CHAPTER 9

DESIGN AND LABORATORY

"Engineering without labs [and design] is a different discipline. If we cut out labs [and design] we might as well rename our degrees Applied Mathematics" (Eastlake, 1986).

We agree with this modified quotation that design and laboratory sessions are at the heart of an engineering education. There is nothing wrong with a degree in applied mathematics, but that is not the degree that students and companies think they are getting. Design and laboratory classes are also important in accreditation (see Section 4.6) and in the ASEE Quality in Engineering Education Project (ASEE, 1986). Despite almost general agreement on the importance of design and laboratory work, there is a tendency to cut these programs since they are expensive, messy, hard to teach, time-consuming, and not connected to the university's other mission—research.

Since this book cannot delve into the technical details which become important in teaching both design and laboratory courses, the discussion will necessarily be more abstract. We will consider the purposes of design and laboratory work and then consider particular methods for teaching these courses.

9.1. DESIGN

Many engineers contend that designing is the heart of engineering. All the mathematics, physics, chemistry, and engineering science courses are background for what makes engineering different from applied mathematics or the physical sciences. Yet there is no universally accepted working definition of what design is, and the Accreditation Board for Engineering and Technology continually struggles despite frequent criticism to be sure that sufficient design is included in the curriculum (Jones, 1991). An inadequate design curriculum is often noted as a deficiency during ABET visits.

In this section we will first discuss appropriate goals for the design part of courses and then explore methods for teaching design and including design throughout the curriculum. Finally, we will examine four different methods for teaching design—design projects, case studies, guided design, and design clinics. What we will not attempt to do is to list activities or projects which are appropriate for teaching design in different areas of engineering.

9.1.1. Design Goals

Instead of trying to define design, ABET (1989) describes activities and processes which may be included in design (see Section 4.6). Design

- Produces a system, component, or process to meet a specific need.
- Is an iterative process which utilizes decision making with economics and employs mathematical, scientific, and engineering principles.
- Includes some of the following: setting objectives, analysis, synthesis, evaluation, construction, testing, and communication of results.
- Has student problems which are often open-ended, require use of design methodology and creative problem solving, require formulation of the problem statement and an economic comparison of alternate solutions, and may require detailed system details.

From this description of design a wide variety of possible goals for the design part of a course can be generated:

Problem definition and redefinition. Students will learn to define and redefine problem statements as they work their way iteratively through open-ended problems.

Synthesis and creativity. Students will be able to synthesize new designs using the principles of creative problem solving (see Section 5.6).

Troubleshooting. Students will be able to take an existing design that does not work up to specifications and make it work. Since troubleshooting is quite different than designing a new device or process, students need a chance to practice (Middlebrook, 1991; Woods, 1980, 1983).

Use of engineering, mathematics, and science principles. Students will be able to integrate a variety of engineering, mathematics, and scientific principles into the solution of design problems.

Computer tools. Students will use computer tools such as spreadsheets, general mathematical packages (MAPLE, Mathematica, MATHLAB, etc.), and engineering discipline-specific simulation packages (ASPEN, PRIMAVERA, SPICE, etc.) to do detailed routine calculations. “A course which does not use a professional software is preparing our students for a type of work which does not exist any more” (Paris, 1991).

Decision making. Engineers must be willing to take the responsibility of making decisions knowing that something could go wrong since perfection can never be attained (Florman, 1987).

Generic design procedures. Students will learn and use generic design procedures. Examples of these procedures are given by Warfield (1989) and Magleby et al. (1991).

Economic evaluation. Students will evaluate solutions based on economic and other criteria to determine the best solution among several alternatives.

Completion of a deliverable. It may be possible to have students carry out all steps of a design including the construction and testing of a deliverable. When this is possible, it is extremely motivating for them to see their design built and used.

Industrial or real-life experience. Design projects are normally much more realistic than engineering science problems which are concocted to illustrate a single principle. An additional goal may be to have students solve actual industrial problems.

Oral and written communication. Students are expected to develop professional skills to communicate their results.

Planning and managerial skills. Students can learn how to plan effectively and direct fairly complicated projects.

Interpersonal skills. While working in groups students can learn interpersonal skills, become adept at teamwork, and start developing leadership skills. Teamwork has become increasingly important as technology becomes more complex (Florman, 1987).

Confidence. Students can develop confidence in their ability to function as engineers. This may be the primary objective of the course (Overholser et al., 1975).

This is a long but certainly not all-inclusive list. Dekker (1989) and Harrisberger (1986a, b) discuss other possible goals. No single course can satisfy all these goals, although some professors make a valiant effort. However, an entire curriculum can be designed so that these and other objectives are satisfied. The professor's task is to select appropriate goals for the design portion of a course. These goals must be appropriate for the student level and the time allotted to design. For example, completely open-ended, unstructured problems with no guidance are not suitable for first-year students but may be very appropriate for seniors. Once the goals have been determined, teaching methods can be selected (see Sections 9.1.2 through 9.1.6).

