B. HYMAN - FUNDAMENTALS OF ENGR. DESIGN

They also recall their experience with science based problems that require combining mathematical manipulations with applications of scientific principles. For example, correct application of the gas laws is needed to solve the following problem:

> A balloon is filled with 1200 ml of $H_2$ at a pressure of 740 mm of Hg and a temperature of 30°C. The balloon is allowed to ascend 1 mile, where the pressure is 640 mm of Hg and the temperature 7°C. Calculate the volume of the balloon at a height of 1 mile.

This perception that engineering is only "applied science and mathematics" is reinforced by traditional engineering curricula, which emphasize science and mathematics courses during the first two years and specialized applications of science and mathematics in what are typically called "engineering science" courses.[1] This emphasis continues in many upper division engineering courses. Whatever the particular field of mathematics or science used in these types of problems, they tend to have four features in common.

First, the problems are well-posed in a very compact form. By well-posed we mean that the statement of the problem is complete, unambiguous, and free from internal contradictions. If it didn't have these features, the students would complain vigorously and the teacher would apologize profusely for presenting a poorly stated problem.

Second, the solutions to each problem are unique and compact. There generally is a single correct answer available, that is, a number, a set of numbers, or symbols. In fact, many textbooks publish the answers to the odd-numbered problems in the back of the book.

Third, these problems have a readily identifiable closure. It is easy to recognize when the answer has been obtained (not necessarily the correct one).

Fourth, these problems require application of very specialized areas of knowledge and there is little doubt what the subject is for each problem. Clearly a problem at the end of Chapter 4 in the calculus book is going to require application of the concepts addressed in that chapter. Some end-of-chapter problem sets are even coded so that the student knows which section of the chapter to focus on. A problem in Chapter 4 is not going to require you to apply the material covered in Chapter 7. And you can bet that a problem in your calculus book is not going to require knowledge of physics to get the solution.

Solving problems that have some or all of these four characteristics is an important part of engineering education. It develops and strengthens specific analytical skills that are essential in most engineering design situations. However, most real-world engineering design problems do not share these characteristics. In particular, many real engineering design problems are poorly posed, do not have a unique solution or a readily identifiable closure, and almost always will require integration of knowledge from several subject areas. Students who have mastered the skills of solving traditional mathematics and science problems but have not had prior exposure to design may find it difficult to adjust to this less precisely defined world of real engineering design problems. Much of our emphasis in the remainder of this chapter and in several subsequent chapters of this book is on appreciating the less-precise nature of engineering design and on developing and utilizing new skills for being a successful design engineer.

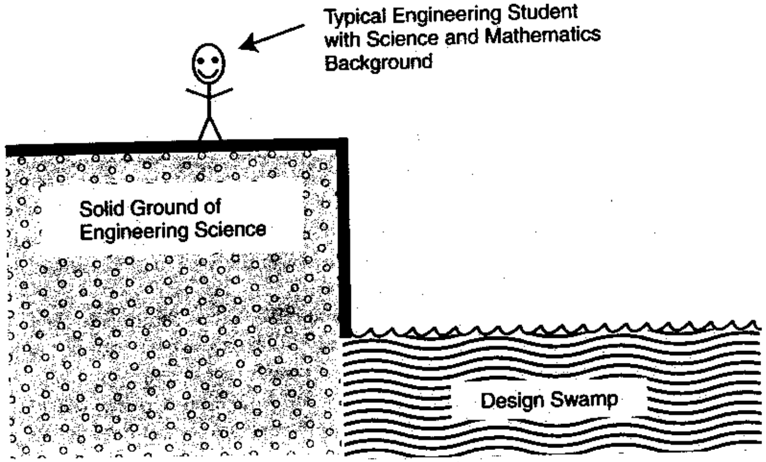

**Figure 1–1.** Contemplating Engineering Design

## 1.3. MOVING FROM THE CLIFF TO THE SWAMP

Professor Donald A. Schön from MIT uses a graphic notion to highlight the difference between solving traditional science and mathematics problems and what is required to address real engineering design problems.[2] He compares the world of traditional mathematics and science problem solving to standing on a rock-solid surface at the top of a cliff. The firm foundation provided by the unambiguous and never changing laws of science and rules of mathematics is a comfortable place for most students about to embark on an engineering curriculum. In contrast, the world of engineering design involves many uncertainties, ambiguities, and inconsistencies. Professor Schön compares this world to a swamp at the base of the cliff (see Fig. 1–1). It is very difficult to get a firm footing in the swamp, and a completely different set of survival skills are needed.

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[1] Engineering science courses deal with applications of scientific principles and mathematical concepts for analyzing a wide variety of engineering problems such as: motion of objects, current in electric circuits, deflection of beams, temperature in fluids, and efficiency of engines.

[2] Schön, p. 42.

