TOOLS AND TACTICS OF DESIGN

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The Coalition has had focus themes to address a broad range of issues pertaining to the educational process. These include curriculum innovation in structure and content; professional development for students and faculty; instructional technologies; programs to enhance continued participation of populations traditionally underrepresented in engineering; linking and sharing across traditional boundaries among departments, colleges, and institutions; and an assessment and feedback program to ascertain the effectiveness and continual improvement of these programs. Design, as a motivator, facilitator, as well as an area of study, has had an important impact on many of the focus themes of the Gateway program. It has its impact, of course, in the curricular aspect directly. In addition, however, design has become a vehicle to address the issues of professional development, communication skills development, leadership skills development, and teaming, not only among long time colleagues but also colleagues across institutions. Design also supports a better understanding of different institutional and individual cultures. Thus, design has become an important player in developing the technical, scientific, professional, and personal attributes of our emerging engineering professionals. This text, *Tools and Tactics of Design*, highlights those multiple facets of the engineering educational process.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO ENGINEERING DESIGN—THE ART OF DESIGN

Imagine life without the following few selected contemporary items: Cellular phones and the network of cells for transmitting sound, electric toothbrushes and the method for getting toothpaste into a tube, portable CD players and the procedures for making CDs, disposable cameras and the chemical process for developing film, modern mountain bikes and bicycle trails, plastic soft drink bottles and their carbonated contents, space stations and the life support systems enabling them to be built. Each of these products, processes, and systems represents major design advancements of the recent past. All were developed by modern design theory where the objective is to bring products to market or create a process that is high in quality, reliable, competitive in terms of cost, and available in a timely fashion.

Design is exciting because you are creating things that did not exist before. In fact, virtually everything not created by nature is designed. Clothes are designed. Artwork is designed. New buildings are designed. Road systems are designed. What does this mean and where does engineering fit in?

In essence engineers are designers. They figure out ways to provide the things that are needed or wanted. They do this by inventing or designing something that was never there before. Many say that the process of designing is what distinguishes the profession of engineering from pure science. In this book and in your engineering courses, you will learn about the engineering design process and how to apply it.

A product or process can be initially designed or initially invented and meet the basic need or desire of the customers. Through additional design (often called development), the product or process can be improved—made cheaper, easier to use, more comfortable, more reliable, and of higher quality. For instance, the first iterations of a new invention or model may include very basic components with a focus being on just getting the design to work. When you add analysis to the design process, optimum levels of power, comfort, shape, size, and functionality may be added. Your engineering design contribution brings a quantitative perspective to the creation of new things to enhance the creative or qualitative perspective.

Individual inventors and designers are remembered for their creations but those individually created items and the individuals tend to be from a past era. We think of Henry Ford, Alexander Graham Bell, and Thomas Edison when we think of the car, the telephone, and the electric light bulb. In the old days, the term inventor implied one person working alone (Figure 1-1). In reality, however, even these three "rugged individualists" recognized the importance of collaborative efforts. In particular, Thomas

Henry Ford
Transmission Mechanism
Patent No. 1,005,186

Alexander Graham Bell
Telegraphy
Patent No. 174,465

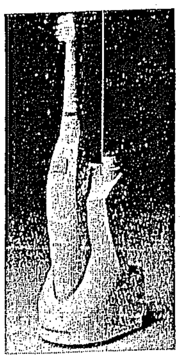
Thomas Alva Edison
Electric Lamp
Patent No. 223,898

FIGURE 1.1 Early individual inventors and their products of the past. [(left): Underwood & Underwood/CORBIS. (center): ©CORBIS. (right): Courtesy Edison Natural History Society.]

Edison is considered by many historians to be responsible for institutionalizing the process of research, development, and invention by teams.

If engineering design ever was a solitary endeavor it certainly is not today. Most new products, systems, and processes are produced by teams. This means that each engineer must be able to work with other engineers, scientists, business managers, communications experts, and industrial designers. As the examples in Figures 1.2 and 1.3 imply, being a engineer in the 21st century also means being part of a team.

Patent Number: 5,613,259

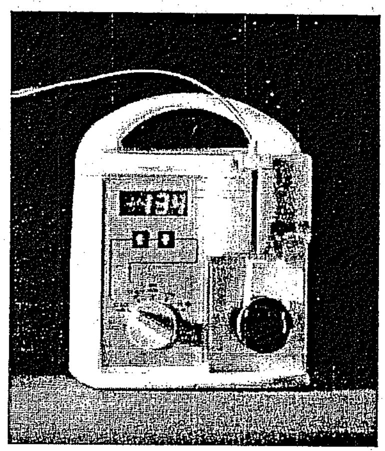


This electronic toothbrush was designed by a cross-functional and colocated product development team, consisting of engineers and scientists with backgrounds in mechanical and electrical design, polymers, magnetics, dynamics, and manufacturing. The design team scrapped the use of a traditional motor that relies on gears or pistons to drive the bristles in favor of a more efficient motor called a resonant mechanical oscillator. This new motor delivered more energy to the end of the toothbrush, resulting in better plaque removal. The product debuted just 13 months after the project began.

Inventors: *Craft; Adam B.* (Fort Collins, CO); *Schleiffer; Keith E.* (Gahanna, OH); *Dvorsky; James E.* (Hilliard, OH); *Graves; Thomas W.* (Fort Collins, CO); *Gray, III; Ronald.* (Columbus, OH); *Senapati; Nagabhusan* (Worthington, OH); *Zelinski; Matthew S.* (Worthington, OH)

FIGURE 1.2 An electronic toothbrush developed by a design team. (Courtesy Battele Memorial Institute.)

This enteral feeding pump was also designed by a cross-functional and colocated product development team in Ohio, consisting of engineers and scientists with backgrounds in mechanical and electrical design, industrial design, polymers, software, and manufacturing. An enteral feeding pump is a device for providing nutrition to people who cannot or will not consume food orally. The design team developed a pump that met a stringent unit manufacturing cost with improved technical features that was easier to use and to maintain.



Patent Number: 5,807,333

Ohio Project Team (*from left to right*): *Clark Fortney, W. Fred Lyon, Cathy Alexander, Grant Wilson, Patina Ripkey, Bill Patton, Doug Vrona, Matt Fleming, Joe Juratovac,* and *Dennis Hoffman*

FIGURE 1.3 An enteral feeding pump developed by a design team. (Courtesy Battele Memorial Institute.)

This book addresses the engineering design process, how to manage the design process in an academic environment, and how to work effectively in a design project team. Good ideas, precise analysis, and good quality control must be communicated effectively among the team members and the sponsors if the design process is to be executed optimally.

The next part of this chapter introduces the organization of this text and describes our approach to explaining design. The third part highlights additional characteristics of the design process and defines some terms with which you should be familiar.