9.1.2. Teaching Design

The old ABET criteria state, "Some portion of this [the design] requirement must be satisfied by at least one course which is primarily design, preferably at the senior level, and draws upon previous coursework in the relevant discipline" (ABET, 1989). This sentence is often interpreted as requiring or suggesting a capstone course in design. The new requirements (see Sec. 4.6) require a meaningful, major engineering design experience. It is explicitly stated that the design experience must be developed and integrated throughout the curriculum. We feel that the strict dichotomy between engineering science and engineering design is a false one. Engineering design should appear throughout the curriculum. Culver et al. (1990) discuss two general ways that this can be done, Green (1991) gives details for an electrical engineering curriculum, and Juricic and Barr (1991) give specifics in mechanical engineering.

Spreading design throughout the curriculum allows the faculty to develop a design experience where students start working open-ended problems as freshmen or sophomores. These first projects are presented with a significant amount of guidance using a procedure such as guided design (see Section 9.1.5). Procedures for teaching freshmen design are discussed by Evans and Bowers (1988) and Evans et al. (1990). Design ideas can be included in traditionally nondesign classes (e.g., Henderson, 1989; Miller et al., 1989; Peterson, 1991; Riffe and Henderson, 1990) in both the second and third years. The traditional design classes and design laboratories would be retained and strengthened in the senior year. However, students would be better prepared for these classes, and professors would see fewer students who are totally unprepared for open-ended design problems.

Introducing some ideas of engineering economics into the curriculum during the first or second year allows a professor to include relatively simple design problems and economic optimizations which can only be talked about instead of being done if the students have not studied economics (Sullivan and Thuesen, 1991). Talking about something is a totally ineffective teaching method; students must do what they are to learn. In our experience, students find some of the economics (costs, cost indices, payout periods) easy, while other parts (such as discounted cash flow) are more challenging. It helps if the textbook talks about economic factors, but unfortunately many engineering textbooks are written in an economic vacuum. Since students see the design problems with economics as real engineering, these problems are motivating as long as the professor does not overburden the problem with detailed calculations. Computer tools such as spreadsheets, mathematical packages, and simulation programs are appropriate here to remove the burden of routine calculations.

How do you add design problems to an already overloaded curriculum and overloaded courses? Cover less in the lectures and expect students to learn some of the material on their own. If the design problem includes this material, students will learn it, and they will learn how to learn on their own. As the professor, you can help by having clear objectives, making sure resource material is readily available, and believing that students can master the material on their own. The design problem can be included as a small project, a case study, or as a guided design project.

An important part of design is creativity and synthesis. Since most traditional curricula cover only application and analysis during the first three years, it should be no surprise that many students have difficulty with creativity and synthesis in senior design. Including creative exercises and synthesis problems throughout the undergraduate program should make most students more creative designers. The methods for teaching problem solving and for fostering creativity discussed in Chapter 5 are appropriate for the design component of classes. Specific methods for teaching creative design classes are discussed by Cundy et al. (1987) and Jansson (1987).

There are many significant difficulties in teaching design at any level. The first difficulty confronting the professor is the development of good design problems. Every engineering professor has one or two good design problems stored in her or his head. Design problems cannot be recycled and reused since students quickly convert the course into an exercise in rewriting files. New problems are needed every year. Thus, the first year is not the problem; it is the second, third, and following years. There are sources of problems which can be tapped by professors but are unlikely to be tapped by students. Published case studies such as the

ASEE case studies (see Section 9.1.4) and the American Institute of Chemical Engineers Contest Problem are useful. Industrial interaction can produce interesting problems with the added benefit that the problems are “real” (Emanuel and Worthington, 1987; Sloan, 1982). Ring (1982) suggests that cities can be used as a source of problems. Other possible sources of projects are bicycle design (Klein, 1991) and designs for handicapped people (Hudson and Hudson, 1991). Finally, we would like to suggest that a group of professors from different schools collaborate on developing design problems. Each year a professor from a different school could develop a problem and all the schools would use the problem and grade their own students. The labor of preparing new problems could thus be reduced significantly.

Since design problems are usually team efforts in industry, it is appropriate that they be team efforts in school. How does the professor select the teams? Some professors allow students to pick their own teams. This does not follow industrial practice and tends to result in teams which are very uneven in ability. Emanuel and Worthington (1987) suggest that the professor assign groups and include the following selection criteria:

- Mix leaders and followers within a team.
- Distribute abilities and experience among teams.
- Place one person with initiative on each team.
- Mix foreign students among teams to force communication in English.
- Do not put roommates on the same team.
- Mix men and women in teams.
- Use teams with three members.
- Be sure at least one team member lives close to the campus as this facilitates copying, computer use, and so forth.
- If travel to a company is required, be sure at least one student in each group has a car.

The MBTI (see Chapter 13) has been used for team selection (Emanuel and Worthington, 1989; Sloan, 1982). However, dysfunctional teams can result if team members try to act in accordance with their Myer-Briggs type instead of as is appropriate for the situation (Emanuel and Worthington, 1989). After trying both selection procedures, Emanuel and Worthington (1989) stopped using the MBTI for selection but instead used it to help the groups function better during the semester.