Because subjective considerations tend to be much more prevalent down in the swamp of engineering design as compared to the objective nature of analytical life up on the cliff, the relationship of the engineering design instructor to engineering students is fundamentally different.

The mathematics, science, or engineering science instructor is an expert in their field, and education consists of a one-way transfer of some of that expertise to the student. While there are many modes for facilitating that transfer (lectures, interactive problem solving, discussion sessions, textbooks) the dominant direction is that the instructor transmits, and the student receives, objective information. The instructor presumably knows the answers, and with luck by the end of the course the student will have learned enough of the right answers.

But since design is much more subjective, there rarely is a single "correct" answer. Judgments as to whether one design alternative is superior to another may be highly dependent on the values and preferences of the evaluator. The design instructor is not so much a transmitter of facts, but a facilitator of the design process and a partner with the students in searching for successful solutions of design problems (see Fig. 1–2).

The design instructor is less like a basketball referee who determines whether the actions are consistent with the rules and more like a fishing guide whose experience can make a fishing trip more enjoyable and productive. The guide can point out the logs and boulders that are scattered throughout the swamp, and provide you with a pair of hip boots to make your journey more pleasant. Studying design will help ease entry into the swamp and make your experience not only survivable but enjoyable (see Fig. 1–3). It won't remove the subjective considerations and uncertainties associated with design problems, but it will help you adapt to this new environment and function effectively in it.

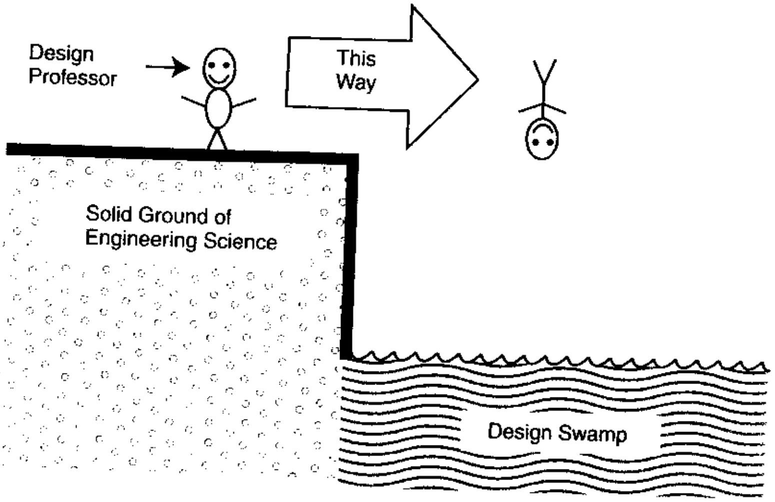

**Figure 1–2.** Guidance Provided by Engineering Design Instructor

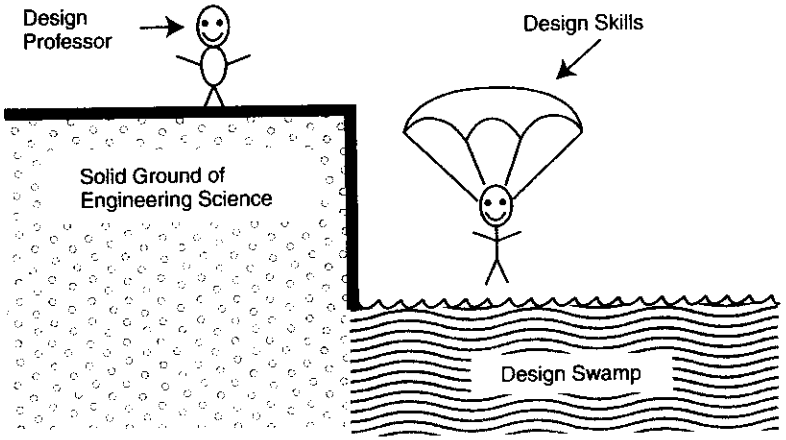

**Figure 1–3.** Benefits of Understanding Engineering Design

## 1.4. DEFINITION OF ENGINEERING DESIGN

### Solving Real Everyday Problems

Engineering design is a more advanced version of a problem solving technique that many people use routinely. The general procedure for solving real everyday problems is straightforward: A problem is encountered, information about the problem is obtained, alternate solutions are formulated, and the best alternative is adopted. Some problems are so straightforward and solutions so obvious that people solve those problems without being consciously aware of the specific steps in the process. For example, a serious problem confronts a child whose pants get caught in his/her bicycle chain. Three ways in which the child may resolve this dilemma are: rolling up the pants cuff, installing a chain guard, or securing the pants with a rubber band. The approach a child uses depends on many factors, including his or her familiarity with the bike, available materials, experience with the problem, and creativity. What works best for Johnny may not work best for Susie. What works best today may not work best six months from now. Whatever the solution, the child progresses through a design process without hesitation. When the problem is more complex (as most engineering problems are), an organized and methodical approach is needed.

