2

What Is Design?

de'sign n: the arrangement of parts, details, form, color, etc. so as to produce an artistic or skillful invention*

Throughout history, the engineer has made useful things from basic raw materials. Even in ancient times, the industrious and inventiveness of the engineer were highly regarded by society. The work of the engineer has left its mark on every era of civilization, from the great pyramids of Egypt, the Roman aqueducts, the rope bridges of Nepal, the Great Wall of China, and the ancient Mayan temples to the Eiffel tower, the Golden Gate Bridge, and the transatlantic cable. From a fundamental perspective, design can be defined as any activity that results in the synthesis of something that meets a need. A refrigerator keeps food cold, a bicycle provides transportation, a keyboard sends data to a computer, and a muffler silences a noisy automobile engine. Although design is practiced every day by many creative people, the notion of "design" in the context of engineering usually implies that knowledge is combined with specialized skills to create a device, machine, circuit, building, mechanism, structure, software program, manufacturing process, or other system that meets a set of desired specifications. In this latter usage, the word "design" answers the simple question, "What do engineers do?"

*Webster's New World Dictionary of American English. V. Neufeldt, ed. New York: Prentice Hall, 1994.

SECTIONS

OBJECTIVES

In this chapter, you will learn about:

- The engineering design process.
- The difference between good design and bad design.
- The design cycle.
- The Peak Performance Design Competition.

2.1 USE OF THE WORD DESIGN

Throughout this book, the word "design" will be used in several ways. It may be used as a verb, as in, "Design a widget that can open a soda can automatically," or perhaps as a noun that defines the creation process itself, as in, "Learning design is an important part of engineering education." Sometimes, design will be used as a noun that describes the end result of the process, as in "The design was successful and met customer specifications." At other times, the word will be used as an adjective, as in, "This book will help you learn the design process."

Sometimes, an alternative word will be needed to describe the end product of a design effort. For this purpose, the word "product" may be used in a generic sense, even if the thing being designed is not a product for sale. Similarly, the word "device" may be used to describe the results of a design effort, even if the entity is not a physical apparatus. Thus the words product and device will refer not only to tangible objects, but also to large structures, systems, procedures, and software.

2.2 THE DIFFERENCE BETWEEN ANALYSIS, REPRODUCTION, AND DESIGN

Students of engineering often are confused by the distinction between analysis, reproduction, and design. In science classes, students are asked to find answers to problems, complete laboratory exercises, and perform calculations. In engineering classes, instructors instead may stress the importance of design. The difference between analysis and design can be defined in the following way: If only one answer to the problem exists, and finding it merely involves putting together the pieces of the puzzle, then the activity is probably analysis. For example, processing data and using it to test a theory, is analysis. On the other hand, if more than one solution exists, and if deciding upon a suitable path demands creativity, choice taking, testing, iteration, and evaluation, the activity is most certainly design. Design can include analysis, but it also must involve at least one of these other elements.

As an example of the distinction between analysis and design, consider the weather station shown in Figure 2.1. This remote-controlled buoy is anchored about ten miles off the coast of Massachusetts and is maintained for the U.S. National Oceanic and Atmospheric Administration. It provides 24-hour data to mariners, the Coast Guard, and weather forecasters. Processing the data stream from this buoy, deciding which parts to post on the Internet*, and using the information to forecast the weather are examples of analysis. Deciding *how* to build the buoy so that it meets the needs of its end users is an example of design.

Another example that illustrates the difference between analysis and design can be found in the medieval catapult of Figure 2.2. Determining the projectile's x-y trajectory is an analysis problem that involves the solution of the following equations:

Newton's law $\mathbf{F} = m\mathbf{a}$:

$$d^2x/dt^2 = 0$$
$$d^2y/dt^2 = mg$$

Initial conditions at $t = 0$:

$$dx/dt = v_x = V_0 \cos \theta$$
$$dy/dt = v_y = V_0 \sin \theta$$

*http://www.ndbc.gov

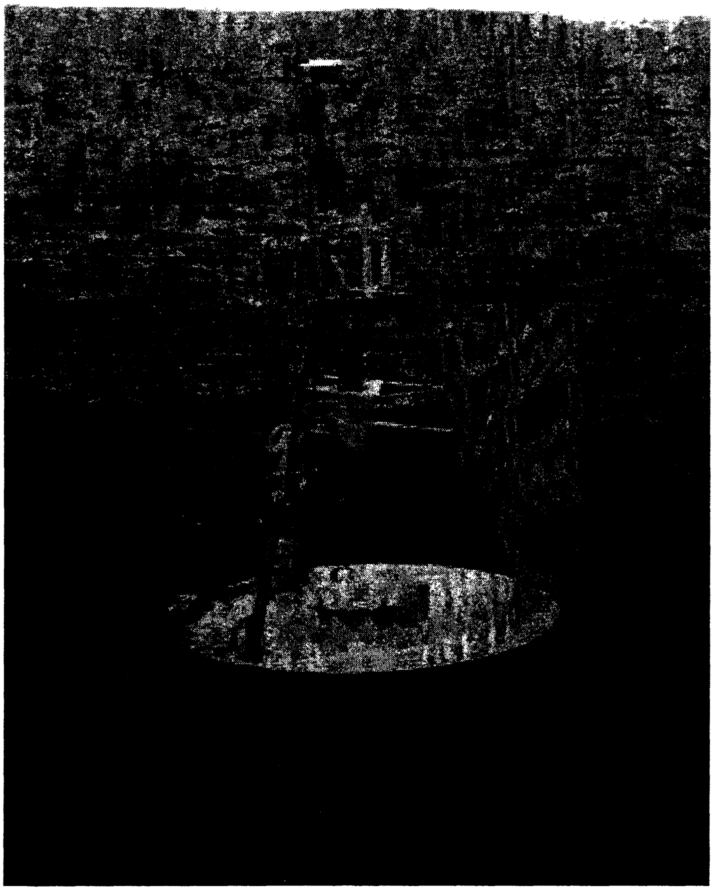
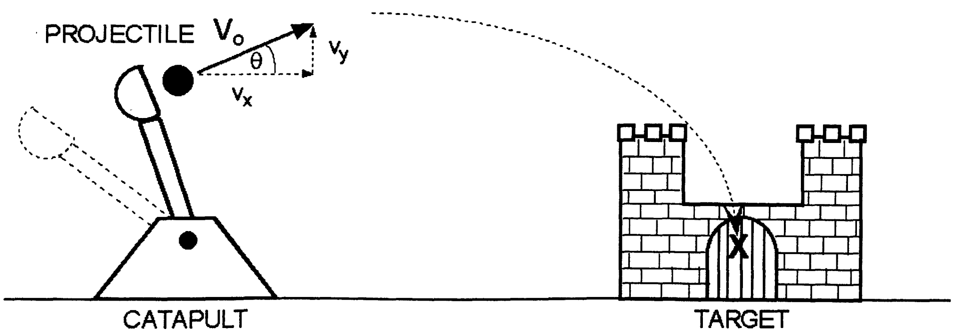


Figure 2.1. NOAA buoy off the coast of Massachusetts provides information about local sea and weather conditions. (*Photo courtesy of National Data Buoy Center.*)

Here g is the gravitational constant, m the mass of the projectile (e.g., a stone,) and v_x and v_y are the x- and y-components of the projectile's velocity, respectively. The second derivatives d^2x/dt^2 and d^2y/dt^2 are the x- and y-components of acceleration. The launch speed V_0 and launch angle θ are set by the user. As suggested by Figure 2.2, the user

Figure 2.2. Catapult sends a projectile along a trajectory toward a target. Computing the parameters needed to hit the target is an example of analysis. Determining how to best build the catapult is an example of design.



first must choose the target point, then adjust V_0 and θ so that the stone hits the desired target. Although this process involves making decisions (which target shall I hit?) and setting parameters (which V_0 and θ shall I choose?), and has more than one possible solution, it requires analysis only and involves no design.