Groups malfunction during the semester for a variety of reasons. Perhaps the most common problem arises when one student does not do a fair share of the work. If the class is to be a learning experience in teamwork, the professor should not ignore these problems. The MBTI can be used as a diagnostic tool to help explain the problems; however, students must not be allowed to use their type as an excuse for behavior. Instead, students should be told that the types show both strengths and weaknesses, and that the weaknesses need to be worked on if they cause group problems. Even without the MBTI the professor should encourage students to discuss group problems, and then he or she should meet with the group to try to find resolutions. Design groups can be considered as a type of cooperative group, and many of the comments in Section 7.2 are appropriate for instruction and management of these groups.

Grading of groups can also be a problem. Since the group is producing a group report, it is appropriate to give the students a group grade. However, students often feel that this is unfair if one student has not done a fair share of the work. This problem can be resolved in several ways. The professor can talk to individual students and then to the group, and if appropriate assign a lower grade to the shirking student (Baasel, 1982). Second, the students can be given a group grade and the group can assign points to each student. Most groups will assign each student an equal number of points, but groups where one student has obviously shirked responsibility will differentiate. However, Eck and Wilhelm (1979) point out that these groups often engage in significant conflict over grade distribution and that some type of arbitration scheme may be necessary. Third, every student can be required to turn in an individual progress report every week (Stern, 1989). From these the instructor can usually make a rational decision on how to partition the final grade (and incidentally can usually predict which groups will turn in good reports). Fourth, all students can be assigned the same grade despite the claims of unfairness. Finally, a formula can be designed for partitioning the grade so that a variety of inputs are included. (Emanuel and Worthington, 1989).

What about important technical content which was either skipped in prerequisite classes or which students did not learn? A significant portion of many design courses covers economics; however, we do not think this time should also be used as a catch-all to reteach other material. Provide the students with resources (perhaps their own textbooks) and have them learn the material on their own. Engineering students can be surprisingly efficient learners when they see the need to learn material in order to complete a design assignment.

A final significant problem in design classes is time—both student and instructor time. Students need to learn how to develop a work plan and how to schedule a design project. In addition, some help in improving efficiency is appropriate. If design is included throughout the curriculum, then efficiency, time management, and scheduling can be discussed every semester. This repetition is helpful in learning how to apply these ideas. The problem with instructor time is that many universities undervalue design classes and overload professors who are teaching these classes. Design classes are time-consuming because of the need to develop problems, consult with student teams, and grade lengthy reports. Providing sufficient resources for design requires an administrative solution, which should include sufficient rewards for professors teaching these courses (Jones, 1991).

9.1.3. Design Projects

The most common way to teach design and to have a "meaningful, major design experience" is with design projects. Students, usually in groups, are given a design problem and told to do the design. Since engineers learn design by designing, this is certainly an appropriate procedure. In addition, people remember the things that they do. We can remember our senior design (and laboratory) projects after twenty-five years, but we don’t remember details of any of the lectures. The projects must be open-ended to be considered design. Multiple solutions of a well-defined problem are optimization, not design (Dekker, 1989).

The amount of guidance students need depends upon their maturity. Freshmen need significant guidance, and a guided design procedure (see Section 9.1.5) should be considered. Seniors need the opportunity to solve significant design problems with little guidance. It is helpful to most students if they have the opportunity to work up to a totally unguided design project by working on increasingly difficult designs with decreasing guidance during their junior and senior years. Design projects can be classified in many ways. Dekker (1989) suggests classifying them on the basis of various dichotomies.

Fun versus serious
Academic versus real world
Paper versus hardware
Creative versus structured
Individual versus group
Disciplinary versus interdisciplinary
Small versus large

Fun projects can include brainstorming a float design for a parade, creating a "Rube Goldberg" design, and so forth. Hardware projects, which mix design and laboratory skills, can be extremely motivating because students can see what they have designed. Dekker (1989) suggests that designing will be creative if students design something which is unknown. For example, have them design a "dollar bill picker-upper." Creative designs can be encouraged by showing students one design for accomplishing a task and then asking them to develop a competing design. This can be made more realistic by giving them the patent and telling them to develop a design which does not infringe on the patent. This procedure also brings up the subject of patents and patent law in a meaningful way. Since many companies use interdisciplinary design teams, an interdisciplinary project is a useful experience. Pierson (1987) discusses administering interdisciplinary design projects. A series of small projects allows for variety, different leaders, multiple grading opportunities, and a gradation in the degree of guidance. Large projects allow for more realistic problems, can be more open-ended, and require much more detailed planning and scheduling. It is useful if students see some of each of these different types of projects during their period in school.