1.2 ORGANIZATION OF THIS DESIGN TEXT

If you are using this text for the first time, you are most likely embarking on some kind of introductory design experience. Along the way, you will be learning first-hand what the art and science of engineering design is all about. This text will assist you as you grapple with the engineering design process and the skills it requires. Those who have some prior design experience may want to use portions of the text more selectively, but there is something of value to improve the engineering design process for everyone here.

As you read this text, you will find different design projects that are used as examples. These include a freshman robot design project and a robotic arm attached to wheelchairs as an assistive feeding device. The robot design project is done by first-year students at Ohio State University and by second- and third-year students at MIT. The robotic arm project has been done by seniors in a collaboration that includes Cooper Union, Drexel University, New Jersey Institute of Technology, and Ohio State. Work on such projects is performed by a team of faculty, research engineers, and graduate and undergraduate students. In addition, there will be one continuing project, the redesign of a dorm room that allows you and your teammates to try out the elements of the design process.

1.2.1 Intersection of Phases and Steps with Skills and Activities

As you read about them, you will see that each of the design projects mentioned above has unique characteristics. On the other hand you should also recognize that regardless of what is being designed, there are common features in the design process. For instance, all design efforts are about systematic problem solving. They are all cyclical and iterative, and they all have a finite beginning and end. There are also some fundamental skills that all designers must develop regardless of what they are designing.

This is not to say that all design is identical across all engineering disciplines. For instance, civil engineering design for construction is different from that of a mechanical engineer engaged in product design. For the civil engineer, there is usually a request for project bids with a set of project specifications. The civil engineer or engineering firm estimates what the engineering design work will cost and submits the bid to a contracting agency. If the bid is accepted, the agency writes a contract with the engineer or engineering firm. Once the contract has been duly signed and witnessed, the actual engineering design work is done. The individual or firm provides a set of drawings and written specifications for the project to the contracting agency. If no changes are required, the agency requests bids for the actual construction work from a construction company. The engineer or engineering firm usually provides engineering oversight for the project and updates the design drawings and details. The contracting agency gets a series of "as-built" drawings that document what was actually constructed.

In contrast, the chemical engineer is usually engaged in designing a process to produce chemicals, petroleum products, food items, and other commercial materials. This requires testing all the process components and may require building a pilot plant to see if the process really works. If it does, then a full-scale plant is constructed. Again, the chemical engineers who did the design may supervise construction and do the testing of the completed plant.

In dealing with product design, design for construction, and process design, there are clearly differences in terms of technical and scientific skills required to do

one instead of the other. These distinctions are important, and you will learn more about them during your engineering education.

Our focus here is on those aspects of engineering design that are common across all engineering disciplines. Specifically, our approach to supporting your design efforts intersects two related ways of thinking about the design process. First, all design processes consist of several iterative phases. We have defined these phases as defining the problem, formulating solutions, developing models and prototypes, and presenting the design.

In addition to thinking about the phases in the design process, it is equally important to understand that *you* are the agent who makes design happen. In other words, another way of thinking about the process of design would be in terms of *your* thoughts and *your* actions. Therefore, design can be characterized by your behavior in relation to four broad skill areas: decision making, project management, communication, and collaboration.

1.2.2 Phases and Steps of the Design Process

We have chosen to break the design process into four phases because they best reflect the design steps that most students encounter in introductory design courses. As you review our definitions for these phases, keep in mind that all design processes have a beginning and an end but in between the process is iterative. To some extent, you will be constantly defining and redefining problems, formulating and reformulating solutions, and building and revising your design concepts as you work your way through the experience of the engineering design process. The boxes in Figure 1.4 provide a more detailed picture of each phase of the design process. The lines with arrows connecting these boxes provide an indication of how the design process is iterative.

Phase One: Defining the Problem Defining the problem means clearly exploring and articulating the nature of the problem to be solved. This is the first and often the most difficult part of the design process. You will learn that an engineer's definition of a problem must reconcile two opposite tendencies. On the one hand, the problem must be fully clarified and articulated in terms that are as definite as possible. On the other hand, the definition must remain open-ended enough so that it does not preclude consideration of all feasible solutions. The kinds of questions you must consider when defining a problem include the following:

- What requirements must our design meet?
- What solutions to the problem currently exist?
- What are the constraints to these solutions (technical, economic, social, political, environmental, etc.)?

Moreover, you will learn that you must define your problem in clear and succinct terms that can be understood not just by other engineers but also by those who

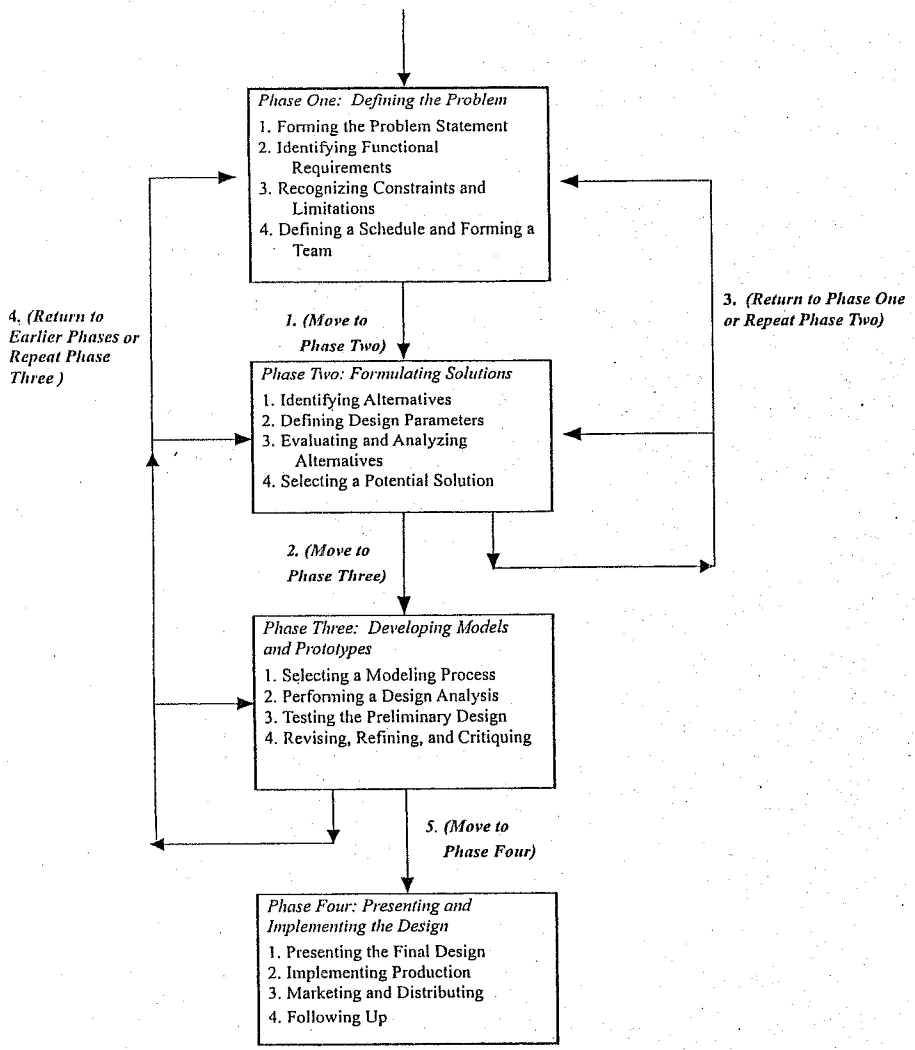


FIGURE 1.4 The iterative phases of the design process.