In contrast, determining how to *build* a catapult capable of launching the stone at a desired velocity and angle clearly involves design. The machine can be built in more than one way, and the designer must decide which method is best. Should the structural members be made from oak or acacia wood? Should twisted ropes, a basket of rocks, or bent branches be used as the energy storage mechanism? How large should the machine be? Should it rest on wheels or skids? Answering these questions requires experimentation, analysis, testing, evaluation, and revision, which are all elements of the design process.

Reproduction

Design involves the creation of a device or product to meet a need or set of specifications. Analysis refers to the process of applying mathematics and other tools to find the answer to a problem. The word *reproduction* refers to the process of recreating something that's already been designed. Reproduction may involve exact replication or perhaps minor revisions whose consequences already have been determined. For instance, copying an oscillator circuit from an electronics book and substituting resistor values to set the frequency is an example of reproduction rather than design. Reproduction is an important part of engineering and lies at the core of manufacturing, but it does not require the same set of skills and tools as does true design.

Exercises 2.1

E1. Determine whether the following task involves analysis, design, or reproduction: Find the best travel route between your place of residence and the nearest airport.

E2. Determine whether the following task involves analysis, design, or reproduction: Find a way to prevent customers from burning their hands on paper cups of hot liquid purchased over the counter from a coffee shop.

E3. Determine whether the following task involves analysis, design, or reproduction: Find a way to stack cans of beans so that the smallest sized box can be used for shipping.

E4. Determine whether the following task involves analysis, design, or reproduction: Find a way to mount a cellular telephone inside an automobile to permit hands-free operation.

E5. Determine whether the following task involves analysis, design, or reproduction: Find a way to rapidly produce pom-poms that can be handed out to the fans at the Home U. versus Visitors football game.

E6. Determine whether the following task involves analysis, design, or reproduction: Find a way to rapidly produce origami (folded paper) nut containers for 400 people at a large alumni dinner.

E7. Determine whether the following task involves analysis, design, or reproduction: Find a way to use a global positioning system (GPS) receiver to automatically drive a vehicle between two preset locations.

2.3 GOOD DESIGN VERSUS BAD DESIGN

Anyone who has taken a car to an auto mechanic recognizes the difference between good and bad mechanics. A good mechanic diagnoses your problem in a timely manner, fixes what's broken at a fair price, and makes a repair that will last. A bad mechanic fails to find the real problem, masks the symptoms with expensive solutions that do not last, and charges too much money for unneeded repairs. Engineers are a bit like auto mechanics in this respect—some are good and some are bad. Just because an engineer produces something does not mean that the product has been well designed. Although the criteria by which a product is judged will vary with the nature of the product, most can be judged by the general characteristics summarized in Table 2.1.

TABLE 2-1 Characteristics of Good Design versus Bad Design

GOOD DESIGN	BAD DESIGN
1. Works all the time	1. Works initially, but stops working after a short time
2. Meets all technical requirements	2. Meets only some technical requirements
3. Meets cost requirements	3. Costs more than it should
4. Requires little or no maintenance	4. Requires frequent maintenance
5. Is safe	5. Poses a hazard to user
6. Creates no ethical dilemma	6. Fulfills a need that is questionable

The contrast between good and bad design is readily illustrated by the catapult example previously introduced. Consider the catapult shown in Figure 2.3. Suppose that Apex Catapult Co. has been asked to produce this device (actually called a trebuchet) for a brigade intent on rescuing their captured king and queen. The buyers will judge the worthiness of the catapult based on the considerations outlined in Table 2.1, as illustrated by the following discussion:

1. Does the Product Work?

A product under development need not work the first time it is tested, but it must work perfectly and repeatedly before it is delivered. It must be durable and not fail after only a short time in the field. Such a catapult provides an excellent example of this principle. Even a bad designer could produce a catapult capable of meeting its specifications upon initial delivery. The catapult might be made from whatever local timbers were harvested from the woods. It might utilize a simple trigger mechanism made from vines and twigs. The bad designer would build the catapult as he went along, adding new features on top of old ones without examining how each feature interacted with those before it. The catapult would likely pass inspection upon delivery and be able to hurl stones several times before fraying a line, cracking a timber, or jamming it's trigger mechanism. After a short period of use, the ill-designed timbers of its launch arm might weaken, causing the projectile to fall short of its mark.

A good designer would develop a robust catapult capable of many long hours of service. This conscientious engineer would test different building materials, carriage configurations, trigger mechanisms, and launch arms before choosing materials and design strategies. The catapult would be designed as a whole, with consideration given to how its various parts interacted. The process typically would involve many test cycles and the reworking of components to identify weak points. Building a battle-worthy catapult capable of heavy use in the field would require stronger and more expensive materials, but would prove more reliable in the long run and allow the user to hit the target repeatedly.

2. Does the Product Meet Technical Requirements?

It might seem a simple matter to decide whether a catapult meets its technical requirement. Either the stone hits its target, or it does not. But success can be judged in many

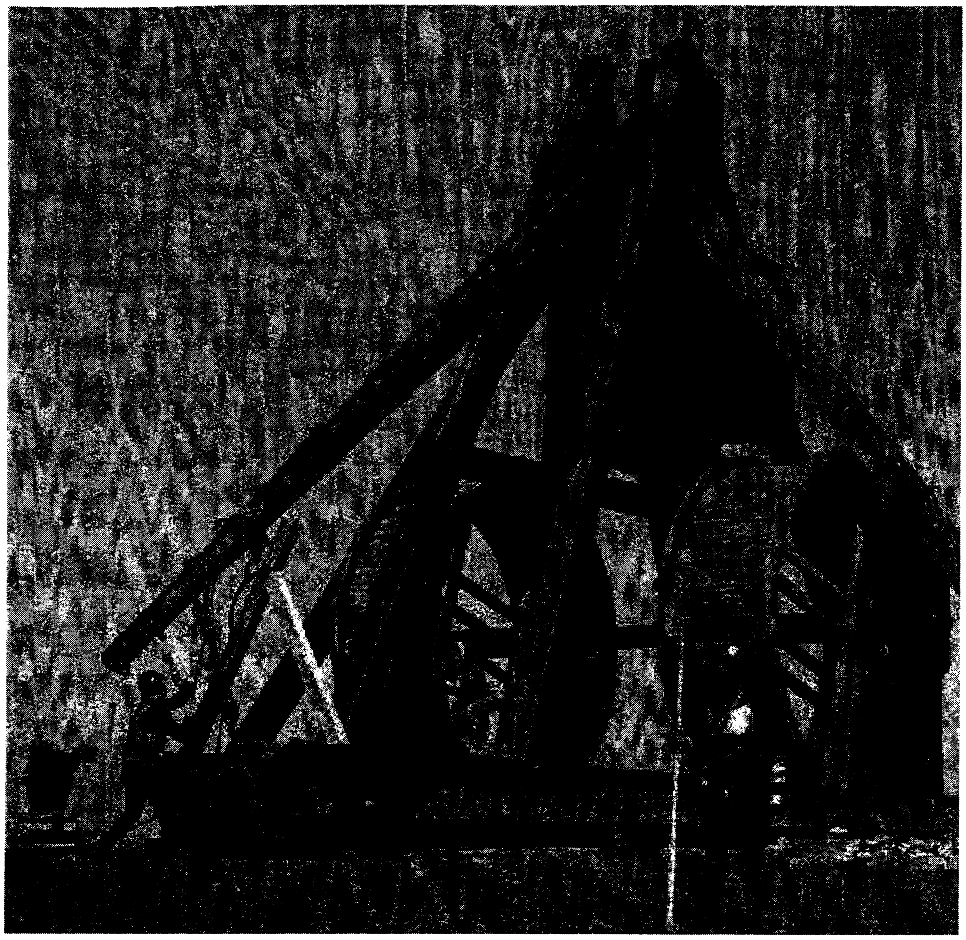


Figure 2.3. Reproduction of a medieval trebuchet. (*Photo courtesy of Middelaltercentret.*)

ways. A catapult that represents good design will accommodate a wide range of stone weights, textures, and sizes. It will require the efforts of only one or two people to operate, and will repeatedly hit its target, even in strong wind or rain. A poorly designed catapult may meet its launch specifications under ideal conditions, but it may accommodate stones of only a single weight or require that only smooth, harder-to-find stones be used. When the arm of a poorly designed catapult is released, it may hit the carriage, causing the stone to lose momentum and fall short of the target.