It is obviously desirable to use projects that are real and have input from practicing engineers from industry or government. A variety of ways of obtaining this input are discussed by Bishop and Huey (1988), Griggs and Turano (1990), Harrisberger (1986b), Manning et al. (1988), Pierson (1987), and Sloan (1982), among others. Setting up the appropriate industrial or government contacts can be very time-consuming for a professor. Once the contacts have been made, he or she needs to arrange for sponsors. Companies are much more serious about design projects if they pay for the direct costs (not including labor) of the projects. Requiring payment helps to ensure their continued interest. Projects must be screened since some may be too easy or too difficult for the time allotted. A company engineer needs to be involved in the evaluation of projects, but if many different companies are sponsoring projects, the professor needs to control grades to ensure uniformity in grading. Other additional problems include the need for student travel to and from the client and the occasional lack of cooperation when a company refuses to release necessary information.

Balancing the difficulties in working with companies on design projects are the benefits. The opportunity to work with practicing engineers can give students contacts for future jobs and references. There is no question in their minds that the project is real and relevant. Professionalism is obviously important, and students are more likely to behave as professionals. Finally, successful performance can give students confidence that they can be successful engineers.

Regardless of the type of project, both oral and written reports should be required to stress communication. Weekly progress reports are useful to help prevent procrastination and to pinpoint problem groups. If a company is sponsoring the project, a presentation to the company is in order, but only after a full-scale dress rehearsal in front of the faculty.

9.1.4. Case Studies

A case study is a detailed description of how a professional approaches a problem. A number of engineering case studies are available from the former ASEE Engineering Case Library which is now the Center for Case Studies in Engineering at Rose-Hulman Institute of Technology. In addition, many descriptions of solving tough engineering problems are available in books (e.g., Herring, 1989; Kidder, 1981) and in the trade literature. Patents can also serve as case studies (Whittemore, 1981). Smith and Kardos (1987) and Durbin (1991) give other references. Video-based case studies are being developed (Sullivan and Thuesen, 1991).

Case studies can be used in a variety of ways and are useful in both design and nondesign classes. Professors can assign case studies to students for reports and as the basis for discussion (Henderson et al., 1983). Many case studies consider ethical questions and serve as an excellent basis for discussion. They also help to introduce the engineering profession and serve to motivate some students. This use of case studies is very appropriate in introductory engineering classes to help show students that the material being studied is relevant.

Case studies can be used in design classes, although they are not a substitute for project work since they are less open-ended (students will consider the case study the solution). Instead, case studies should complement projects. They are particularly useful in showing the human aspect of engineering. And they can show the importance of nontechnological factors, such as marketing, in the success of products.

Case studies can also be the basis for instructor-generated projects. In this instance the instructor does not show the students the case study, but obtains project ideas, data, a scenario, and so forth, from the case study. Professors can also have students work through the case study step by step and use it for feedback. This procedure is discussed in the next section.

Case studies are extensively used in law and business schools. Myers (1991) discusses the history of case studies and provides references for applications outside engineering. He notes that Harvard Business School introduced a seminar for professors to teach them to teach with case studies.

9.1.5. Guided Design

Guided design is a structured way of having students work through case studies. This procedure is particularly appropriate for introducing students to open-ended design problems since there is considerable guidance and feedback throughout. The guided design procedure was developed by Charles Wales and his coworkers (e.g., Bailie and Wales, 1975; Stager and Wales, 1972; Wales and Stager, 1973, 1977; Wales et al., 1974a,b; Wales and Nardi, 1982). Guided design was first developed for engineering classes and has since spread to a variety of other disciplines.

The guided design procedure is well summarized by Wales and Nardi (1982). The professor uses printed handouts to guide teams of five to six students through an open-ended problem in "slow motion." After the groups are formed, the guided design procedure starts with a printed handout which explains the problem situation and the student roles. The student groups then define the problem statement and set goals. This is done by a cooperative group discussion (see Section 7.2). After five to twenty minutes the groups receive a printed sheet which tells what the professional engineer did. It is important to stress at this point that this feedback sheet does not represent the solution but shows what one professional did. This point can be made quite clearly if some of the feedback sheets contain actions which are not particularly clever or are ethically dubious. The student groups then discuss the printed feedback sheet and compare their responses to that of the professional engineer. Since it is the design process which is being taught and not a particular answer, the professor must be careful in evaluation.

The guided design procedure then advances step by step through a specific problem-solving or design procedure. For example, the problem-solving strategy in Section 5.3 can be used. Wales and Nardi (1982) recommend the following ten steps:

1 Outline situation
2 Define goals
3 Gather information
4 Suggest possible solutions
5 Establish constraints
6 Choose solution path
7 Analyze factors needed for solution
8 Synthesize solution
9 Evaluate solution
10 Make recommendations.

For each step the students first complete the step and then receive and discuss the feedback. Guided design projects can take from two hours to several weeks. At the end of the guided design students can be required to communicate their results orally and in writing. While the guided design proceeds in class, the students can be assigned readings and homework for outside class. The groups can be encouraged to meet outside class as cooperative learning groups.