will benefit from your work. Remember that you will probably be working as a member of a concurrent-design team. By concurrent, we mean that most design teams in industry include professionals from other disciplines such as marketing, manufacturing, quality control, and frequently customers. These other team members may or may not have an engineering background but they are all stakeholders in the design process. Bringing people together concurrently improves coordination and understanding across functions. For instance, it helps to ensure that designers do not create something the manufacturers cannot realistically produce. You will learn more about the concurrent design process in Section 1.3.6.

Phase Two: Formulating Solutions Formulating solutions centers on systematically exploring and evaluating alternatives in relation to the requirements of the design problem. You will learn that there is typically more than one solution to your design problem. Your challenges in this phase include first identifying as many of these alternatives as possible and then assessing their pros and cons in order to determine the optimal solution. When formulating solutions, engineers typically have to make tradeoffs between various design parameters. In other words, an ideal solution for one part of your design problem may confound solutions to other parts of your problem. This text will provide you with some guidelines for evaluating your design efficiently and systematically. It will also help you answer questions such as: What kinds of data should we consider? What skills will we need? What kinds of analyses must we do to demonstrate that our solution will solve the problem? As a result, you will be in a better position to justify the rationale behind the solution that you have chosen.

Phase Three: Developing Models and Prototypes This phase of the design process involves translating design solutions into tangible outputs that demonstrate and help to refine the feasibility of your solution. In this section of the text, you will learn about how to select the right kind of modeling process for your design, how to perform a design analysis, how to test your design, and finally how to revise and critique it. This is truly the hands-on part of the design process. Modeling brings your design to life and helps you gain a better understanding of its eventual effectiveness. Like all aspects of design, you will find this phase to be quite iterative. As you develop your model, you may find yourself going back to revise your alternatives or perhaps even to redefine your problem.

Phase Four: Presenting and Implementing the Design This last step in the design process involves pulling all the pieces together so that you can present your design in a complete and compelling manner. It requires organizing and displaying the feasibility of your design in a way that helps others (namely, your client or, in an academic setting, your professor and fellow students) appreciate how it will meet their needs. Your design may represent a great idea or innovation but it will be of value only if you are able to convince others to use it. This is where presenting and implementing your design becomes important.

In 1857, Elisha Graves Otis demonstrated an innovative braking system on his passenger elevator at an exposition in New York City: he cut the elevator's cables while it ascended a 300-ft tower, and the brakes stopped the elevator from falling. His design became a huge success. You may never have to be this dramatic, but you will have to provide credible documentation that is easy to follow and you will have to be able to show that you have considered all relevant details in order to develop your design. In classroom settings, this aspect of the design process usually ends with the presentation and/or the final report. This text will give you some guidelines on how to do both effectively and will provide you with some insight to how design implementation occurs in industry.

1.2.3 Skills and Activities

As you progress through your engineering education you will be learning many essential technical concepts that apply to your chosen majors. Obviously, you cannot be an engineer without this discipline-specific knowledge. Of equal importance, however, are the four professional skill areas we will be discussing in this text (decision making, project management, communication, and collaboration). An understanding and appreciation of these skills will help to ensure that you can put your growing technical knowledge to its greatest use.

In fact, these four skills are so important to today's engineers that for a school to receive accreditation from the Accreditation Board for Engineering and Technology (ABET), it must demonstrate that its graduates have mastered them. For instance, according to ABET, engineering programs must demonstrate that their students have "an ability to function on multi-disciplinary teams." Collaboration, communication, and project management skills are essential to success in a team environment. ABET also requires that graduates have "an ability to identify, formulate, and solve engineering problems." Decision making is an inherent part of this ability. ABET also specifies that graduates must have "an ability to communicate effectively."

Like all skills, the best way to master the four skill categories we describe is through understanding, experience, and practice. These professional skills are usually subjects of separate textbooks. However, our goals are to introduce these skills to you in the context of engineering design and to provide you with some resources so that you can practice them and begin applying them to your own engineering work.

As you move through the various phases of the design process, different aspects of each skill become important or need to be emphasized. For example, different kinds of decision-making skills are required during the initial phases of a design problem than at the point when a solution is being proposed. At the initial stages, you need to understand specific skills and techniques for defining problems. Later, the focus shifts to being able to identify alternatives followed by an evaluation of the adequacy of those alternatives. In all instances, at each point in the process, you are making decisions, but there are different tools and procedures that you will want to master in order to make the best possible decisions. In a similar way, the various aspects of the other skill areas are presented at appropriate times. Thus, the materials for each of the four skill areas in this textbook are designed to move through the four phases of the design process with you. The design process consists of separate sections that will help you better understand each skill area as it relates to each phase of the process.

Table 1.1 provides an overview of how different tools and techniques for each skill area relate to the four phases of the design process. Each skill area is briefly described, and, although a number of the tools are useful at multiple points during the design process, we have tried to introduce them in an order that provides an understanding of the tool "just in time," borrowing a phrase from modern inventory control and manufacturing processes. By the time you complete this text and your design course, you will have had ample opportunity to understand, experience, and practice all the tools in each of the skill areas outlined in Table 1.1.

Decision Making As problem solvers, engineers are constantly making decisions. They need to be sure the decisions they make are sound and well-reasoned. They do this by systematically gathering information and evaluating alternatives. Decision making for engineers includes integrating diverse ideas, creating innovative solutions, and ensuring that a clear rationale forms the basis for each decision made. The kinds of decision-making activities you will learn include how to define a problem, eliminating biases, how to establish decision-making criteria, data gathering, brainstorming, and testing. You will also learn how these activities fit together to create a systematic and iterative approach to solving engineering problems.

Project Management Project management skills focus on the actual tasks and activities that need to be performed. Project management is the organizational form best suited for engineering, and its long history extends at least to the building of the great Egyptian pyramids. This means the challenge of managing projects has also been around a long time. In this text, we will describe some of the project management issues that must be considered and introduce you to some tools and techniques you can use for managing your own design projects. These include creating working agreements, establishing priorities, using Gantt charts, and record keeping. We insist upon Continuous Quality Improvement (CQI) throughout the project rather than quality inspected in at the end of the design process.