3. Does the Product Meet Cost Requirements?

Some design problems can be solved without regard to cost, but most of the time cost is a major factor in making design decisions. Often a tradeoff exists between adding features and adding cost. A catapult made from cheap local wood will be much less expensive than one requiring stronger, imported wood. Will the consumer be willing to pay a higher price for a stronger catapult? Durable leather thongs will last longer than links made of less expensive hemp rope. Will the consumer absorb the cost of a more durable product? Painting the catapult will make it visually more attractive but will not enhance performance. Will the customer want an attractive piece of machinery at a higher price? A designer must face similar questions in just about every engineering endeavor.

4. Will the Product Require Extensive Maintenance?

A durable product will provide many years of flawless service. Durability is something that must be planned for as part of the design process. At each step, the designer must decide whether cutting corners to save money or time will lead to component failure later on. A good designer will eliminate as many latent weaknesses as possible. A bad designer will ignore them as long as the product can still pass its specification tests. If Apex Catapult Co. wishes to make a long-lasting product worthy of its company name, then it will design durability into its catapult from the ground up.

5. Is the Product Safe?

Safety is a quality measured only in relative terms. No product can be made completely hazard free, so when we say a product is "safe," we mean that is has a significantly smaller chance of causing injury than does a product that is "unsafe." Assigning a safety value to a product is one of the harder aspects of design, because adding safety usually requires adding cost. Also, accidents are subject to probability and chance, and it can be difficult to identify a hazard until an accident occurs. An unsafe product may never cause harm for a particular user, while a statistical fraction of many users may sustain injury. The catapult provides an example of the safety-vs.-cost tradeoff. Can a catapult be designed that provides a strategic advantage without injuring people? When a stone is thrown at a castle wall, a probability exists that it will hit a person instead. Designing a device that can throw, say, large bags of oil instead of stones would reduce this hazard to people, but at the added cost of hard-to-find oil. Features also could be added to the catapult to protect its users. Guards, safety shields, and interlocks would prevent accidental misfirings, but would add cost and inconvenience to the unit.

6. Does the Product Create an Ethical Dilemma?

The catapult has been chosen as an example for this section because it poses a common ethical dilemma faced by engineers: Should a device be built just because it *can* be? When asked to build a catapult, does Apex Catapult Co. have the responsibility to suggest alternatives to the rescue brigade? A less destructive battering ram might help save the king and queen while sparing innocent lives. Perhaps quiet diplomacy will lead to resolution and peaceful cooperation? As contrived as this fictitious example may be, it exemplifies the ethical dilemmas faced by engineers all the time. If asked by a future employer to design offensive military weapons, would you find it personally objectionable? If your boss asked you to use cheaper materials but bill the customer for more expensive ones, would you comply with these instructions or defy your employer? If you discovered a serious safety flaw in your own product that might lead to human injury, would you insist on costly revisions that would reduce the profitability of the product? Or would you say nothing and hope for the best? Questions of this type are never simple, but engineers must be prepared to answer them. As part of your training as an engineer, you must learn to apply your own ethical standards, whatever they may be, to problems that you encounter on the job. This aspect of design will be one of the hardest to learn but is part of your professional responsibility as an engineer.

Choose a Good Designer for a Mentor

In this section, we've highlighted the differences between good design and bad design. Practicing engineers of both types can be found in the engineering profession, and it's important that you learn to distinguish between the two. As you embark upon your transformation from student to professional engineer, you are likely to seek a mentor at some point in your career. Be certain that the individual you choose practices good design. Seek an engineer who has an intrinsic feeling for why and how things work. Find someone who adheres to ethical standards that are consistent with your own. Avoid "formula pluggers" who memorize equations and blindly plug in numbers to arrive at design decisions but have little feeling for what the formulas mean. Likewise shun engineers who take irresponsible shortcuts, ignore safety concerns, or choose design solutions without thorough testing. Do emulate engineers who are well respected, experienced, and are practiced at design.

2.4 THE DESIGN CYCLE

Design is an iterative process. Seldom does a finished product emerge without changes along the way. Sometimes, an entire design approach must be abandoned and the product redesigned from the ground up. The sequence of events leading from idea to finished product is called the *design cycle.* Although the specific steps of the design cycle may vary with the product and field of engineering, most cycles resemble the sequence depicted in Figure 2.4. The following sections explore this diagram in more detail.

Define the Overall Objectives

You should begin any new project by defining your design objectives. This step may seem a nuisance to the student eager to build and test, but it is an important one. Only by viewing the requirements from a broad perspective can an engineer determine all factors relevant to the design effort. Good design involves more than making technical choices. The engineer must ask the following questions: Who will use the product? What are the needs of the end user? What will the product look like? Which of its features are critical, and which are only desirable? Can the product be manufactured easily? How much will it cost? What are the safety factors? Who will decide how much risk is acceptable? Answering these questions at the outset will help at each subsequent stage of the design process.

Gather Information

At the early stages of a new project, you should devote time to gathering information. Learn as much as possible about technology related to the project. Identify useful off-the-shelf items that can be incorporated into your design. Send for catalogs, data sheets, and product information. Keep this information in a file folder where you'll find it easily. Also look for reports, application notes, or project descriptions in the same general area as your own project. A Web search can be extremely helpful in this respect, but filter information with care. Just because information has been posted on a Web site does not necessarily mean that it is accurate. Stick to official company Web sites or other reliable sources for technical information and application notes. View information from unknown sites with possible skepticism until you can verify its accuracy on your own.

Full product information, often more comprehensive than that available on the Web, usually can be obtained directly from the manufacturer. Perusing advertisements in trade magazines and journals can be a good way to learn what types of products are available in your field of interest. Often the magazine itself has a master reply card on which you can circle several requests for product information. Each field of engineering has many such publications. A few examples include *Electronic Design News* (electrical); *Compliance Engineering* (electrical); *Mechanical Engineering* (mechanical); and *Machine Design* (mechanical).