Although guided design was first developed as a procedure where all information transfer was in printed form (books and handouts), it can easily be adapted to the laboratory portion of a lecture class (Eck and Wilhelm, 1979). For students who are unfamiliar with working in cooperative groups, it is useful to use the first laboratory period for exercises in interpersonal communication, such as paraphrasing, self-disclosure, maintenance contributions to the group, and an ethics exercise with student observation (Eck and Wilhelm, 1979). After every group exercise it is useful to do some group processing to help students improve their skills.

What does the professor do in guided design? The professor must prepare or select the case studies and put them into a guided design format. Some prepared projects are available (Wales et al., 1974; Wales and Stager, 1973; Eck and Wilhelm, 1979). If a prepared guided design project is not available, then the professor can convert old design projects, convert case studies, or develop new projects in the guided design format. Potential users need to be aware that developing a good guided design project from scratch is very time-consuming.

Wales and Nardi (1982) discuss the development of new guided design projects. First the project must be outlined and divided into labeled steps following the problem-solving or design strategy of choice. A story line and realistic roles must be developed for the students. This step is important since it establishes a need for the project and helps to motivate the students, who must be active in each step. Since learning the process is the important goal, students should gather information only once and have an opportunity to practice the decision-making steps. Students should be asked to make important decisions. Asking them to make trivial decisions reduces the credibility of the entire project.

The form of the written feedback is important. This feedback models what an experienced engineer does to solve the problem. Be sure to write that the engineer would have done the following, not that *you* should have done the following. Since the problems are open-ended, the feedback can serve only as a model of possible actions. The students may tend to resist this at first, and the professor must be careful not to reinforce their beliefs that this is the correct solution. Be sure that the feedback responds to the questions that the students were asked in the instruction.

In a guided design class students must learn the content outside class by reading, discussing in their groups, doing homework, and so forth. In class they learn how to apply this content to open-ended design problems. The professor needs to be sure that the printed learning materials are good. If the textbook is not clear by itself, then additional notes or study guides must be developed. Some class time needs to be available for answering questions, reviewing the homework, making class assignments and so forth.

Once the guided design period starts, you, as the professor, are a guide and coach, not a lecturer. The first challenge is to form groups and to get the groups off to a good start. Group assignments are discussed in Sections 7.2 and 9.1.2. During the project the professor and the TA can circulate among the groups. If a group is functioning well, the professor or the TA can just listen and then briefly provide some positive feedback such as, “This is a great discussion. Keep it up.” Some groups will need help getting started. Ask the group questions about the project or about group processing. If necessary, appoint a leader and a recorder. The behavior of students is often markedly more focused if they have an assigned role. In order to provide proper feedback to the groups, a professor or a TA should be available for every twenty-five to thirty students.

There are a variety of ways to assign group project grades. One approach is to have the groups assign the grade that they think they have earned. If their grade is higher than what you think they have earned, make them redo their project and their report until they have earned the higher grade (Eck and Wilhelm, 1979). This procedure is most appropriate for long projects.

The results reported for guided design have been impressive (Eck and Wilhelm, 1979; Feldhusen, 1972; Stager and Wales, 1972; Wales and Nardi, 1982). The instructor spends much more time with the students on high-level cognitive tasks. And they show better retention, higher grades both in the guided design course and in follow-up courses, increased confidence, and greater motivation. The classes show more cooperation and better group dynamics than other design classes. Students rate guided design classes higher than they do other design classes. However, it is not uncommon to have one or two poor groups which do not function well. The members of these groups do not fully benefit from the guided design experience.

9.1.6. Design Clinics

Actual practice in engineering is obviously beneficial to students. A design clinic is one way of providing an internship activity. Other approaches to providing industrial experience are industrial cooperative programs and summer internships. The following are advantages of the design clinic approach (Harrisberger, 1986a,b):

- Students have a significant industrial experience.
- Students make contacts with practicing engineers.
- Students become confident and more professional.
- The design clinic can fit into the normal course structure.
- Students need no extra time for graduation.
- The design clinic can be controlled by faculty members.
- The design clinic can be self-supporting.

There are models of the design clinic approach at Harvey Mudd College and at the University of Alabama. Our discussion is based on the University of Alabama model (Harrisberger, 1986a,b).

The design clinic assumes that basic technical knowledge has been covered in other courses. In the clinic students first learn a variety of skills and then apply them in a supervised professional practice working on a real industrial problem. Students take a three-credit skills course in the first semester of their senior year which consists of two seminars and one three-hour lab every week. In the seminars the students have lectures, take diagnostic tests such as the Myers-Briggs Type Indicator, make and critique presentations, listen to panels, and so forth. The content is concerned with the practical aspects of engineering instead of technical content. Thus students learn skills for presentation, listening, writing, record keeping, teamwork, leadership, project planning, creative problem solving, design methodology, retrieving and finding information, persuasion, and assertiveness.

The laboratory portion of the skills course consists of group projects in which students have the opportunity to practice the skills covered in the seminars. The laboratory is also used to introduce them to the solution of open-ended design problems. The projects done in the laboratory consist of an ideation exercise, a management simulation game, an extensive guided design project, and an extensive competitive design study. Note that the class starts with significant guidance in solving open-ended problems and then reduces the amount of structure.