Communication Today's engineers must interact with many people from within and outside their profession. Good technical skills are essential to your success as an engineer, but they are of little use if you cannot clearly communicate your ideas and convey an understanding of client needs and perspectives. As one manager of engineers in a Fortune 500 company recently stated, "I don't think it's possible to go through the ranks now and not have good people skills and good communication skills."

Your ability to write and speak in a clear, engaging manner will help you convey your thoughts and win support for your ideas. At the same time, your abilities to listen well and to continuously probe for information can help ensure that you fully understand the problems you are solving. Communication also helps to create an environment in which the technical information, so critical to your success, will flow freely.

Collaboration As we mentioned at the beginning of this chapter, history is filled with heroic images of solitary inventors and engineers tinkering in their workshops to develop new ideas, innovations, and products, from Gutenberg's printing press to Benjamin Franklin's lightning rod to Thomas Edison's light bulb. The inquisitiveness, tenacity, and creativity of these individuals are traits to be admired and emulated, but the reality of our complex world is that engineering initiatives are almost always multifunctional efforts requiring the coordinated input of many people.

This kind of integrated effort characterizes the great engineering achievements of today. The Pathfinder mission to Mars, the personal computer, and the Internet are all examples of multifunctional engineering achievements based on teamwork and collaboration.

TABLE 1.1 Relationship of Skill Areas to the Phases of the Design Process

Steps in the engineering design process	Skills and tools for the process: Decision making	Project management	Communication	Collaboration
Phase one: Defining the problem 1. Forming the problem statement 2. Identifying functional requirements 3. Recognizing constraints and limitations 4. Defining a schedule and forming a team	• Research and data gathering • Eliminating biases and overcoming assumptions • Analyzing key phrases • Using objective trees • Using sketches • Clarifying the problem over time	• Discussing and defining project expectations • Coordinating schedules and planning meetings • Establishing working agreements • Adhering to your working agreement	• Active listening and probing skills • Laboratory record book • Composition skills	• Group formation and development
Phase two: Formulating solutions 1. Defining design parameters 2. Identifying alternatives 3. Evaluating and analyzing alternatives 4. Selecting a solution	• Innovation versus origination • Considering external factors • Brainstorming • Nominal group and delphi techniques • Lateral thinking • Systematic decision grids • Force field analyses • Making estimates	• Preparing and using Gantt charts • PERT/CMP techniques • Establishing and maintaining records	• Sharing the data gathered • Writing proposals • Preparing bibliographies	• Ensuring open participation • Reaching consensus and building commitment • Managing conflict • Avoiding groupthink
Phase three: Developing models and prototypes . Selecting a modeling process . Performing a design analysis . Testing the overall design . Revising, refining, and critiquing the design	• Quantitative and qualitative analysis • Conducting design and critical reviews	• Clarifying roles and responsibilities • Obtaining resources	• Writing progress reports • Providing feedback • Seeking input and feedback	• Managing role conflict and role ambiguity • Recognizing style differences • Eliminating social loafing
Phase four: Presenting and implementing the design Presenting the final design Implementing production Introducing and distributing Following up	• Dealing with last-minute changes, retrofits, and workarounds • Checklisting • Seeking a fresh perspective	• Assuring quality management • Applying Continous Quality Improvement (CQI) to your design project • Reviewing performance	• Developing presentation skills • Preparing visual displays • Making the presentation • Writing final reports	• Involving all team members • Reviewing team effectiveness • Celebrating success

Teams are a way of life for engineers. In the words of one engineering manager, "Each way you slice it, it's some sort of team structure that is making things happen, not just individuals." In this text, you will learn more about the collaboration skills required of productive team members. These skills include things like managing conflict constructively and ensuring open participation, as well as a general awareness of team development.

Synergies among the Skill Areas When students work on a team project of several weeks or a term (quarter or semester) they must apply all four skill areas in an integrated way. Students write a team working agreement that details how they will make decisions and work together (decision making, collaborating). They develop a schedule with a series of tasks, people assignments, a timeline (beginning and due dates), estimates of time with a column for actual time provided, and a set of columns that show percentage complete for each task (project management). They also have to plan when and where they are going to meet (project management, collaboration, communication). The team must establish how they are going to document what they do and when they are going to do it—meeting notes, analysis of components, progress reports, final reports, and oral presentations (project management, communication).

1.2.4 Case Examples, Projects, and Other Learning Tools

To help you learn about and apply the four skills described, the text provides a variety of case examples, projects, assessment tools, practice exercises, and review questions. Before you begin working with them we want to provide you with a quick overview of what they are and how they can help.

Case Examples Most of our examples are drawn from student projects with which we have been involved. Hopefully, you will see that these examples are not unlike your own design projects. Although the students working on these projects all struggled at times, they eventually succeeded by applying the principles, skills, and techniques about which you will read.

Dorm Room Design Project A project to design a dorm room is ongoing throughout the text. You will find different assignments for this project in each of the remaining chapters. We chose a dorm room, because we thought it was something most students, regardless of engineering discipline, could relate to. On the otherhand, you may already have an ongoing design project as part of your course. If this is the case, you can substitute your project for the dorm room and complete the assignments in a way that will help you finish your design project.

Assessment Tools You will also find assessment tools and other questions for reflection. For instance Chapter 5 contains a conflict management questionnaire that you can complete with your design team members. In addition, each chapter ends with a behavioral rating form you can use to self-assess your own and your design team's effectiveness.

Exercises and Review Questions Practice exercises have been woven into each chapter. These are brief assignments that will help you better understand a particular topic or skill. In addition, you will find review questions at the end of each chapter. Answering these questions provides you with an opportunity to summarize the main themes for a chapter.

1.2.5 Tips on Using this Text

We have written this text to be a resource tool that will support your own design experiences and there are at least two ways to use it. The first way is to move through the material sequentially. This approach enables you to learn about each phase of the design process at roughly the point at which you are actually working on that phase (just-in-time). In other words, read the chapters on defining a design problem (Chapters 2 and 3) just before or while you are working on defining your own design problem. Once you have more or less completed that phase of your design project, read the chapters on formulating design solutions (Chapters 4 and 5) and so on.

In general, you will find that the even-numbered chapters in this text introduce you to the specific steps associated with a design phase. They also describe the decision-making skills you will need to execute those steps. The odd-numbered chapters describe how project management, communication, and collaboration skills can be used in relation to each phase. For example, Chapter 2 explains the steps relating to Phase 1 of the design process—defining the problem. It also introduces related decision-making techniques like analyzing key phrases. Chapter 3 also deals with defining the problem; however, it focuses on particular project management, communication, and collaboration skills that are likely to help during Phase 1.

We strongly recommend the sequential, just-in-time approach if you are learning about engineering design for the first time. For a clear picture of how this approach organizes the text material, refer to Table 1.1 and look at each row of the matrix.