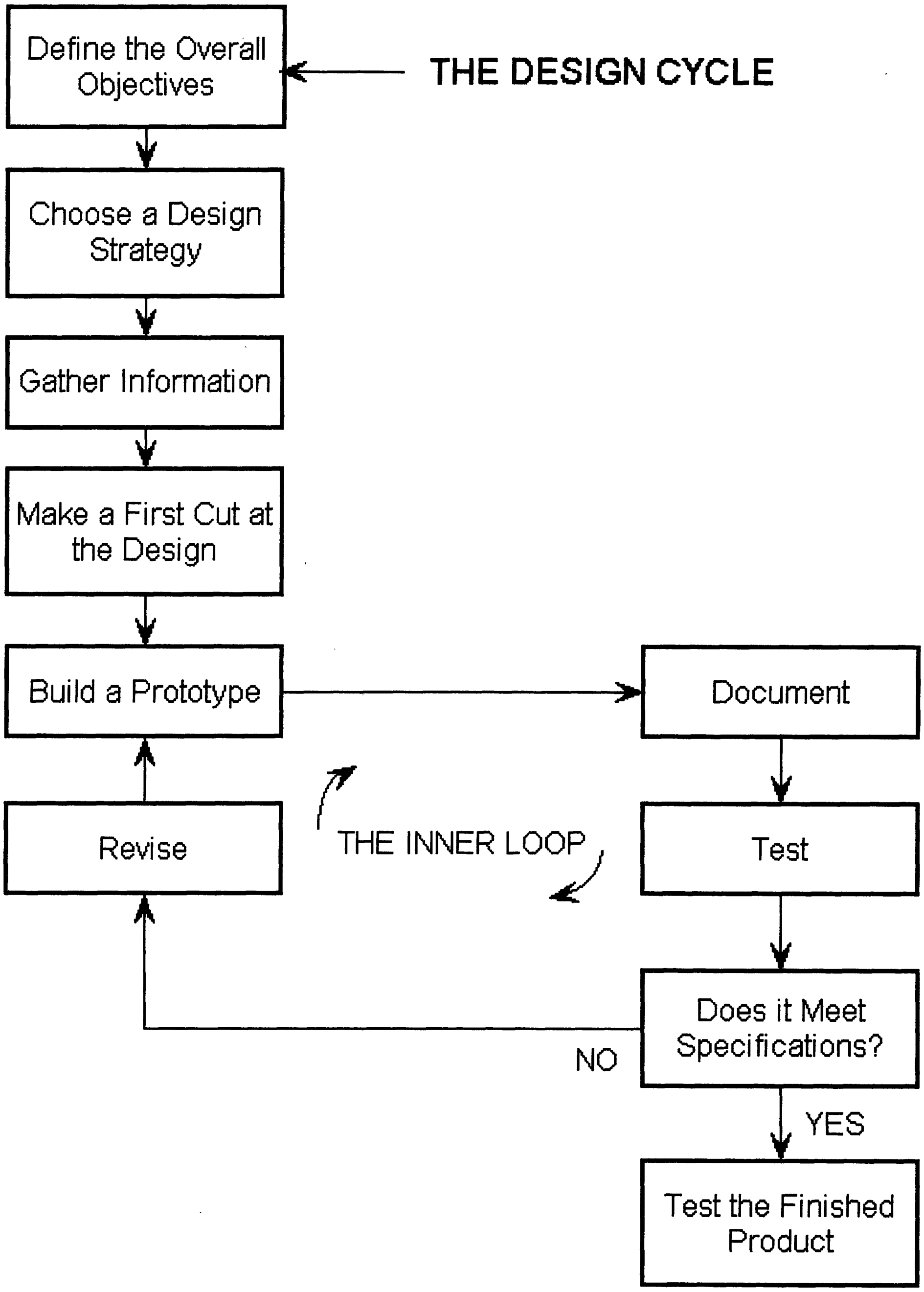


Figure 2.4. The design cycle.

Choose a Design Strategy

The next step in the design process involves the selection of a design strategy. This strategy will define the *methods* that you'll use to meet your design objectives. At this stage, the engineer (or, more likely, the design team) might decide whether the design will involve an electrical or mechanical solution, or whether the product will be synthesized from off-the-shelf components or from basic raw materials. If the system is complex, it should be broken up into simpler, smaller pieces that can be designed independently and later interconnected to form the complete product. These subsections, or *modules*, should be designed so that they can be tested individually before the entire system is assembled. Subdividing a large job into several more manageable tasks simplifies synthesis, testing, and evaluation. In a team design effort, the modular approach is essential. The various components of an automobile, for example, such as the engine, cooling system, electrical system, suspension, braking system, chassis, and drive train, are each tested individually before the entire automobile is assembled.

The design strategy also should consider any similar designs that are ongoing or have been created in the past. Perhaps a new technology exists that will be useful for your design? It may be that a partial solution is already available in commercial form. The wise engineer makes use of existing products and components to simplify the design task. There is no shame in using off-the-shelf ingredients or subsystems if they can help you achieve your design objectives more quickly and inexpensively. Typically, labor is the most expensive part of any development effort, so it's often cheaper (and sometimes more reliable) to buy something ready-made than to design it from scratch. For example, imagine how needlessly complex the task of designing a desktop computer would be without making use of the disk drives, memory chips, power supplies, monitors, and central processors available from other vendors. One caution: Be certain that using another company's product does not create patent infringement problems if yours is destined for commercial sale.

Make a First Cut at the Design

After the design strategy has been solidified, it is time to make an a first cut at the design. If the product is to be a physical entity, a detailed layout or engineering drawing is helpful at this stage. Tentative values of dimensions and other parameters should be assigned wherever possible. Key sizes, dimensions, construction materials, part numbers, electronic component values, and other relevant parameters are specified. This step typically involves *rough approximations* and gross estimates. Its primary purpose is to determine whether or not the design approach has a chance of working, and it should result in a rough, tentative prototype for the system or each of its subsections. If the object of the design effort is a software product, its outer shell, overall structure, and user interface are laid out as part of the first-cut attempt.

Build, Document, and Test

After the first cut has been committed to paper, it's next translated into a working prototype. The first prototype will be revised many times before the design cycle has been completed. It should be functional, but need not be visually attractive. It's primary purpose is to provide a starting point for evaluation and testing. If the product is software, for example, the prototype might consist of the main calculation sections without the fancy graphical interfaces that the user will expect in the final version. If the product is mechanical, it can be built up as a mock-up from easy-to-modify materials, such as wood or prepunched metal strapping. For instance, a prototype for a new washing machine engine might be built inside an open wooden box made from framing lumber and hinged plywood. Such a structure would permit easy access to the inner machinery during testing but obviously would never make it to the sales floor. If the product is electrical, its prototype could be wired on a temporary circuit breadboard. A new digital clock, for example, might be built in this way so that the designer could have easy access to its timing and display signals for test purposes. This arrangement would allow for circuit revisions before final construction and packaging.

During the prototyping phase of design, computer simulation tools such as AutoCAD™, ProENGINEER™, SPICE, or Simulink™ can save time and expense by allowing you to predict performance before actual construction of the prototype. These software packages can help you identify hidden flaws *before* the product is built and give you some indication as to the success of your design approach. However, they should never be used as a substitute for physical testing. Glitches, bugs, and other anomalies caused by physical effects not modeled by the simulator have a nasty habit of appearing when the real product is tested. Despite the usefulness of computer-aided design tools and simulators, there is simply no substitute for constructing and testing a real physical prototype.

Note that documentation is part of the inner loop of the design cycle of Figure 2.4. The typical engineer faces considerable temptation to leave documentation to the very end. Pressed with deadlines and project milestones, many an inexperienced engineer thinks of documentation as a nuisance and an intrusion rather than as an integral part of the design process. After working diligently on a design project, this engineer then faces the dread realization, "Oh, my gosh, now I've got to write this up!" Documentation added as an afterthought is often incomplete or substandard, because most of the relevant facts and steps have been forgotten by the time writing takes place. Haphazard, after-the-fact documentation is the cause of many a design failure. Many a product, developed at great cost, but delivered with pathetic documentation, has found its way to the trash heap of engineering failures because no one could figure out how to use or repair it. Poor documentation also leads to duplication of effort, or reinvention of the wheel, because no one can remember or interpret the results of previous work.

A good engineer recognizes that documentation is absolutely critical to every step of the design process. He or she will plan for it from the very beginning, keeping careful records of everything from initial feasibility studies to final manufacturing specifications. It's a good idea to write everything down, even if it seems unimportant at the time. Documentation should be written in such a way that another engineer who is only slightly familiar with the project can pick up the work at any time by simply reading the documentation. Also, careful documentation will aid in writing product literature and technical manuals should the product be destined for commercial sale. Good documentation provides the engineer with a running record of the design history and the answers to key questions that were asked along the way. It provides vital background information for patent applications, product revisions, and redesign efforts and serves as insurance in cases of product liability. Above all, documentation is part of an engineer's professional responsibility, and it's importance to engineering design cannot be overemphasized. Because the issue of documentation is so important, we shall revisit it in more detail in later chapters.