During the second semester students take an internship course. Groups of three work on company-sponsored problems. The companies are expected to pay all direct costs, which average less than $1000 per project plus a clinic fee of $350 to cover administrative expenses. The design group visits the company for an initial visit to learn about the problem and for a final written and oral presentation. Other visits may be scheduled if needed. All companies are within a four-hour drive of the campus, and student groups are selected so that at least one member has a car. The companies are expected to provide the necessary information and to have an engineer work with the students as needed.

Every group meets with a faculty coach once a week for twenty minutes. This coaching helps keep the students from procrastinating and keeps them focused on solving the problem on time. Each group presents a midterm progress report in the clinic. A dress rehearsal is presented in front of a faculty jury before the final presentation to the company. All faculty in the department are modestly involved by coaching two design teams, which takes about one hour per week. Administrative details of running a clinic are discussed by Harrisberger (1986b).

Although the design clinic idea has not been widely adopted, it does appear to be a cost-effective way of providing an industrial internship for all engineering students. In addition, design clinics do not require that the faculty have extensive industrial design experience to teach design.

9.2. LABORATORY COURSES

More than any other topic in this book, teaching laboratory courses in engineering is specific to the field of engineering and the type of laboratory. Since we must avoid discipline specificity, this section is an abstract discussion of the most concrete part of engineering education—the laboratory.

9.2.1. Purposes of Laboratory Courses

Laboratory courses can have a variety of different purposes, many of which are explored by ASEE (1986), Eastlake (1986), Jumper (1986), Kersten (1989), and Radovich (1983). Since the laboratory and the course structure depend upon the purposes of the laboratory course, these objectives should be decided upon first. No laboratory can be optimal for all purposes. The goals for the course can include:

Experimental skills. Students can learn a variety of skills involved in doing experimental engineering work. These can include certain psychomotor skills, planning an experiment, recording, analyzing and interpreting data, and using modern measuring instruments.

Real world. Students can learn to function in a real-world environment where the theory may or may not work and the equipment occasionally malfunctions. They can learn to distinguish reality from theory. They can also experience working in a climate of uncertainty and can learn the manifold meanings of Murphy’s law.

Build objects. Students can actually build and test their designs. A sense of craftsmanship can be gained. They can learn to use working models to solve engineering problems (Hills, 1984). Models are used in many industrial settings but are often ignored in the education of engineers.

Discovery. Students can discover results which can improve theory and reinforce their ability to predict the results of using complex devices.

Equipment. Students can work with modern equipment, which adds a concrete aspect to an otherwise abstract education. While working with equipment, students can also learn about the importance of safety.

Motivation. “The theoretical work was difficult—some of it exceedingly so—but the physical *doing* made it seem worthwhile” (Florman, 1987, p. 8).

Teamwork. Many laboratories are team efforts, and students can learn to function as part of a team. This can include an opportunity to be the team leader.

Networking. In addition to teamwork, students may have to find information from a variety of sources including industrial contacts, professors not connected with the laboratory, technicians, and so forth. This is an appropriate experience before accepting their first industrial position.

Communication. Both written and oral communication skills can be emphasized through preparation, progress, and final reports.

Independent learning. Since all the knowledge needed for laboratory classes will not be at their fingertips, students will have to independently review old material and learn new material. This can help prepare them for the real world where independent learning is important.

We have not tried to be encyclopedic, and there are obviously other purposes for laboratory courses.

9.2.2. Laboratory Structure

The structure of the laboratory should depend upon the major purposes of the course. It can range along a continuum from a totally structured, cookbook-type approach to a partially guided experience to an unstructured class (Alexander et al., 1978). A cookbook approach can be satisfactory if the purpose is to develop psychomotor skills and the ability to use measuring instruments. These purposes have become less important as easy-to-use digital instruments have replaced analog instruments which often required considerable expertise. However, learning to use instruments or tools is still a legitimate purpose for a laboratory course. A cookbook approach may be used when the purpose is to reinforce theory. Unfortunately, this does not tend to be extremely convincing, and a discovery approach is more effective.

In an unstructured laboratory students are given fairly general instructions or goals. For example, the goal may be to design and build a new logic circuit, to survey a new subdivision, or to scale up a chemical process. The students must decide what needs to be done and how best to do it. An unstructured laboratory might ask students to explore a phenomenon such as the effect of pH and temperature on a biochemical reaction. No other directions are given. Unstructured laboratories are certainly appropriate for seniors who are mature enough to handle the uncertainty and who need the experience in planning and decision making before graduation.

Lower-division students may be lost in an unstructured laboratory. A partially guided experience is appropriate. A student is given some guidance in setting up the experiment and told what to do first. For later parts of the experiment much of the detail is left to the student. For example, a student can be told to look at the effect of several temperatures in a given range but not be told how many or which temperatures to use. In addition, the student would not be told what to expect although he or she might be told to predict the behavior.

