable. Firms should also ensure that computer users are experienced engineers who can verify that computer-generated results are correct.

Some firms try to cut costs by hiring young engineers for their computer expertise, not their engineering experience. "The electronic brain is sometimes promoted from computer or clerk at least to assistant engineer in the design office," wrote author Petroski.

Atis Liepins, senior associate with Simpson Gumpertz & Heger Inc., in Arlington, Mass., examined some structural failures and presented the results at ASCE's annual convention in New York last September. A long-span roof truss designed with the aid of a computer collapsed in a snowstorm under less than half of the design snow load because of improperly placed and calculated centers of gravity for the diagonals and the chord of the truss. The designer was an inexperienced engineer who was not well supervised.

Reducing Liability

Whether or not software developers should assume more liability on their own or be required to by law is debated. Friedlander argues that in some cases developers should be held at least partly accountable. Developers agree that they have a responsibility to scrupulously test their software, but they don't agree they should accept greater liability. Habibullah says software is an engineering tool and engineers should take responsibility when the results are incorrect, as with any other tool. "Failures occur because people go in there and use computers blindly," he says.

Engineers can try to reduce liability associated with using computers by trying to negotiate special contracts with developers, changing the laws or by creating a consumers union, says Schiff Hardin & Waite's Lurie. A consumers union may also help in negotiating contracts with software developers. "If you have any brains, you try to negotiate those warranties," says Lurie.

Negotiation may not be that easy, however, no matter how great the economic clout of the engineering firm. Alfred Benesch & Co. has had little luck in that area, says Parmelee. "Developer attitude seems to be take it or leave it." This leaves the firm in a bind if a client requires that certain software be used.

Milliken says it is futile to try to negotiate with developers of mass-marketed software. He likened it to buying a bottle of aspirin. The average aspirin buyer can't expect a large pharmaceutical company to negotiate a special liability clause in the contract created by the sale for each consumer, and the same goes for purchasers of off-the-shelf software.

CSI's Habibullah says that unless a company were to offer him a contract large enough to justify financing long-term liability insurance, he would not agree to one accepting greater liability for software errors.

Remain Skeptical

Computers and computer software are tools that must be used properly. Should a bug in the software cause economic loss in the long run, engineers and their clients have little legal recourse with developers. Engineers are ultimately liable for their designs, whether computer-aided or not, and should be skeptical of the software they use. As Petroski wrote, "The computer is both blessing and curse for it makes possible calculations once beyond the reach of human endurance while at the same time also making them virtually beyond the hope of human verification.

8.5 Recent Civil Engineering Education Innovations

Other civil engineering departments are addressing the challenge of educating students in both science and design. A significant amount has been written in engineering education literature about how the standard civil engineering curriculum is changing. In July 1996, a publication in the *Journal of Professional Issues in Engineering Education and Practice* compiled recent innovations in undergraduate civil engineering education after surveying civil engineering departments, the eight National Science Foundation funded engineering education coalitions, and literature published in two engineering education journals. The authors, Pauschke and Ingraffea, conclude that the current reform movement in undergraduate civil engineering education exhibits the following themes:

- a decrease in credit hours required for the undergraduate degree
- new degree options and degrees in environmental engineering
- strong emphasis on design courses with multi-disciplinary approach, group interaction, multi-mode communication, industry projects, and practitioner input and evaluation
- increasing emphasis on oral and written communication skills
- innovations in the area of multimedia presentations, simulation software, and communication via the Internet and World Wide Web
- hands-on design and analysis experience in laboratories
- synthesis of previously separated courses
- interest in education evaluation and assessment

To provide a flavor of this wave of educational innovation, brief descriptions of curriculum changes in institutions around the country, particularly those that might be of particular interest to 1-C faculty, are given below. Capstone design innovations discussed in Chapter 5 are not included here.