Alternatively, you may want to use the text more selectively if you have some prior experience with engineering design. Recall, the chapters discuss specific skill areas in relation to phases of the design process. However, perhaps your goal is to improve your project management skills (or decision-making, communication, or collaboration skills). If this is the case, you should focus on those sections that pertain specifically to the skill(s) that interests you. Look at each column of the matrix in Table 1.1 for a clear picture of the content highlighted by this selective, skill-focused approach.

The approach that works best for you depends on the extent of your prior design experiences and, of course, the guidance of your course instructor. In any event, we hope you find this text helpful during your current course or project and also as a resource that supports design projects you undertake in the future.

1.3 OTHER IMPORTANT CHARACTERISTICS OF THE DESIGN PROCESS

We have told you about our text but before you begin working with it, some additional background will be helpful. In this section, we briefly describe that characterize engineering design. You will see most of these concepts reflected in your own design projects and some familiarity with them will better prepare you to deal with the challenges they pose.

1.3.1 Products and Systems

Engineering design consists of products and systems. Products are machines, components, or devices that people actually use. The system is the supporting environment that makes it possible to use the product. For example, a light bulb is a product but the receptacles for the light bulb—the wiring and power grid and the electrical power generating plant—constitute the system that makes the light bulb functional.

Similarly, the automobile is the engineering design product but the electrical and mechanical controls, the roadways, bridges, and traffic signals constitute its system. A team of civil, mechanical, electrical, and computer engineers are included in this transportation system design. Products and systems are highly interdependent. When designing a product it is critical that you understand the system in which it will operate or be a part of. By the same token, you cannot successfully design a system without comprehending the related products.

1.3.2 Multiple Goals

One of the biggest challenges designers face is how to create something that successfully satisfies a number of criteria, many of which may appear to be contradictory. For example, the book *All Corvettes Are Red* chronicles the reinvention of GM's legendary sports car in the early 1990s. The Corvette team set a number of design goals: The new model had to be as fast or faster than the model it was replacing, it had to meet the new crash standards, it had to meet the new fuel economy specifications, it still had to have traditional Corvette looks, and it could not cost more than the current model. Thus, as the team reached each stage of the design process, they had to find ways to address each goal. Typically, a very fast car is not very fuel efficient. However, if the car can be made lighter, it can be fuel efficient and fast. As the process evolved, the engineers developed a formula that said they could increase the production costs by $10 per car to save 1 kg of weight. Another innovative contribution to the lighter, stronger philosophy was the design of the side rails that formed the outer portion of the chassis. Closed, thin-walled tubes were filled with water and then high pressure was used to form the tubes in molds (hydroforming). This allowed the design to be strong enough to meet the side impact standards, and it saved weight over conventional manufacturing methods.

1.3.3 Closed Versus Open-Ended Problems

Engineering design is about solving problems, that range from simple one-answer problems (such as knowing the height a ball can reach given an initial velocity and direction) to more complex problems (such as determining the terminal velocity of a

rocket with more than one booster). However, most problems engineers have to solve are open-ended and have several possible solutions. The challenge is to identify an optimal solution by careful and systematic analysis of multiple alternatives.

1.3.4 Application of Established Scientific Principles and Technologies

The information, materials, and processes that are available at a particular time will significantly impact the design solution that is reached and, for that matter, how a problem is conceived in the first place. An example from history illustrates this point. You may know that during the late 1400s and early 1500s Leonardo DaVinci attempted to design a flying machine. Fascinated by the movement of a bird's wings, he based his design on his observations of their graceful and effortless propulsion. His designs essentially imitated nature by equipping a person with wings to flap. However, it is a good thing he never built any of his designs because they would not have worked. Even in its simplest formulation, flying requires lifting a load from the ground against the field of gravity (lift) and moving it in a specified direction (thrust). Birds, with their remarkable power-to-weight ratio, can easily master these requirements. During Leonardo's time the concept of gravity had not even been defined let alone other key concepts such as lift and thrust! Had he been aware of them he might have recognized the futility of his designs. The natural materials of his day (wood, leather, cloth, metal) would have been too heavy. In fact, it is estimated that a person propelling a machine made from those materials would need the strength of 100 people. Today, however, with our knowledge of aerodynamics and the existence of high-tech lightweight materials, it is possible to design a human powered flying machine.[1]

1.3.5 Iteration and Feedback

At every stage in the design process something new will pop up requiring you to reexamine what you have already done and try something again, perhaps differently or repeatedly. As your team works together and gathers information on materials, devices, processes, and human factors, you will almost always find that the problem needs to be defined more clearly and that you need to repeat some steps by using new knowledge or perhaps applying a new technology. As shown in Figure 1.5, closer examination of your design may show that the materials you use and/or your arrangement of them simply will not allow the problem to be solved as the team initially perceived the solution.

Making these choices requires good decision-making skills. For example, in the book *All Corvettes Are Red*, the design team found that they could save weight by making the floor of the passenger compartment out of balsa wood instead of metal. The weight savings were needed so that the car could satisfy more stringent government regulations coming from the Corporate Average Fuel Economy (C.A.F.E.). Needless to say, this was an innovative solution that had not been anticipated.

[1] This example is adapted from *Discovering the Principles of Design Through Reverse Engineering* by Jean LeMee and John Razukas, Gateway Coalition, 1997.

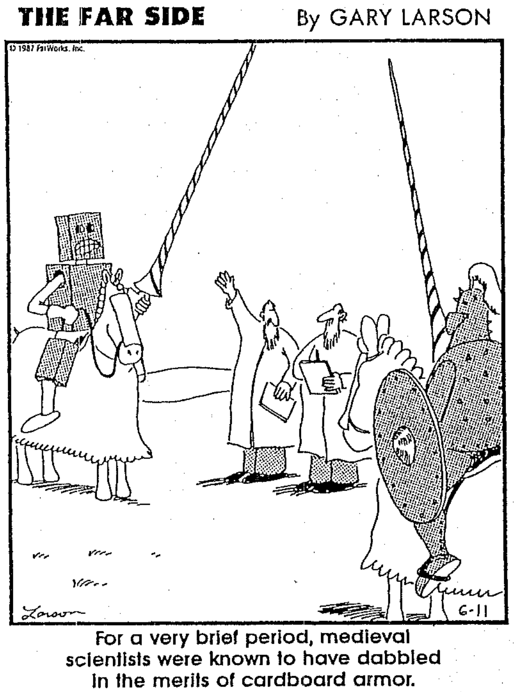


FIGURE 1.5 Iteration is critical to design success. (Gary Larson/ Universal Press Syndicate.)