Laboratory experiments appear to be most effective when the solution is not known ahead of time (Jumper, 1986). Measuring an orifice coefficient when fifty other students have already done so is not the stuff of a marker event. As a professor you need to be creative. Assume, for example, that the method of measuring an orifice coefficient is important in a fluids laboratory. The method will be learned much better if the student is given a noncircular hole as the orifice. Where does one look up the orifice coefficient for ellipses, rectangles, parallelepipeds, and triangles? What about five- or six-pointed stars and quarter moons? By varying the dimensions and the shapes, each student group can do a unique experiment, and the groups will not be able to dry-lab the results. In addition, this sort of “research” can eventually result in a technical note. Being the coauthor of a technical note or presentation (even if it is in a student magazine or at a student convention) will make the laboratory a marker event for the students. If time is available, this type of laboratory experiment can be made even more useful by asking students to predict the behavior of their orifice ahead of time.

Laboratory classes can be structured to reinforce lectures not with cookbook exercises but with the scientific learning cycle (see Section 15.1.) Do the laboratory work before the topic is covered in lecture and have the students explore the phenomenon. Let them discover many of the characteristics of the device. For instance, in the orifice example the students can determine the general form of the equation relating velocity to pressure drop. Then in lecture the theoretical development will be much more believable and would already have been partially verified. The students will be more likely to appreciate the power of theory to include additional terms without needing additional experimentation. The lecture would be the term introduction step in Figure 15-1. For concept application students can use their data to determine the orifice coefficient and solve additional problems.

Design laboratories are often unstructured. Students may be asked to design a large-scale apparatus. The purpose of the laboratory is to determine certain coefficients or efficiencies needed for the design. The students must determine what must be measured and must allocate their time between laboratory experimentation and design calculations. A design laboratory can also be used to design, build, and then test something. Hills (1984) suggests having students design and build simple working models, while Balmer (1988) believes that they should solve real industrial problems and test their solutions in the laboratory. Williams (1991) requires students to design and then build microcomputer boards. Many electrical and mechanical engineering problems can fit into these types of design laboratories.

9.2.3. Nitty-Gritty Details

A number of decisions must be made in any laboratory course. Should the laboratory be part of a lecture course or should it be a stand-alone course? Both arrangements have their advantages. If the purpose of the laboratory is to reinforce the theory and allow students to discover results, then a laboratory attached to a theoretical course makes sense. Scheduling is easier, and the connection between experiments and theory will be more obvious to the students. If the purpose of the laboratory is to synthesize several theory courses and have students design or build something, then a stand-alone course with appropriate prerequisites makes sense. In either case, the laboratory workload should be congruent with the credit granted (Radovich, 1983). If students are supposed to be able to finish laboratory experiments and reports in the laboratory, then it needs to be structured so that at least the better groups can do this.

Should students work individually or in teams? Although there are a number of reasons why teamwork is beneficial to students, the decision may be made on the basis of availability of apparatus. Equipment availability often determines team size, but most schools seem to have settled on two students for bench scale equipment, and three or four students per group for larger equipment. If teams are used, how should they be selected? This question is discussed in detail in Section 9.1.2. It is better to make a rational choice than just to continue what has been done for many years.

Students should be required to plan their experiments in advance. Many laboratory courses require students to pass an oral readiness quiz before they can go into the laboratory. This is a good safety precaution which encourages students to think before experimenting. In a design laboratory with projects lasting four weeks, we found it useful not to allow students to collect any experimental data during the first class. This time was spent in planning.

What types of records should students keep, and how should they report their results? Laboratory notebooks are commonly used in industry to support possible future patent claims. Experience in keeping a neat laboratory notebook which follows industrial practice is appropriate in an engineering laboratory (McCormack et al., 1990). Since communication is often an important goal of the laboratory (and all too often of *only* the laboratory), both oral and written reports are often required. The best feedback for oral reports can be provided by videotaping student presentations and having them watch their tapes (see Section 8.1.3). For written reports the most improvement in writing will occur if students receive prompt feedback and then rewrite the report for a grade. This obviously requires proper scheduling of the laboratory session and diligence on the part of the instructor.

The quality of the equipment in the laboratory is a never-ending problem (ASEE, 1986), and obsolete equipment and poor maintenance are often problems when programs are accredited. We do not see any substitute for modern instrumentation. Components such as resistors and transistors and major pieces of equipment such as nuclear reactors, distillation columns, or jigs do not have to be new, but the analytical instrumentation does. Mechanical balances, for example, are now obsolete and should be retired. If the purpose is discovery, much of the equipment can be simple and homemade. If the purpose is to familiarize the student with industrial equipment, then it is better to use commercial equipment. There is no substitute for a planned and funded maintenance and equipment replacement program. Safety should be a primary concern when equipment is repaired and when new equipment is purchased. Safety needs to be stressed with undergraduates (and with TAs). Stern measures are taken in industry when workers fail to follow safety rules, and stern measures should be taken with students who do not follow safety rules.