New/Revised Freshman Year Design Courses

- Alabama A&M University. Four to six laboratory sessions of an engineering graphics course investigate civil engineering applications (roof truss design and drawing, contour interpolation, topographic mapping).
- California Polytechnic State University. A fundamentals course devotes a week to each of the following topics: professionalism/professional societies, design, ethics, transportation, geotechnics, structures, environmental and water resources. A team design project involves a building prototype and written and oral presentations.
- California State University, Chico. A freshman subject is used to introduce CE design in environmental, structural, and transportation engineering. Field trips are made to industrial sites and design firms, lectures are given by practicing engineers, and students complete small design projects.
- Catholic University of America. A computer programming, graphics, and engineering design class emphasizes the interdisciplinary nature of engineering and includes innovate CE design projects.
- Duke University. Historical case studies of engineered artifacts and engineering projects are used to introduce structural engineering. Students complete a design project and case study paper.
- University of Evansville. In the freshman project laboratory, students work in teams to identify and solve problems.
- Harvey Mudd College. Design is presented in a project-based context supplemented by lectures on design methodology. Projects involve proposals, progress reports, and written and oral presentations. External juries judge in design competitions.
- Howard University. A two semester course introduces engineering design. Students work in teams to design and build entries for a design competition.
- Ohio Northern University. An elective creative design course teaches idea generation,

creativity, writing, proposal submission, design, drawing, building and final reporting.

- University of Oklahoma. A computer laboratory simulates an engineering office. Computers are used to solve engineering problems, present results, and manage project tasks.

New/Revised Sophomore and Upper Division Courses

- Auburn University. Ethics modules are integrated in required engineering courses.
- California Polytechnic State University. A professional practice course is taught entirely by practitioner volunteers. The team term project is an actual industrial project.
- University of Cincinnati. A case studies in construction course uses an industry committee as mentors and evaluators of student team projects. Course funded by industry.
- Cornell University. An undergraduate sequence in structural engineering/constructed facilities uses a synthesis approach to horizontally integrate multiple sub-disciplines (geotechnical engineering, mechanics, materials, and construction). Multimedia, simulated case studies are used, and teamwork is emphasized.
- Cornell University. "Aedificium" (Macintosh-based multimedia case studies in structural engineering including 1,500 construction photos, earthquake damage images, and notable structural failures) used to integrate case studies in several undergraduate classes.
- McMasters University. Communications in civil engineering course places all sophomore students on a technical project assignment with local engineering offices; introduces engineering problem solving, involves students in a real civil engineering project, and stresses communication skills.
- Southern University and A&M College. Innovative courseware module integrates multimedia material and uses guest lectures for dam safety courses.
- Villanova University. Sophomore civil engineering measurements course examines data use in context of major engineering projects.

New/Revised Sophomore and Upper Division Design Courses

- Duke University. An advanced structural design and construction course unifies concepts taught in reinforced concrete, structural steel, and prestressed concrete; focuses on buildability, durability, economy, construction management, and safety; and emphasizes communication skills.
- Illinois Institute of Technology. A computer-aided capstone design course includes 2 or more sub-disciplines (structural, geotechnical, etc.) and utilizes a new computer-aided design (CAD) laboratory funded by industry.
- University of Maine. The capstone design course involves team work, extensive practitioner input, and mock public hearings.
- University of Missouri. A bridges course is taught for civil engineering and history students emphasizing interaction among technology and social sciences. Interdisciplinary teams design and build a bridge and complete a research paper.
- Northern Arizona University. A sophomore design course completes an interdisciplinary, hands-on, team oriented engineering project simulating a midsize engineering firm. The team-taught subject uses state-of-the-art computing tools
- Pennsylvania State University. A civil engineering measurements course uses AutoCAD, spreadsheets, and geographic information systems (GIS) as design and analysis tools for civil engineering assignments.
- University of South Florida. Team design projects in a soil mechanics course are presented to and evaluated by practicing geotechnical engineers.
- Stanford University and University of California, Berkeley. Computer-integrated architecture/engineering/construction course focuses on interdisciplinary teamwork, information integration, and organization modeling; illustrates how the three disciplines integrate product and process; and uses Internet-mediated design communication, CAD, groupware, and multimedia technology.