During the product design process, team members must keep others informed about design decisions and changes. When particular components are tested or analyzed, it is critical for the rest of the team to be made aware of the problems. Sometimes pressure to get the job done, meet a deadline, or contain costs discourage iteration and feedback. In the long run this is almost always a mistake. Their importance is illustrated in a book titled *In the Name of Profit*. The book depicts conflict between ethics and desire for profit. One corporation was designing brakes for a new aircraft. The test engineers experimented with one brake design, found that it did not work, and immediately provided the information to the design team. However, the head of the design team did not want to admit that the design would not work. Communication just shut down. Iteration and feedback are critical to progress, and team members must be willing to listen even when disturbing information is provided.

1.3.6 Stepwise, Sequential Design vs. Concurrent Design

Through the early 1950s to the late 1970s and into the 1980s, design and subsequent production were typically viewed as a sequential process in which the manufacturing or construction teams did not become involved until the design engineering team completed all their work. This provided a structured way for engineers to approach

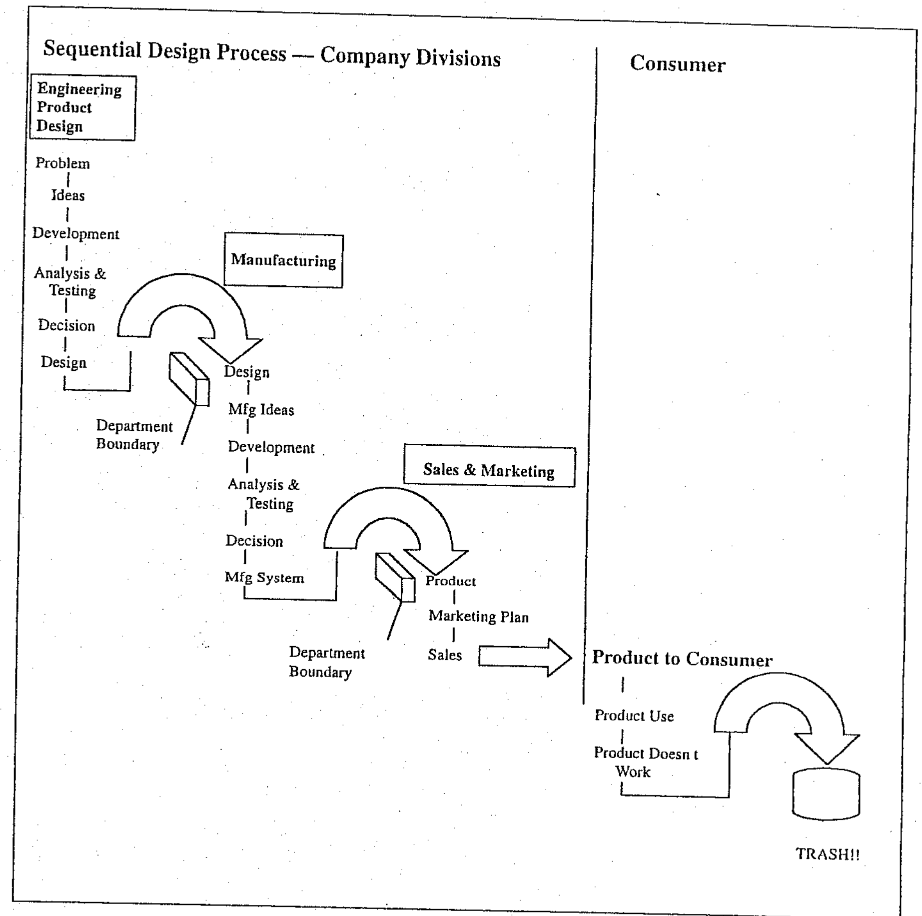


FIGURE 1.6 Stepwise or sequential design process.

a design or process that eliminated some problems and, as industry learned later, created others (Figure 1.6).

Many times a team believed they had the solution for a particular problem when, in fact, they really did not. As it turns out, this single-minded, single-track approach simply perpetuated an error of thinking that occurred early in the design process until the discovery was made at the end of the entire design process. The design team then had to do the ultimate iteration and go back to the start.

The main problem with the traditional design process is that a second design process began only after the initial design was completed. For example, when the manufacturing (construction) engineers got a preliminary design, they had to develop a manufacturing (construction) process to bring the design to life. As they looked at a design in light of the tools available, they found that parts could not be produced as originally conceived by the product designers. They then sent it back to the original design team or redesigned the part themselves. In other instances, the manufacturing engineers spent considerable effort and capital to manufacture a feature that was not necessarily of the greatest importance. Either approach meant that more time was required to get from the idea stage to the finished product. Communication with the design team early in the process could have resulted in substantial savings.

As companies find they need to bring products to the marketplace at an increasing rate and in shorter time periods, they have evolved the design process so that the initial design team includes those who have to produce, assemble, and maintain the design. In addition, a number of other areas of the company, such as marketing, finance, field support, and service, are represented on the design team. This is known as concurrent engineering. The design of the product is done in parallel with the design of the process used to manufacture the product and both are consistent with the needs of the marketing activities, field service, and technical support. This means good communication. Today design team members may even be physically separated, but the information, data, and decisions must be easily and efficiently shared.

Concurrent designing (Figure 1.7) requires thinking about many things simultaneously. For instance, in addition to the design and manufacturing considerations, thought must be given to the distribution, use, maintenance, operation, probable effect of a product or process on the environment, and eventual recycling not just at the end of production but throughout the design/build process.

When team members plan how they are going to bring about a new design, they must consider how much time it will take for each part of the process and which team members are going to be involved. They also have to figure out how much longer it will take to get into production and how much time will be required for resolving construction or manufacturing problems. These activities are all examples of project management skills and are dealt with in the following chapters. Before they start the process, the team must determine how they will work together and how they will resolve problems and conflicts (collaboration skills). These topics are also covered in later chapters in this text.

Although most college design projects are not going to be put into mass production or constructed, student teams can benefit from applying the concurrent design process. For example, if a prototype is to be produced or a model constructed, a successful team will begin experimenting with the production or assembly methods at a relatively early point in the project. This enables them to make sure they can complete the project on time and within budget.

At the Ohio State University, freshman design teams who build robots typically have constructed a chassis that is not "stiff" enough for the drive train so the chassis has to be redesigned. They also find that they have not done a good job of taking into account frictional losses in the drive train, and they have to generate new ideas for a solution that works. Smart teams do it concurrently.