Teaching assistants may try to avoid laboratory assignments because they are often more work than the grading of papers in other courses. The department needs to be sure that the workloads for all TA assignments are appropriate and roughly equal. Laboratory TAs usually have significant contact with the students; thus, they should be able to communicate well. TAs often need to be trained, and a convenient time to do this is the week before classes start.

Group grading needs to be carefully considered. It is appropriate in laboratory courses to foster both interdependence and individual responsibility (see Section 7.2.2). Each student's grade should be partly based on the team effort and partly on the individual effort. Groups should be encouraged to make the laboratory a group effort, not merely a leader with two drudges. Professors and TAs should make a regular practice of circulating through the laboratory and observing the groups at work. After a few weeks of casual observation, it is usually clear who the malingerers are. This regular observation and a perusal of laboratory notebooks also help to discourage dry-labbing. Students can also be asked to assign part of the grade to the other students on their team. This procedure can work, but abuses can occur.

9.2.4. Advantages and Disadvantages of Laboratory Courses

From the student's point of view, laboratory work can provide a concrete learning experience where principles can be discovered. The chance to design and possibly build equipment can serve as a marker event in the student's undergraduate career, and friendships developed in laboratory teams may last for years. In addition, a student may get to know his or her laboratory instructors better than any other professors, and the student will rely on the laboratory professor for advice and letters of recommendation.

Of course, everything is not always this ideal, and there can be disadvantages. The laboratory may be an incredible time sink as an overzealous professor tries to have the students learn everything about engineering in one course. The equipment may not work or may be obsolete. Files may be readily available, and drylabbing of cookbook experiments may be rampant. A student's group may malfunction, leaving him or her with all the work and only one-third of the rewards. The professor may be absent, and the TAs may not speak English. Other than tradition, the reason for a laboratory course may be unclear.

The professor, whose task is to make the reality closer to the ideal, can have significant student contact and a chance to make a real difference in students' careers. Design laboratories often require a synthesis of the material from several courses. This helps the professor stay current in areas other than his or her research specialty. Working with real equipment can also help the professor be a better teacher of theoretical concepts.

Grading can be a chore when a number of long reports are turned in. It helps to have someone trained in English available to grade the communication aspects of the reports and to work with students on their communication skills. This reduces the burden on the engineering professors and provides the students with better instruction. Unfortunately, the workload is often heavier in laboratories than in other courses, and less credit may be given for teaching laboratory courses. This unfair workload has been criticized by ASEE (1986).

From the departmental point of view excellent laboratories are a source of pride. If you don't believe this, visit a department with an excellent undergraduate laboratory and note the attitude of the professor who guides you through the laboratory. Excellent laboratories also help produce well-prepared engineering graduates. And excellent laboratories are an advantage at accreditation time. Of course, the department gets what it pays for. Excellent laboratories require money for equipment, maintenance, a technician, and dedicated professors, who will remain dedicated only if suitably rewarded. Departments which use the laboratory as a way to save money when the budget is tight will pay the price of less-than-excellent laboratories fairly quickly.

9.3. CHAPTER COMMENTS

It should be clear that we believe that design and laboratory classes are important. We also believe that there are a variety of nontechnical skills which are critical for the successful practice of engineering. These include communication skills, management skills, and interpersonal skills. More engineers are removed from positions because of a deficiency in these skills than because of a lack of technical ability. Design and laboratory courses provide an opportunity for teaching these skills. Students learn by doing. However, the doing is more effective for learning if it is initially guided and supervised. Thus, we have included teaching procedures which specifically guide the student and provide feedback.

We enjoy teaching laboratory courses. The extra student contact makes up for the burden of grading laboratory reports. In addition, our school has done an adequate job of financing the laboratory and rewarding the participation of professors. Since we enjoy teaching laboratory classes, most students don't mind taking them from us.

9.4. SUMMARY AND OBJECTIVES

After reading this chapter, you should be able to:

• Discuss what design and laboratory work add to the education of engineers. Discuss the problems inherent in teaching design and laboratory courses.

• Develop a plan to incorporate design throughout the undergraduate engineering curriculum.

• Compare and contrast the different ways to teach design. Highlight the advantages and disadvantages of each method.

• Describe how you would select groups for a design project or laboratory experiment. Justify your method.

• Explain the appropriate laboratory structure for students at different levels.

HOMEWORK

1 Determine what roles design and laboratory classes play in the curriculum at your school. Do they meet the spirit of the ABET requirements? If not, what can be done to improve them? Or, why do you think the ABET requirements are irrelevant?

2 Develop a plan to include design throughout the engineering curriculum at your school.

3 Choose one of the methods of teaching design. Outline how to incorporate this method into one of the design courses at your school. Explain how this method would help students achieve the course objectives.

4 Assume one of the design groups in your class is not functioning well. Develop an intervention strategy to help get this group back to healthy functioning.

5 Select appropriate objectives for a laboratory course at your school. Outline a structure to help students meet these objectives.

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