- Tennessee Technological University. Capstone course involves a comprehensive facility design. Team work is evaluated by practitioners and faculty.
- University of Vermont. Projects for the senior capstone are provided by local design practitioners. Students work in teams.
- University of Oklahoma. Capstone senior design is co-taught by a local consulting firm and departmental faculty using teamwork and written/oral presentation.

9. References

General Engineering Education References

Bailie, Richard C. "The Evolution of a Design-Based Curriculum in ChE." *Journal of Education*, vol. 80, 1990, pp. 568-570.

Culver, Richard S., et al. "Gaining Professional Expertise Through Design Activities." *Journal of Engineering Education*, vol. 80, 1990, pp. 533-536.

Ehrmann, Stephen Charles. "Academic Adaptation: Historical Study of a Civil Engineering Department in a Research-Oriented University." MIT Thesis, 1978.

Ernst, Edward W. And Jack R. Lohmann. "Designing Undergraduate Design Curricula." *Journal of Engineering Education*, vol. 80, 1990, pp. 543-547.

Evans, D. L., et al. "Design in Engineering Education: Past Views of Future Directions." *Journal of Engineering Education*, vol. 80, 1990, pp. 517-522.

"History of Engineering for Engineering Students: A Challenge for Engineering Education." Report on Conference at Stanford University, July 1992.

Lovas, Charles M., and Paul F. Packman, eds. *Engineering Design Projects Compendium: National Science Foundation Workshop on Enhancement of Faculty Design Capabilities.* Dallas, TX: Southern Methodist University, 1995.

Mann, Robert W. "Engineering Design Education." Unpublished talk presented at ASME Winter Annual Meeting, 1965.

Masi, Barbara Mendez. "MIT/ECSEL Project: Fourth Year Evaluation Report." Unpublished, 1994.

McCaulley, Mary H. "The MBTI and Individual Pathways in Engineering Design." *Journal of Engineering Education*, vol. 80, 1990, pp. 537-542.

McMasters, John H. And Stephen D. Ford. "An Industry View of Enhancing Design Education." *Journal of Engineering Education*, vol. 80, 1990, pp. 526-529.

McNeill, B. W., et al. "Beginning Design Education With Freshmen." *Journal of Engineering Education*, vol. 80, 1990, pp. 548-553.

Davidson, Cliff I., and Susan A. Ambrose. *The New Professor's Handbook: A Guide to Teaching Research in Engineering and Science.* Bolton, MA: Anker Publishing Company, Inc., 1994.

Nuccitelli, Saul A. "Design Education: Theories and Practice." MIT Thesis, 1994.

Olds, Barbara M., et al. "Teaching the Design Process to Freshmen and Sophomores." *Journal of Engineering Education*, vol. 80, 1990, pp. 554-559.

Peterson, Carl R. "The Desegregation of Design." *Journal of Engineering Education*, vol. 80, 1990, pp. 530-532.

Reinschmidt, Kenneth F. "Project-Based Learning in Engineering Management Education." *Technology Management*, vol. 1, 1995, pp. 187-191.

Schon, Donald A. *Educating the Reflective Practitioner.* San Francisco: Jossey-Bass Publishers, 1987.

Tribus, Myron. "Afterthoughts From a Found(er)ing Father." *Journal of Engineering Education*, vol. 80, 1990, pp. 523-525.

Viets, Hermann. "Designing Across the Curriculum." *Journal of Engineering Education*, vol. 80, 1990, pp. 565-547.

Wankat, Phillip C., and Frank S. Oreovicz. *Teaching Engineering.* New York: McGraw-Hill, Inc., 1993.

West, Harry, et al. "Hands-on Design in Engineering Education: Learning by Doing What?" *Journal of Engineering Education*, vol. 80, 1990, pp. 560-564.