Engineering design is a methodical approach to solving a particular class of large and complex problems. How can we distinguish engineering design from other kinds of problem solving activities and from other kinds of design? A few moments of reflection on how to answer this question should make you aware that you are already in the swamp! There is no single correct answer to this question—there is no universally agreed upon definition of engineering design. However, we should not let this situation paralyze us into inaction. Let us select one reasonable definition in order to get moving (if you remain stationary in the swamp, you will surely drown).

### ABET Definition of Design

For the subsequent discussion, let us use the definition of engineering design adopted by the Accreditation Board for Engineering and Technology (ABET). ABET is the organization that evaluates and accredits engineering curricula in the United States. Since many U.S. firms and government agencies will only hire engineers who graduate from ABET-accredited schools, and since many U.S. graduate engineering programs will only admit students from ABET-accredited undergraduate programs, ABET has an enormous influence on engineering education in the U.S. Equivalent certification and quality control entities play similar roles in other countries. Therefore, the ABET definition of engineering design is an appropriate starting place for our discussion. ABET defines engineering design as follows:[3]

> Engineering design is the process of devising a system, component, or process to meet desired needs.[4] It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.
>
> The engineering design component of a curriculum must include at least some of 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 essential to include a variety of realistic constraints such as economic factors, safety, reliability, aesthetics, ethics, and social impact.

Note that engineering design is not a single isolated action, but a "process" (we will examine the nature of this process in detail in Sec. 1.5). ABET identifies the goal of engineering design as, ". . . devising a system, component, or process to meet desired needs." Note also that the result of design might not be a physical piece of hardware; it can be a process. This latter kind of design is of particular interest to chemical engineers, materials engineers, industrial engineers, and computer software engineers.[5] The ABET

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[3] ABET, p. 7.

[4] ABET uses the word 'process' in two different ways in this sentence: first, to describe the ongoing design activity; and second, to describe a particular type of outcome or product of the design effort. The intended meaning should be clear from the sentence context.

[5] For example, a chemical engineer might be faced with the design problem of selecting the temperature and pressure at which two chemicals are to be mixed in order for the chemical reaction to proceed in the desired manner. As another example, an industrial engineer may be asked to design the order in which the components of a system should be assembled so that the assembly costs are minimized.

definition also hints at some of the analytical tools engineers use in their design activities; "basic sciences, mathematics, and engineering sciences." Finally, the ABET definition identifies some elements of the design process; "the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation." As a whole, the ABET definition serves as a guide from which to start. The ABET definition gives the design engineer the freedom and responsibility to determine what is appropriate and necessary to create a design and solve a problem. There are no absolute rules for what to do, when to do it, or how to do it; only experience and blurred, soft, marshy "rules of thumb." Engineering design is a swamp.

### The Centrality of Design

In spite of the difficulties we encounter when trying to reduce the complexities of engineering design to simple, universally agreed upon definitions and models, the centrality of design to the engineering profession is unchallenged. Design is the culmination of all engineering activities, embodying engineering analysis and other engineering activities as tools to achieve design objectives.

## 1.5. A MODEL OF THE ENGINEERING DESIGN PROCESS

Just as the ABET statement is only one of many definitions of engineering design, there are many approaches to describing how design is done. Some of these descriptions have been formalized into simplified step-by-step "models" of the design process. While no one model is universally accepted by the engineering community, it is helpful to organize our discussion using one model. In doing so, we recognize that there are many other approaches that are just as useful.

In this section we briefly outline a nine-step model of the engineering design process. Before discussing each of the nine steps in this model, a few general comments are in order. First, it is important to recognize that any model is a simplified description of a more complicated reality. The value of a model lies in its ability to help us organize our thoughts and gain insight into important aspects of reality. So keep in mind while we discuss these nine steps that actual designs do not necessarily evolve in a linear, orderly progression from step one through step nine. Not every step will be used to the same extent in every design, and some steps may be performed out of order.

We defer more detailed discussion of each step to later sections in the book. In fact, some of the steps are the topics of entire chapters. The nine steps and the parts of the book in which they are further elaborated are summarized in Table 1–1. The fact that the sequence of topics presented in the book doesn't match up exactly with the nine steps in our design process model reinforces the non-sequential nature of the model.