Teams that participate in the American Society for Civil Engineers (ASCE) projects such as a steel bridge contest or a concrete canoe contest must learn about the materials and fastening methods early in the design process so they can do proper

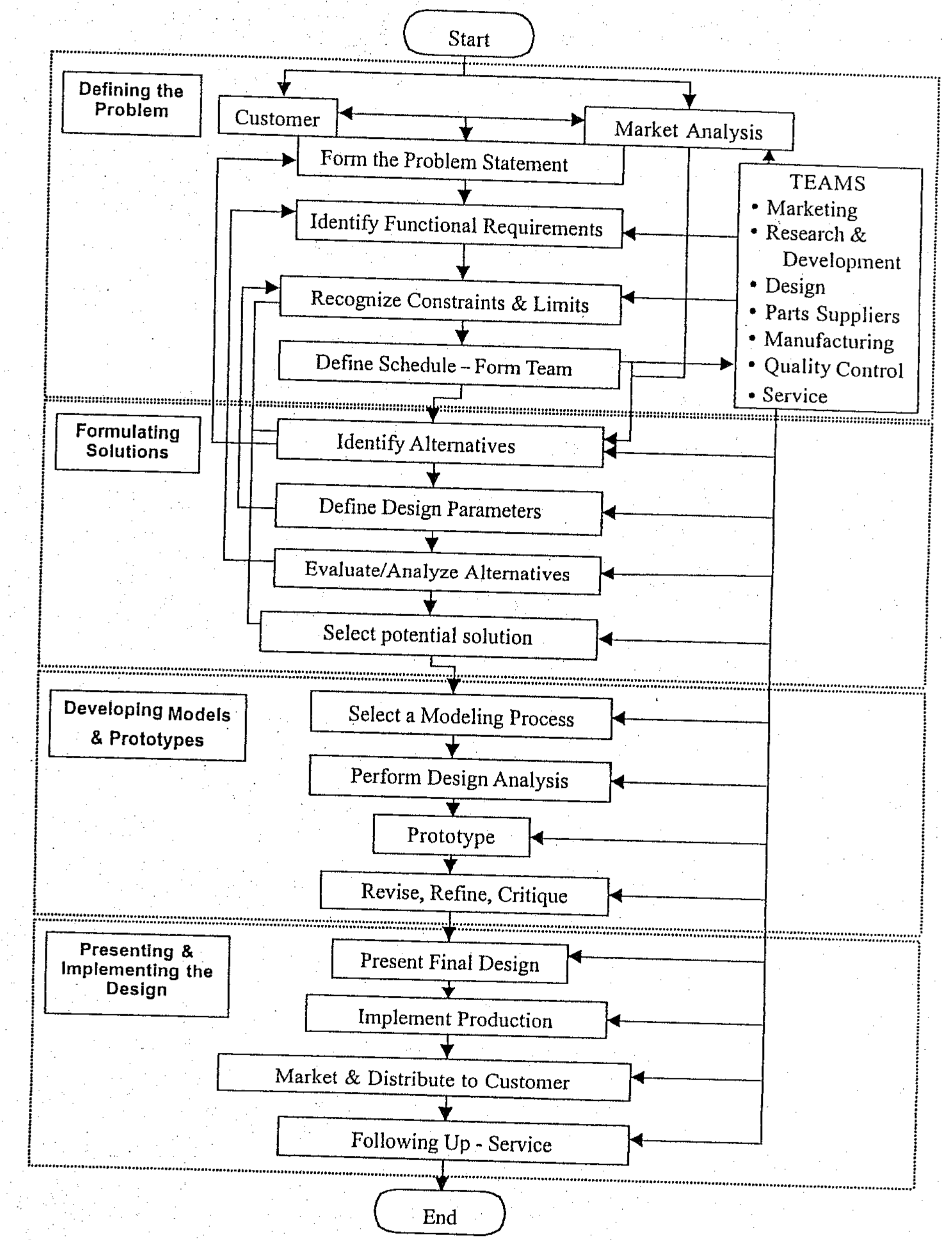


FIGURE 1.7 Concurrent design process.

design and analysis. Concurrent engineering helps greatly in this process to save time and rework effort.

The multischool design teams in the Gateway Engineering Education Coalition, described in the Preface, use a variety of methods to keep the geographically separate groups up to date. They have used e-mail, telephone conferences, videoconferences, and the World Wide Web to provide communications. They have evolved to a process whereby each school's group creates a Web site, and when they have a phone conference, all the Web pages are brought up to date and the design groups gather to discuss progress. As a group from one location talk, the other groups bring up their own Web pages to check their figures and calculations.

1.3.7 Safety and Reliability Issues

One of the many benefits of concurrent design processes includes increasing the likelihood that engineers can identify safety and reliability problems before a design is completed. These two issues must be addressed in every design, although they are more important in some instances than in others. We want to design all products so they will not harm or hurt others. This requires careful attention to details and the ability to visualize all ways the product might be used or misused. In the United States especially, society demands that engineers identify and correct any product flaws that might hurt the consumer during the life of the product.

As the design evolves, the engineer should attempt to identify any safety defects that might be present and correct them before they become a problem. For example, the assistive feeding device project that is discussed throughout this text involved designing a robot arm that attached to a wheelchair. During their work the student engineers recognized that potential users (quadriplegics) would have little fine motor control in their hands and arms. As a result, they would not necessarily be able to stop the arm from striking them in the face once the arm came close. The design team had to develop a control system that would restrict the range of motion of the robot arm. This was done by putting limit switches on the robot joints and programming the linkage to stop if the robot hand came too close to the user's face. Also, power to the joints was intentionally limited so the arm could be stalled if it contacted any part of the body.

As indicated before, the designer should look for any applicable design codes to apply to a given situation. These design codes often are developed with a viewpoint toward safety, and they should be used as a design guide even if the codes are not strictly required for the design situation.

In the "old days," engineers could concentrate on the intended function of a product, and they could assume that the consumer would be careful. If the consumer were careless or misused the product, the design engineer was unlikely to be considered responsible for any accidents. As a result, guards on machines and other products were rare, but amputations and other serious injuries were not! This is definitely not the case today.

Safety issues should be an integral part of the design process, and the design team should do a safety review as well as review that the product performs as intended.

In addition to checking the design relative to any applicable design rules or codes, the team should attempt to visualize how the product could be misused. Currently, society is placing more and more responsibility on the designer to anticipate how products can be misused to the detriment of the consumer. The team can use "brainstorming" (see Section 4.2.1) to identify ways the product can be misused. They can then either design the product to remove unsafe situations or, at worst, place labels on the device to warm the user of dangerous conditions.

Reliability is similar to safety; however, the intent here is to produce a product that will perform its intended function for the design life of the part. Note that it is not necessary to design every part to last forever. In fact, designing for infinite life may be unnecessary and prohibitively expensive. The design team should determine how long the product must last as part of the design definition phase of the process. In practice, the design team is expected to warranty the part for its design life. If premature failure occurs, the designer's company is expected to repair or replace the defective part. To assess the reliability of a product, the design team should perform a design review and assess the reliability of the product. The team must model the parts so the modes of failure can be identified. Typically, this involves functional analyses such as strength and heat transfer analyses. Ultimately, the designer would like to determine a factor of safety or the statistical chances of premature failure. Note that reliability issuse are more broad than safety issues. In safety issues, the designer is concerned about not harming the consumer, whereas reliability issues address preventing premature failure. Both should be addressed in the design stage before the product is manufactured. As in most aspects affecting product life cycles, the idea is to anticipate problems as early in the design cycle as possible. The longer a problem remains unresolved, the more expensive it is to resolve.