Chapter 2: Integration

Brereton, Margot, et al. "How Students Connect Engineering Fundamentals to Synthesis Activities: Observations and Implications for the Design of Curriculum and Assessment Methods." *Proceedings of the 1995 Annual Conference on Frontiers in Education*, Atlanta GA, Nov. 1995.

Ramirez, Martin R. "Synthesis and Integration: Motivation and Connection: A Theory of Mindful Instruction." *Proceedings of the 1994 Annual Conference on Frontiers in Education*, San Jose, CA, Nov. 1994.

Chapter 3: Computer Use

Anagnos, Thalia and Pavel Marek. "Application of Simulation Techniques in Teaching Reliability Concepts." *Proceedings of the 1996 Annual Conference on Frontiers in Education,* Salt Lake City, UT, Nov. 1996, pp. 950-953.

Backman, Lisa. "Computer-Aided Liability." *Civil Engineering,* vol. 63, no. 6, 1993, pp. 40-43.

Baker, Nelson C. and Glen J. Rix. "Computing in Civil Engineering: Current Trends and Future Directions." *Journal of Professional Issues in Engineering Education and Practice,* vol. 118, no. 2, 1992, pp. 139-155.

Billington, David P. "Design in Education." *Journal of the International Association for Shell and Spatial Structures,* vol. 37, no. 120, 1996, pp. 17-20.

Brohn, D. M. "Engineering on the Right." *Structural Engineer,* vol. 74, no. 22, 1996, pp. 380-382.

Brohn, D. M. "A New Paradigm for Structural Engineering." *Structural Engineer,* vol. 70, no. 13, 1992, pp. 239-242.

Fleming, John F. "Computing in Analysis and Design in Structural Engineering: An Educator's Point of View." *Proceedings of the Eleventh Conference on Analysis and Computation,* Atlanta, GA, April 1994, pp. 362-368.

Godfrey, K. A., Jr. "Computers: What Do Students Need to Know?" *Civil Engineering,* vol. 57, no. 6, 1987, pp. 72-75.

Hrabok, M. M. and M. U. Hosain. "Use of Structural Analysis Programs in Consulting." *Journal of Professional Issues in Engineering Education and Practice,* vol. 119, no. 4, 1993, pp. 409-415.

Jermann, William H. "Using Computers in an Engineering Curriculum." *Proceedings of the 1996 Annual Conference on Frontiers in Education,* Salt Lake City, UT, Nov. 1996, pp. 1402-1404.

Meyer, Karl F. and Stephen J. Ressler. "A Tool But Not a Crutch: Using Design Software in an Undergraduate Structural Steel Course." *Proceedings of the Second Congress on Computing in Civil Engineering,* Atlanta, GA, June 1995, pp. 264-269.

Nahvi, Mahmood. "Dynamics of Student-Computer Interaction in a Simulation Environment: Reflections on Curricular Issues." *Proceedings of the 1996 Annual Conference on Frontiers in Education*, Salt Lake City, UT, Nov. 1996, pp. 1383-1386.

O'Neill, Robert J., et al. "Not Just a Black Box: Personal Computer Use in Undergraduate Structural Analysis Courses. *Proceedings of the Second Congress on Computing in Civil Engineering*, Atlanta, GA, June 1995, pp. 248-255.

Parmelee, Richard A. "Computing and Design in Structural Engineering: A Practicing Engineer's Point of View." *Proceedings of the Eleventh Conference on Analysis and Computation*, Atlanta, GA, April 1994, pp. 369-375.

Puckett, Jay A. and Jerry C. Hamann. "A Model for Using Productivity Software in the Engineering Classrooms." *Proceedings of the 1996 Annual Conference on Frontiers in Education*, Salt Lake City, UT, Nov. 1996, pp. 1084-1088.

Stubbs, Geneen and Mike Watkins. "Re-Engineering CBL Development." *Proceedings of the 1996 Annual Conference on Frontiers in Education*, Salt Lake City, UT, Nov. 1996, pp. 1387-1390.