Revise and Revise Again

One of the characteristics of design that distinguishes it from reproduction is that the finished product may be totally different from what was envisioned at the beginning of the design cycle. Elements of the system may fail during testing, forcing the engineer to rethink the design strategy. The design process may lead the engineer down an unexpected path or into new territory. A good engineer will review the status of a product many times, proceeding through numerous revisions until the product meets its specifications. In truth, this revision process constitutes the principal work of the engineer. An experienced engineer recognizes it as a normal part of the design process and does not become discouraged when something fails on the first or second try. The revision cycle may require many iterations before success is achieved.

Thoroughly Test the Finished Product

As the design process converges on a probable solution, the product should be thoroughly tested and debugged. Performance should be assessed from many points of view, and the design should be modified if problems are identified at any stage. If the product is a physical entity, the effects of temperature, humidity, loading, and other environmental factors, as well as the effects of repeated and prolonged use all must be taken into account. A physical product should be subjected to an extended "burn-in," or use period, to help identify latent defects that might cause it to fail in the field. The human response to the product also should be assessed. No two people are exactly alike, and exposing the product to different individuals will help identify problems that may not have been apparent during the development phase. Similarly, a software product should be tested at numerous "beta sites" so that a variety of different users can weed out hidden bugs. Only after a comprehensive test period is the product ready to be put into actual service.

PROFESSIONAL SUCCESS: HOW TO TELL A GOOD DESIGN ENGINEER FROM A BAD DESIGN ENGINEER

As you pursue your engineering career, you will encounter many individuals. Some will be good engineers, and others will be bad engineers. In your quest to identify and emulate only good engineers, you should learn the differences between the two. The following list highlights the traits of both types of engineers.

A Good Engineer:

- Listens to new ideas with an open mind.
- Considers a variety of solution methodologies before choosing a design approach.
- Does not consider a project complete at the first sign of success, but insists on testing and retesting.
- Is never content to arrive at a set of design parameters solely by trial and error.
- Uses phrases such as "I need to understand why" and "Let's consider all the possibilities."

A Bad Engineer:

- Thinks he/she has all the answers and [illegible] tens to the ideas of others.
- Has tunnel vision; pursues with intensity the first approach that comes to mind.
- Ships the product out the door without thorough testing.
- Uses phrases such as "Good enough" and "I don't understand why it won't work, so-and-so did it this way."
- Equates pure trial and error with engineering design.

Exercises 2.2

E8. Without looking at Figure 2.4, draw a diagram of the design cycle that includes the following steps: *define, gather, choose, first cut, build, document, test, revise.*

E9. Make a list of the various ways in which an engineer might gather information as part of the design cycle.

E10. Draw a modified design cycle, similar to Figure 2.4, that includes feedback from a test group of individual users.

E11. Define the design strategy that might have gone into the invention of the wheel.

E12. Describe the various elements of the design cycle as they might have applied to the development of the common paper clip.

2.5 A DESIGN EXAMPLE

The principles presented in Section 2.4 describe the essence of the design process. Let's illustrate these steps using a simple example. In this section, we'll introduce a specific design problem and use it to follow the phases of the design cycle. We will revisit the same design problem in later chapters as we explore elements of the design process in more detail.

The Peak Performance Design Competition

Suppose that your professor has announced a design competition as part of an introductory engineering course. The rules of the contest are outlined in the following flyer:

COLLEGE OF ENGINEERING
PEAK-PERFORMANCE DESIGN COMPETITION

OBJECTIVE

The goal of the competition is to design and construct a vehicle that can climb a ramp under its own power, stop at the top of the ramp, and sustain its position against an opposing vehicle coming up the other side of the ramp. The illustration of Figure 2.5 shows the approximate dimensions of the ramp. The 30-cm width of the carpet-covered track may vary by ±0.5 cm as the vehicle travels from the bottom to the top of the ramp. A vehicle is considered to be on "top of the hill" if it, including any extensions, strings, or jettisoned objects, is completely within the two 120-cm lines at the end of a 15-second time interval. (See illustration.)

VEHICLE SPECIFICATIONS

1. The vehicle must be autonomous. No remote power, control wires, or remote control links are allowed.
2. The vehicle's exterior dimensions at the start of each run must not exceed 30 cm × 30 cm × 30 cm. A device, such as a ram, may extend beyond this limit once activated, but cannot be activated before the start of the run.
3. The vehicle must be started by an activation device (e.g., switch, mechanical release, etc.) on the vehicle. Team members may not activate any device before the start. Vehicles cannot be running and dropped to start.
4. The vehicle can be powered only by one of the following energy sources:
   - Batteries of up to 9 volts
   - Rubber bands (4 mm × 10 cm maximum size in their unstretched state)
   - Mouse traps (spring size 1 cm × 3 cm maximum)
5. The vehicle's weight, including batteries, must not exceed 2 kg.
6. The vehicle must not use chemicals or dangerous substances. No rocket-type devices, CO_2 propulsion devices, or chemical reactions are allowed. No mercury switches are permitted. Mercury is a toxic substance, and a risk exists that a mercury switch will break during the competition.
7. The vehicle must not be anchored to the ramp in any way before the start. At the end of the run, the vehicle and all its parts, including jettisoned objects, extensions, etc., must lie completely within the top of the hill and the 30-cm track width.

8. The vehicle must run within the 30-cm wide, carpet-covered track. It may not run on top of the guide rails.
9. The vehicle must compete in six 15-second runs against opposing vehicles. The vehicles with the most wins after six runs will be selected for the Grand Finale, which will determine the winner of the competition. Modifications to the vehicle are permitted between (but not during) runs.

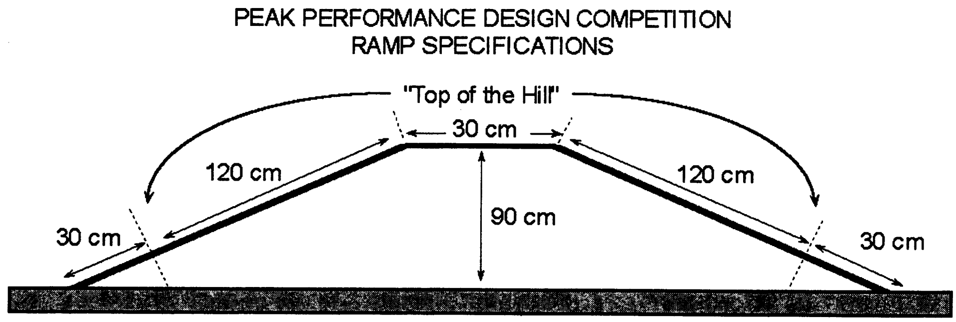


Figure 2.5. Ramp specifications for the Peak Performance Design Competion.

Let's now examine this problem statement in the context of the design cycle presented in Figure 2.4. Remember that the problem can be addressed in any number of ways, but some design solutions will work better than others.

Define the Overall Objectives

When faced with the task of designing something, many an engineer is tempted to begin with construction right away, before a careful planning stage. Building things is fun and satisfying, while estimating, sketching, calculating, simulating, and checking design parameters seems less glamorous. Its important, however, to begin any project by taking time to define its objectives.

Suppose that you and a classmate have decided to enter the design competition. Your first step should be to write down a list of general criteria to be met by your design effort. You make a list of tradeoffs that characterize the problem as you try to foresee problematic areas and develop strategies for overcoming them. You arrive at the following set of design objectives:

1. *Design for speed.* The fastest vehicle will not necessarily be the winner, but a in order to win, the vehicle must reach and maintain the center line well before the 15-second time limit.
2. *Design for defensive and offensive strategies.* Not only must your vehicle reach the top of the ramp and stop on its own, but it must maintain its position as your opponent tries to do the same. Although offensive and defensive strategies are not necessarily mutually exclusive, you've decided (somewhat arbitrarily) that defense will be given a higher priority than offense.
3. *Design for easy changes.* The rules state that modifications to the vehicle are permitted between runs. During the contest, you may see things on other vehicles that will prompt you to make changes in your own vehicle. Adopting an easy-to-change construction strategy will facilitate on-the-fly changes to your vehicle. The likely tradeoff in choosing this approach is that your car will be less durable and more likely to suffer a disabling failure.