Many engineering designs are performed by teams of engineers and not every team member participates in every step of the process. Some team members may be specialists in one or more of the nine steps. In many situations, design engineers unconsciously blend some of these steps together. Also, each step may be revisited sev-

**TABLE 1-1.** RELATION BETWEEN DESIGN PROCESS MODEL AND ORGANIZATION OF THIS BOOK

| Steps in Design Process Model | Location of Detailed Discussion |
|---|---|
| 1. Recognizing the need | Chapter 2: Problem Formulation |
| 2. Defining the problem | Chapter 2: Problem Formulation |
| 3. Planning the project | Chapter 7: Project Planning |
| 4. Gathering information | Chapter 3: Information and Communication |
| 5. Conceptualizing alternative approaches | Chapter 6: Concept Generation |
| 6. Evaluating the alternatives | Chapter 8: Engineering Economics |
| 7. Selecting the preferred alternative | Chapter 9: Decision Making |
| 8. Communicating the design | Chapter 3: Information and Communication |
| 9. Implementing the preferred design | Section 1.7: Life Cycle of Engineering Designs |

eral times during the evolution of a design. However, even experienced engineers will regularly step back from their immersion in design details and rely on such a model to assure themselves that they haven't overlooked key elements in their search for a design solution. The map of the design swamp shown in Figure 1–4 depicts the relationships among the nine steps.

Note the absence of a "STOP" activity in the Design Swamp. Does the design process continue without end? Possibly. It continues as long as the need continues, and it ends only when the cost of continuing the design process exceeds the value of an improved design. The decision to stop the design process is difficult and requires careful thought. It may be made by the engineer or the client, or it may be a result of a schedule constraint. This is what we mean when we say design is an open-ended process; there frequently is no readily identifiable closure point.

The automobile, for example, is a solution to the need for transportation, and automobile design has evolved continuously since its invention. From a longer range perspective, automobiles evolved from horse drawn wagons or from ancient push carts. In any case, automobile design continues to evolve because no automobile is perfect and because the needs themselves change. Even the best-selling automobiles are redesigned regularly because a need exists for new or different features such as pollution control equipment, airbags, and anti-lock brakes.

### Step 1: Recognizing the Need

The first step in the design process establishes the ultimate purpose of the project via a general statement of the client's dissatisfaction with a current situation. Consider the hypothetical conversation between Jane, a design engineer for an automotive engineering company, and Sandra, her immediate supervisor.

| | |
|---|---|
| Sandra: | "Jane, we need you to design a stronger bumper for our new passenger car." |
| Jane: | "Why do we need a stronger bumper?" |

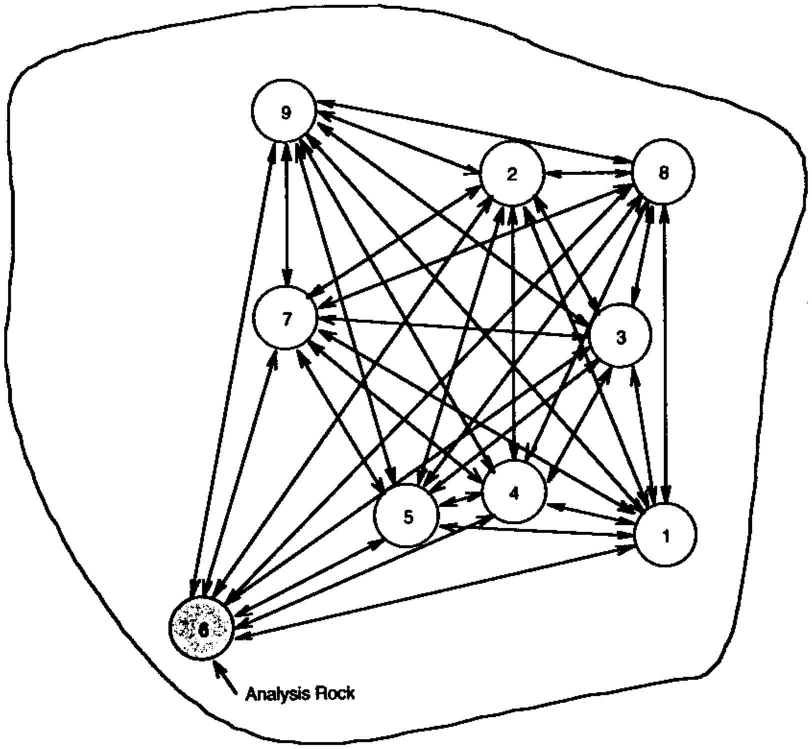

Figure 1–4. A Map of the Design Swamp

| | |
|---|---|
| Sandra: | "Well, our current bumper gets easily damaged in low-speed collisions, such as those that occur in parking lots." |
| Jane: | "Well, a stronger bumper may be the way to go, but there may be better approaches. For example, what about a more flexible bumper that absorbs the impact but then returns to its original shape?" |
| Sandra: | "I never thought of that. I guess I was jumping to conclusions. Let's restate the need as 'there is too much damage to bumpers in low-speed collisions.' That should give you more flexibility in exploring alternative design approaches." |

- Notice that Sandra's revised needs statement is more general than her initial one, focuses on what is unsatisfactory with the present situation, and is silent in terms of the design approach to use. See Chapter 2 for a more detailed discussion of this topic.