Vanegas, Jorge A. "An Integrated Computer-Based Total Design Environment for Civil Engineering Education." *Proceedings of the Fifth International Conference on Computing in Civil and Building Engineering*, Anaheim, CA, June 1993, pp. 439-446.

Wester, Ture. "Morphological Aspects in Teaching Conceptual Design of Structures or the Art of Asking 'Stupid' Questions." *Journal of the International Association for Shell and Spatial Structures*, vol. 37, no. 120, 1996, pp. 21-22.

Chapter 4: Integrating Subject History at MIT

Accreditation Board for Engineering and Technology. *Criteria for Accreditation Programs in Engineering in the United States*. New York, 1991.

Ehrmann, Stephen Charles. "Academic Adaptation: Historical Study of a Civil Engineering Department in a Research-Oriented University." MIT Thesis, 1978.

Lovas, Charles M. "Capstone Engineering Design: A History." *Proceedings of the 1994 Advances in Capstone Education Conference*, Provo, UT, Aug. 1994, pp. 103-108.

Masi, Barbara Mendez. "MIT/ECSEL Project: Fourth Year Evaluation Report." Unpublished, 1994.

Chapter 5: Current Engineering Capstone Practice

Anderson, Donald A. "Civil Engineering Capstone Design Course." *Journal of Professional Issues in Engineering Education and Practice*, ASCE, vol. 118, no. 3, 1992, pp. 279-283.

Beaufait, Fred W. "Teaching Structural Engineering in the Year 2000." *Structural Engineering in Natural Hazards Mitigation, Proceedings of the Fifth International Conference*, Irvine CA, Apr. 1993, pp. 439-446.

Bohinsky, J. A. And J. P. Lee. "Educating a Structural Engineer." *Structures Congress XII, Proceedings of the Structures Congress*, Atlanta, GA, Apr. 1994, pp. 1352-1357.

Bright, Anthony. "Teaching and Learning in the Engineering Clinic Program at Harvey Mudd College." *Journal of Proceedings of the 1994 Advances in Capstone Education Conference*, Provo, UT, Aug. 1994, pp. 113-116.

Chinowsky, Paul S. And Jeffrey Robinson. "Facilitating Interdisciplinary Design Education Through Case Histories." *Journal of Proceedings of the 1995 Annual Conference on Frontiers in Education*, Atlanta, GA, Nov. 1995, pp. 439-446.

Dolan, Charles W. And Gary Searer. "Design Projects in Civil Engineering Curriculum." *Journal of Professional Issues in Engineering Education and Practice*, ASCE, vol. 119, no. 3, 1993, pp. 309-316.

Frantz, Patricia G., et al. "Collaboration in the Engineering Classroom." *Journal of Professional Issues in Engineering Education and Practice*, ASCE, vol. 121, no. 3, 1995, pp. 47-53.

Glynn, E. F. And W. B. Ferguson. "Innovative Introduction to Civil Engineering Curriculum." *Journal of Professional Issues in Engineering Education and Practice*, ASCE, vol. 120, no. 2, 1994, pp. 149-157.

Groves, James R. "Capstone CE Design Course: An Undergraduate college Experience." *Proceedings of the 22 nd Annual Conference on Integrated Water Resources Planning for the 21 st Century*, Cambridge, MA, May 1995, pp. 1125-1127.

Hamilton, Patrick H. "Enhanced Engineering Design Education By Cooperation: A Contribution From 'SEED'." *Journal of Proceedings of the 1994 Advances in Capstone Education Conference*, Provo, UT, Aug. 1994, pp. 109-112.

Knox, Robert C., et al. "A Practitioner-education Partnership for Teaching Engineering Design." *Journal of Engineering Education*, vol. 84, no. 1, 1995, pp. 5-12.

Koehn, Enno. "Practitioner and Student Recommendations for an Engineering Curriculum." *Journal of Engineering Education*, vol. 84, no. 3, 1995, pp. 241-248.

Kruchoski, Brian L. "Planning and Managing a Multi-disciplinary Capstone Project." *Proceedings of the 22 nd Annual Conference on Integrated Water Resources Planning for the 21 st Century*, Cambridge, MA, May 1995, pp. 1121-1124.