4. *Design for durability.* The vehicle must endure six, and possibly more, trips up the contest ramp. Opposing vehicles and accidents can damage a fragile design. You must weigh the issue of durability against your desire to produce a vehicle that's flexible and easy to modify.
5. *Design for simplicity.* By keeping your design simple, you will be able to repair your vehicle quickly and easily. An intricate design might provide more performance features, but it also will be more prone to breakdowns and will be more difficult to repair.

Note that these goals are not independent of one another. For example, designing for easy changes may conflict with building a durable vehicle. Designing for both offensive and defensive strategies will lead to a more complicated vehicle that is harder to repair. Engineers typically face such tradeoffs when making design decisions. Deciding which pathway to take requires experience and practice, but making any decision at all means that you've begun the design process.

Choose a Design Strategy

Many different design strategies will lead to a vehicle capable of competing. Building a *winning* design, however, requires careful planning and attention to numerous details and design features. Success requires making the right choices at each step in the design process. How can you know ahead of time what the right choices will be? In truth, you cannot know, especially if you have never built such a vehicle before. You can only make educated guesses based on your experience and intuition. You test and retest your design choices, making changes along the way if they increase your vehicle's performance. This process of *iteration* is a crucial part of the design process. Iteration refers to the process of testing, making a change, and then retesting to observe the results. Good engineering requires many iterations, trials, and demonstrations of performance before a design effort is completed. In the world of engineering, the first cut at a design seldom resembles the finished product.

The rules of the competition provide for many alternatives in vehicle design. Regardless of the details of the design, however, all vehicles must have the same basic components: *power source*, *propulsion mechanism*, *stopping mechanism*, and *starting device*. Although not required, a defense mechanism that prevents an opponent from pushing the vehicle back down (or off) the ramp will increase your chances of winning. After some discussion with your teammate, you develop the *choice map* shown in Figure 2.6. This diagram displays some of the many design choices available to you. Although it does not provide a complete list, it serves as an excellent starting point for your design attempt. As your teammate points out, "We have to start somewhere." You remark in return, "Let's begin with our best guesses about which of these choices will work." The choice map of Figure 2.6 includes the following elements:

Power Source According to the rules of the competition, you may power your vehicle from standard nine-volt (9V) batteries, rubber bands, or mousetrap springs. Batteries are attractive because they require no winding or preparation other than periodic replacement. They will, however, be more expensive than the two alternatives. Rubber bands will require much less frequent replacement, but will store the least amount of energy among the three alternatives. Like a rubber band, a mousetrap needs no frequent replacing. It stores more energy than a rubber band, but offers the fewest options for harnessing its stored energy.

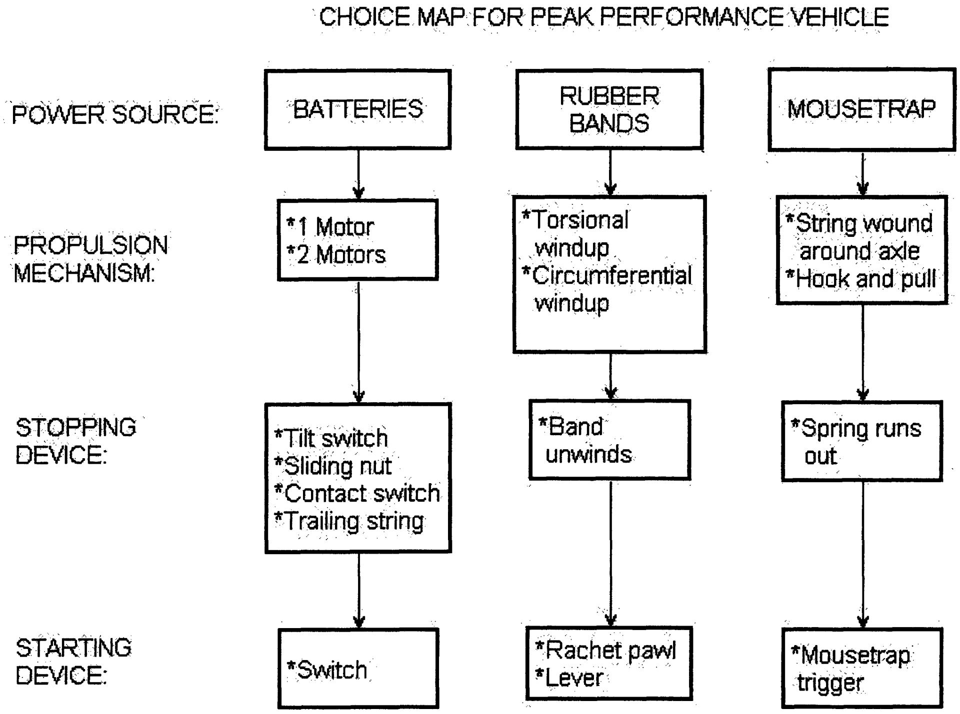
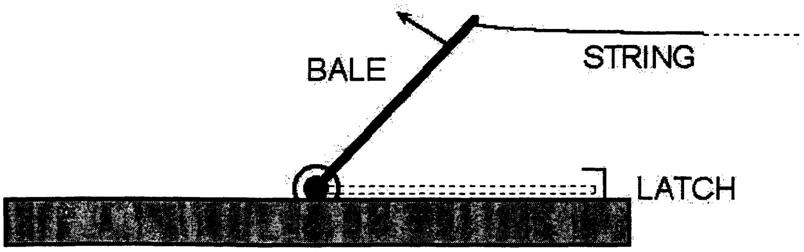


Figure 2.6. Choice map that outlines the decision tree for the first phase of the design process.

Propulsion Mechanism Your choice of the propulsion device, or *prime mover,* will depend entirely on your choice of power source. If a battery is used as the power source, an electric motor seems the obvious choice for turning the vehicle's wheels. Rubber bands can be stretched to provide linear motion or twisted for torsional energy storage and used to turn an axle or power shaft. Alternatively, a rubber band can be stretched around a shaft or spool like a fishing reel and used to propel the vehicle's wheels. A mousetrap can provide only one kind of motion. When released, its bale will retract in an arc, as depicted in Figure 2.7. This motion can be harnessed and used to propel the vehicle.

Stopping Mechanism Your vehicle must stop when it arrives at the top of the ramp. This requirement can be met by interrupting propulsion power precisely at the right moment. A braking device to augment power shutoff should also be considered. If the

Figure 2.7. Harnessing the stored mechanical energy of a mousetrap. The bale retracts in an arc when the mousetrap is released.



vehicle is powered by batteries, there are many possibilities for a stopping device. A simple tilt switch that disconnects the battery when the vehicle is level, but connects the battery when the vehicle is on a slope, will certainly do the job. For safety reasons, however, the rules prohibit the use of mercury switches (elemental mercury is toxic to humans), so any tilt switch used in the vehicle must be of your own design. One interesting concept would be to use an electronic timer circuit that shuts off power from the battery after a precise time interval. Through trial and error, you could set the elapsed time to just the right value so that the vehicle stops at the top of the ramp. One problem inherent to this open-loop timing system is that the vehicle does not actually sense its own arrival at the top of the hill, but rather infers it by precise timing. The possibility exists that the speed of the vehicle may be inconsistent from run to run, especially if the vehicle is battery powered. As battery energy is depleted, the speed of the vehicle will decrease, requiring more time to reach the top of the hill. Another alternative might be to connect a mechanism that cuts off power to the wheels after the car has traveled a preset distance as measured by wheel rotations. This scheme will work well if the wheels do not slip.

If a rubber band or mousetrap propulsion system is chosen, then stopping the vehicle will require something other than an electrical switch. One crude way of stopping a vehicle propelled by mechanical energy storage is simply to allow the primary power source to run out (e.g., by allowing the rubber band to completely unwind). However crude this method, it is reliable, because power input to the vehicle will *always* cease when the source of stored energy has been depleted.