1.3.8 Ethical Issues in Design

Safety and reliability are closely related to another important design issue—ethics. You need to be aware that the technical challenges engineers face more often than not have broader implications for all aspects of society including economics, politics, privacy, and safety to name just a few. We cannot separate engineering and science from the broader social system in which it occurs. It is essential therefore that engineers have a constant awareness of the broader ramifications of their work.

They must also realize that their work often brings with it potentially conflicting obligations to a variety of stakeholders. These may include clients, consumers, workers, the government, and other engineering professionals. For example, one obligation engineers may have is to control costs and deliver a product on time. But what if, at the end of their work, they find out there is a slight chance their design will have unintended environmental consequences? Moreover, what if any further implementation delays would also cause many people to lose their jobs? Regardless of how this situation eventually might be resolved it is not too difficult to imagine how an engineer might feel pulled in different directions. No matter what our profession, we will be confronted with dilemmas that require us to make decisions based on our own internalized conceptions of right and wrong.

Our own internal standards are important, but what we mean by ethics is slightly different. The world is far too complex and diversified to expect that we all naturally share identical conceptions of right and wrong. Therefore, in terms of our roles as professional engineers, it is important that we rely on more universally defined guidelines and standards that can transcend our individual differences. Over the years such standards have been developed by engineering societies to help guide their members. Figure 1.8 shows the code of ethics adopted by the Institute of Electronics and Electrical Engineers (IEEE). Figure 1.9 lists another ethics code developed by the American Society for Civil Engineers (ASCE).

Although there are some differences between these two codes, both indicate how engineers should act with regard to clients, other engineers, and the general public. Moreover, the differences between them are a reflection of differences in the way electrical engineering and civil engineering are practiced. For instance, most civil engineers work in smaller firms. They frequently provide services to clients and obtain their work through public bidding. In contrast, electrical engineers frequently work for large corporations that sell products instead of services.[2]

Of course, the fact that standards exist does not mean that they, in and of themselves, resolve ethical dilemmas. These standards may help, but not all ethical situations are so black and white that we can just point to the standards for an answer. For instance, both the ASCE and IEEE codes stress that safety, health, and welfare should be paramount concerns. Later in this text, we describe how counterproductive group dynamics may have led to the launch decision that resulted in the explosion of the space shuttle Challenger. Those engineers who argued against the launch strongly believed that lives might be lost. It is difficult to argue, however, that the managers who favored launching did so because they did not care whether people would be hurt. Therefore, were these managers acting unethically? Perhaps one still could argue that they did not give enough ethical consideration to the potential (and, tragically, actual) consequences of their decision. But one also might argue that their decision, although clearly wrong in hindsight, was not made in an ethical vacuum.

The point of the above example is that ethical situations frequently are true dilemmas. We may not know for sure what the consequences of our actions will be. We can, however, do our best to acknowledge the broader responsibilities associated with our work and continue to develop our skills throughout our careers. We can also strive to always evaluate our work in relation to ethical standards and also to serve as sources of ethical support for one another.

CHAPTER REVIEW

In this chapter we have described how the text is organized and the recurrent themes that run through the subsequent chapters. Specifically, we have divided the design process into four distinct phases and have also indicated that there are four core skill areas for you to master. As you progress through each phase of the design process,

[2]C. Dym and P. Little. *Engineering Design: A Project-Based Introduction*, John Wiley & Sons, New York, 2000, p. 222.

IEEE CODE OF ETHICS

We the members of the IEEE, in recognition of the importance of our technologies in affecting the quality of life throughout the world, and in accepting a personal obligation to our profession, its members and the communities we serve, do hereby commit ourselves to the highest ethical and professional conduct and agree:

1. to accept responsibility in making engineering decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;
2. to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist;
3. to be honest and realistic in stating claims or estimates based on available data;
4. to reject bribery in all its formats;
5. to improve the understanding of technology, its appropriate application, and potential consequences;
6. to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;
7. to seek and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;
8. to treat fairly all persons regardless of such factors as race, religion, gender, disability, age, or national origin;
9. to avoid injuring others, their property, reputation, or employment by false or malicious action;
10. to assist colleagues and co-workers in their professional development and to support them in following this code of ethics.

FIGURE 1.8 IEEE code of ethics.

ASCE CODE OF ETHICS

Fundamental Principles

Engineers uphold and advance the integrity, honor, and dignity of the engineering profession by:

1. using their knowledge and skill for the enhancement of human welfare and the environment;
2. being honest and impartial and serving with fidelity the public, their employers, and clients;
3. striving to increase the competence and prestige of the engineering profession; and
4. supporting the professional and technical societies of their disciplines.

Fundamental Canons

1. Engineers shall hold paramount the safety, health, and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
2. Engineers shall perform services only in areas of their competence.
3. Engineers shall issue public statements only in an objective and truthful manner.
4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees and shall avoid conflicts of interest.
5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
6. Engineers shall act in such a manner as to uphold and enhance the honor, integrity, and dignity of the engineering profession.
7. Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional development of those engineers under their supervision.

FIGURE 1.9 ASCE code of ethics. Issue applying different aspects of each of these skills will help you get the job done. Keep in mind the matrix in Table 1.1 as you continue to read this text. It is essentially a road map to help you navigate your way through the material.

We have also described some key characteristics of all design processes. These characteristics further illustrate the relevance of the four design phases and the importance of developing your competence in each of the four skill areas.

REVIEW QUESTIONS

1. How has engineering changed over the years and in recent times? What implications do you think these changes have had on the skills required of engineers?

2. What is the difference between sequential and concurrent design? How do these differences impact design teams?

3. What makes engineering design different from pure science? In what ways do you think it might be the same?

4. What is the difference between a product and a system? From the perspective of engineering design, how are they distinct? How are they similar?

5. It is sometimes said that engineering design is as much an art as it is a science. Explain why you agree or disagree.

6. Why are teams an important aspect of engineering design? What do you think are some challenges teams pose?

7. What do we mean when we say that design is an iterative process?

8. How do ethical issues impact the engineering design process? Identify some of the major technological and scientific innovations of the past 10 years. For each that you identify, try to list some of the ethical issues they pose for engineers, scientists, and society in general.

9. Prepare a list of ethical guidelines appropriate for student design projects.

10. For each of the four skill areas (decision making, project management, communication, and collaboration) try to identify something you do well. Also identify something you would like to learn about or improve upon.

11. Explain what the terms safety and reliability mean. How are these concepts similar and how are they different? Why are they both important?

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