Lovas, Charles M. "Capstone Engineering Design: A History." *Journal of Proceedings of the 1994 Advances in Capstone Education Conference*, Provo, UT, Aug. 1994, pp. 103-108.

Mahbub, Uddin, et al. "Fostering Industrial Partnerships in Undergraduate Capstone Design Courses at Trinity University." *Journal of Proceedings of the 1994 Advances in Capstone Education Conference*, Provo, UT, Aug. 1994, pp. 25-28.

McEwen, Everett E. "Integrated Capstone Design Experience." *Journal of Professional Issues in Engineering Education and Practice*, ASCE, vol. 120, no. 2, 1994, pp. 212-220.

Miller, Arthur C. "Capstone Course With a Writing Twist." *Proceedings of the 22 nd Annual Conference on Integrated Water Resources Planning for the 21 st Century*, Cambridge, MA, May 1995, pp. 1109-1112.

Miller, Ronald L., and Barbara M. Olds. "A Model Curriculum for a Capstone Course in Multidisciplinary Engineering Design." *Journal of Engineering Education*, vol. 8, no. 4, 1994, pp. 311-316.

Morris, C. D. and R. A. LaBoube. "Teaching Civil Engineering Design: Observations and Experiences." *Journal of Professional Issues in Engineering Education and Practice*, vol. 121, no. 1, 1995, pp. 47-53.

Morris, C. D. and R. A. LaBoube. "Capstone Education: Faculty Issues." *Journal of Proceedings of the 1994 Advances in Capstone Education Conference*, Provo, UT, Aug. 1994, pp. 141-143.

Mulvihill, Michael E., et al. "Integration of Design in the Civil Engineering Curriculum." *Proceedings of the 22 nd Annual Conference on Integrated Water Resources Planning for the 21 st Century*, Cambridge, MA, May 1995, pp. 1113-1116.

Pauschke, Joy M. and Anthony R. Ingraffea. "Recent Innovations in Undergraduate Civil Engineering Curriculums." *Journal of Professional Issues in Engineering Education and Practice*, ASCE, vol. 122, no. 3, 1996, pp. 123-133.

Todd, Robert. H., Magleby, Spencer P., Sorensen, Carl D., Swan, Bret R., and Anthony, David K. "A Survey of Capstone Engineering Courses in North America." *Journal of Engineering Education*, vol. 84, no. 2, 1995, pp. 165-174.

Vanegas, Jorge A. "An Integrated Computer-based Total Design Environment for Civil Engineering Education." *Computing in Civil and Building Engineering, Proceedings of the Fifth International Conference*, Annaheim, CA, June 1993, pp. 439-446.

Wheeler, Orville E. And Jerry L. Anderson. "Decade of Capstone Design." *Proceedings of the 22 nd Annual Conference on Integrated Water Resources Planning for the 21 st Century*, Cambridge, MA, May 1995, pp. 1117-1120.

Chapter 6: Group Work in Engineering Education

Aller, Betsy M. "'Just Like They do in Industry': Concerns About Teamwork Practices in Engineering Design Courses." *Proceedings of the 1993 Annual Conference on Frontiers in Education*, Washington, D. C., Nov. 1993, pp. 489-492.

Brickell, James L., et al. "Assigning Students to Groups for Engineering Design Projects: A Comparison of Five Methods." *Engineering Education*, vol. 83, no. 3, 1994, pp. 259-262.

Brown, R. W. "Autorating: Getting Individual Marks from Team Marks and Enhancing Teamwork." *Proceedings of the 1995 Annual Conference on Fontiers in Education,* Atlanta, GA, Nov. 1995, pp. 3c2.15-18.

Christie, Richard D. "Applying Cooperative Learning to a Graduate Power Systems Analysis Course: It Works For Me!" Unpublished.

Cordes, David, et al. "Teaming in Technical Courses." *Proceedings of the 1995 Annual Conference on Fontiers in Education,* Atlanta, GA, Nov. 1995, pp. 4c3.14-16.