Starting Device If the vehicle is powered by a battery, then an electrical switch becomes the most feasible starting device. A rubber band power source will require a ratchet pawl, trip lever, or other similar device in order to initiate power flow to the wheels. A mousetrap can make use of its built-in trigger mechanism or any other starting mechanism that you can devise.

Make a First Cut at the Design

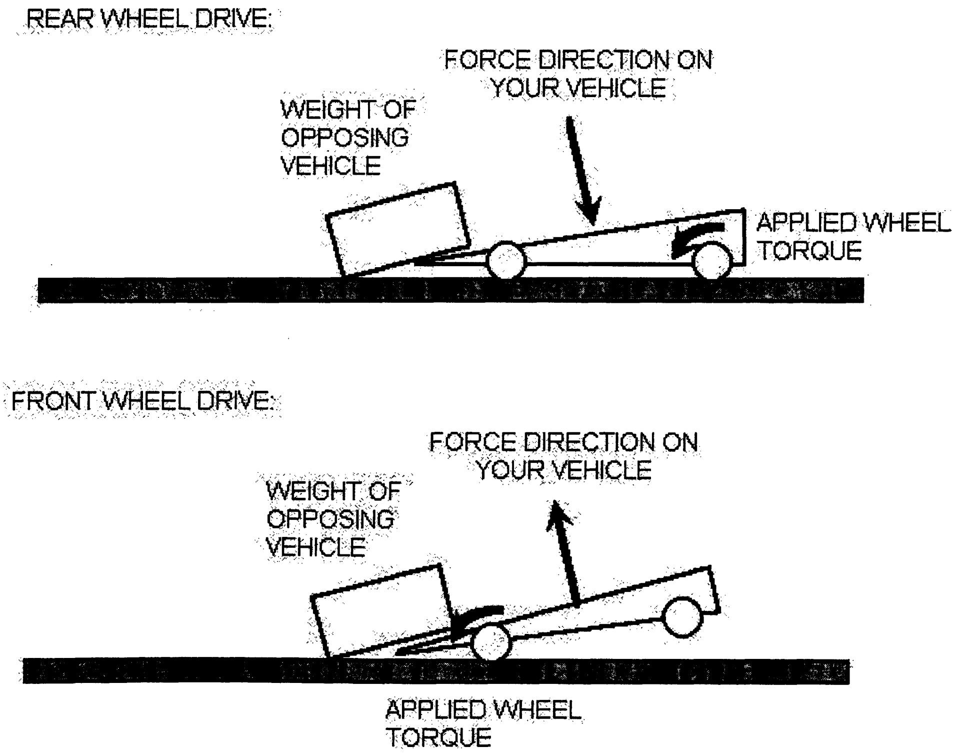
The first design iteration begins with rough estimations of the dimensions, parameters, and components of the vehicle to make sure that the design is technically feasible. After discussing the long list of design choices, you and your teammate decide upon a battery-powered vehicle. This decision makes available many choices for the stopping device and power train that far outweigh the advantages of mechanical propulsion schemes. You decide upon a defensive strategy and agree to build a slower-moving, wedge-shaped vehicle driven by a small electric motor. The advantage of this design strategy is that the motor can be connected to the wheels using a small gear ratio, thereby providing higher torque at the wheels and a mechanical advantage unavailable to a very fast vehicle. You plan to use plastic gears and axles purchased from a hobby shop. The gear box will reduce the speed of the wheels relative to the motor shaft speed, providing added mechanical torque that will significantly increase the force available to push the opposing vehicle off the ramp. Because your vehicle will be slower than others, it may not reach the top of the ramp first, but its wedge shaped design will help to dislodge the front of any opposing vehicle that arrives first at the top of the hill. If your vehicle should happen to arrive first at the top of the hill, your car's defensive wedge shape will cause your opponent's car to ride over your car's body, allowing you to maintain your place in the center of the ramp.

You decide to use one motor with a single driven axle attached to both rear wheels. An alternative strategy would be to drive each rear wheel separately, thereby allowing the driven wheels to turn at different speeds. Such *differential* capability is essential for vehicles that travel curved paths, but in this case the vehicle must travel along a straight path only. By driving the wheels from a common shaft, you will reduce slippage, because *both* wheels will have to lose traction before forward motion will be impaired. You briefly consider front-wheel drive, because you assume from listening to many car advertisements that front-wheel drive is superior to rear-wheel drive. Your teammate is quick to point out that the advantage of front-wheel drive for automobiles lies in its ability to help the car negotiate curves. Despite the media-driven message of "better traction," the advantages of front-wheel drive have nothing to do with your application. In fact, front-wheel drive may be a disadvantage to your wedge-shaped design, because it may cause your car to flip over forwards if another car travels on top of it. Your teammate draws the sketch of Figure 2.8 to illustrate this scenario. You abandon the idea of front-wheel drive.

Build, Document, Test, and Revise

A rough preliminary sketch of your car is shown in Figure 2.9. You've entered this sketch into a notebook in which you've been recording all information relevant to the project. Included in your notebook are design calculations, parts lists, and sketches of various pieces of the car. Shown in Figure 2.9 are the car's wedge-shaped design, a single drive shaft driven by a motor, belt, and pulleys, and a single switch to turn off the motor when the vehicle arrives at the top of the hill. Your design concept represents a tradeoff between several competing possibilities, but you and your teammate have decided that the car's electric motor drive and defensive shape have the best chance of winning the competition.

Figure 2.8. Front and rear wheel drive options for a moving wedge vehicle.



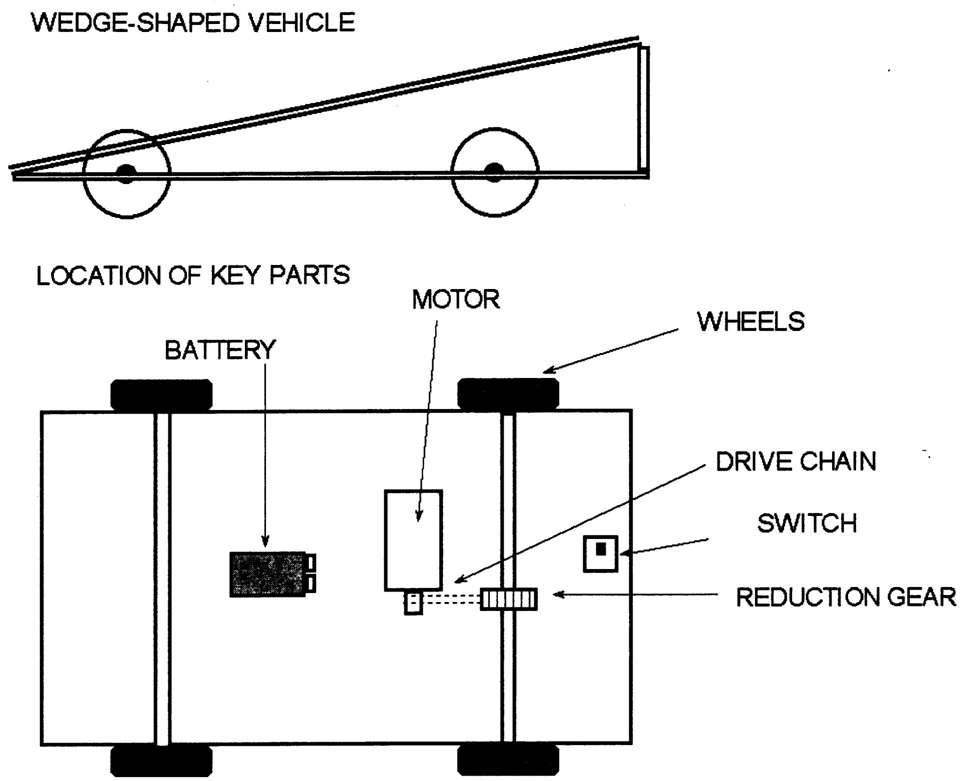


Figure 2.9. Rough, preliminary sketch of car for the Peak Performance Design Competition.