Deming, W. Edwards. *The New Economics for Industry, Government, Education.* Cambridge, MA: MIT Center for Advanced Engineering Study, 1993.

Dyer, William G. *Team Building: Issues and Alternatives.* Reading, MA: Addison-Wesley Publishing Co., 1987.

Dyson, Mark. *Grow Your Own Quality Improvement Team.* London: Thomas Telford Publishing, 1996.

Felder, Richard M. and Rebecca Brent. *Effective Teaching: A Workshop.* Rapid City, SD: South Dakota School of Mines and Technology, 1996.

Frantz, Patricia G., et al. "Collaboration in the Engineering Classroom." *Journal of Professional Issues in Engineering Education,* vol. 121, no. 3, 1995, pp. 297-303.

Free, Joseph C., et al. " Strategies for Developing Robust Teamsmanship in the Context of Design Education for Product Development: A Progress Report." *Proceedings of the 1993 Annual Conference on Fontiers in Education,* Washington, D.C., Nov. 1993, pp. 482-488.

Fuller, O. Maynard. "Unhindered Learning." *Engineering Education,* vol. 66, no. 5, 1976, pp. 402-404.

Gabriele, Gary A., et al. "Guidelines For Forming and Building Student Design Teams." *Proceedings of the 1994 Advances in Capstone Education Conference,* Provo, UT, Aug. 1994, pp. 121-125.

Hensey, Mel. *Collective Excellence: Building Effective Teams.* New York: American Society of Civil Engineers, 1992.

Hensey, Mel. "Making Teamwork Work." *Civil Engineering,* vol. 62, no. 2, 1992, pp. 68-69.

Hilliard, D. K. "The Communicator's Role in Project Teams." *Proceedings of the IEEE International Professional Communication Conference*, Philadelphia, PA, Oct. 1993, pp. 315-319.

Katzenbach, Jon R. and Douglas K. Smith. "The Discipline of Teams." *Harvard Business Review*, vol. 71, no. 2, 1993, pp. 111-120.

Koehn, Enno. "Interactive Communication in Civil Engineering Classrooms." *Journal of Professional Issues in Engineering Education*, vol. 121, no. 4, 1995, pp. 260-261.

Light, Richard. *The Harvard Assessment Seminars: Exploration with Students and Faculty about Teaching, Learning, and Student Life: First Report.* Cambridge, MA: Harvard UP, 1990.

McCaulley, Mary. "The MBTI and Individual Pathways in Engineering Design." *Engineering Education*, vol. 80, no. 5, pp. 537-542.

McKeachie, Wilbert J., et al. *Teaching Tips: Strategies, Research, and Theory for College and University Teachers.* Lexington, MA: D.C. Heath and Co., 1994.

Nicholson, Kevin. "Effective Leadership Techniques for Work Teams." *Journal of Applied Manufacturing Systems*, vol. 7, no. 1, 1994, pp. 23-25.

Rhinehart, R. Russel. "Experiencing Team Responsibility in Class." *Chemical Engineering Education*, vol. 23, no. 1, 1989.

Seesing, Paul and Laurel K. Grove. "Successful Collaborative Communication." *Proceedings of the IEEE International Professional Communication Conference*, Philadelphia, PA, Oct. 1993, pp. 311-315.

Simpson, Bill. "Moving Work Teams to the Next Level." *Proceedings of the IEEE International Engineering Management Conference*, Dayton North, KY, Oct. 1994, pp. 43-47.

Smith, Karl A. "Cooperative Learning: Effective Teamwork for Engineering Classrooms." *Proceedings of the 1995 Annual Conference on Fontiers in Education*, Atlanta, GA, Nov. 1995, pp. 2b5.13-18.

Ward, Allen C. "Design Team Leadership: Principles and Experiences." *Proceedings of the 1994 Advances in Capstone Education Conference*, Provo, UT, Aug. 1994, pp. 127-135.