The sketch in Figure 2.9 represents a beginning, but it is not the finished product. You still have many hurdles to overcome before the design is ready to compete. The next step in the design process involves building and testing a first-cut prototype. To help you in this phase of the design process, your professor has constructed a test ramp available to all contestants. You begin by constructing a chassis shell in the form of a wedge, but without a motor drive or stopping mechanism.

You run your wedge-shaped vehicle up the ramp by hand. You soon discover that the bottom of the vehicle hits the ramp at the top of the hill, as depicted in Figure 2.10(a). The change in angle of the ramp is large, and all four wheels do not always maintain contact with the track surface. You discuss several solutions to this problem with your teammate. One solution would be to increase the size of the wheels, as shown in Figure 2.10(b). This change would decrease the mechanical advantage between the motor and the wheels, requiring you to redo your calculation of how much force will be required from the motor. Another solution would be to make the vehicle shorter, as shown in Figure 2.10(c), but you realize that this solution would lead to a steeper angle for the wedge shape of the vehicle and reduce its effectiveness as a defensive strategy. (The largest thickness of the vehicle must stay the same to accommodate the motor and gear box.)

Revise Again

Your teammate suggests keeping the wheels and shape of the wedge the same and simply moving the rear wheels forward, as depicted in Figure 2.11. You rebuild the vehicle by moving the rear shaft mount forward, and you test the vehicle again. The redesigned vehicle no longer bottoms out on the track, and you claim success. Your professor sees

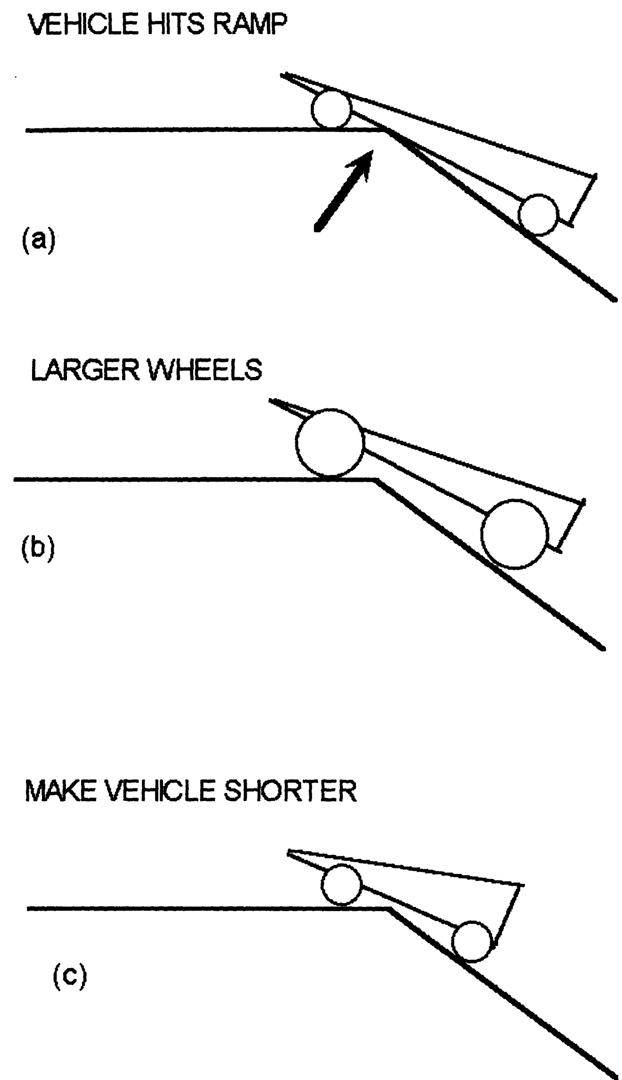


Figure 2.10. Vehicle at the top of the ramp. a) Bottom of vehicle hits the ramp; b) vehicle with larger wheels; c) a shorter vehicle.

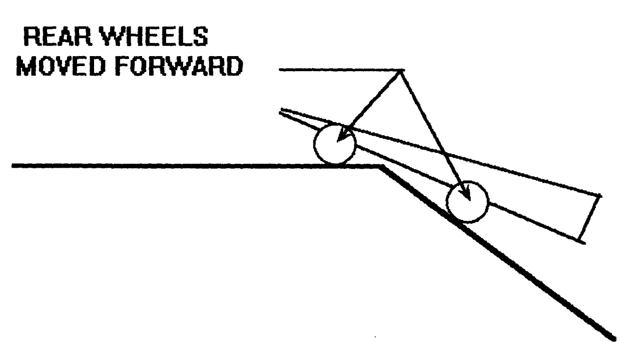


Figure 2.11. Moving the rear wheels forward.

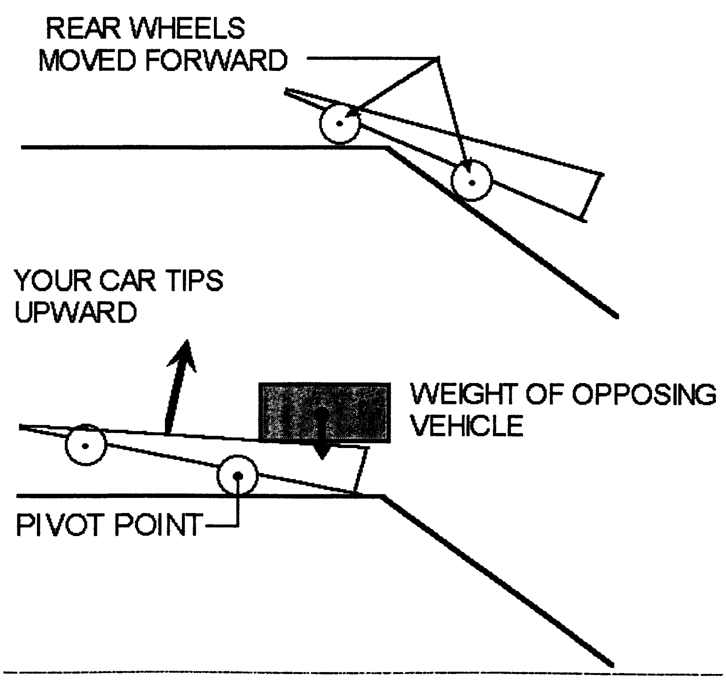
your design changes and suggests that you test your vehicle under more realistic conditions. For example, what will happen when another vehicle rides over the top of your wedge-shaped body? You proceed to simulate such an event by placing a weight at various positions on the top of the car. The results of these additional tests suggest that the wheel location modification may not be the best solution to your problem. When you move the rear wheels forward, you change the base of support for the car's center of gravity. You discover that if an opposing vehicle rides over the top of your car, the net center of gravity moves toward the rear, eventually causing your car to topple backwards, as depicted in Figure 2.12.

These discoveries and setbacks may seem discouraging, but they are a normal part of the design process. Some things work the first time, while others do not. By observing and learning from failure and by building, testing, revising, and retesting, you can converge on the best solution that will meet your needs.

After some thought, you decide that increasing the size of the wheels may be the best option after all. Your teammate points out that you can simply change the ratio of the gear box to preserve the net mechanical advantage between the motor and the drive shaft. This change will allow you to accommodate larger wheels. You buy some new wheels and try them with success. With the rear axle moved to its original location and the larger wheels in place, your car no longer bottoms out on the track.

You next consider the motor that will power the drive shaft. Motors of all sizes and voltage ratings are available, including some alternating current (ac) motors, as well as direct current (dc) motors. Given that your car will be powered by batteries, your obvious choice is a dc motor. What voltage rating should you choose? You find no motors rated at 9 volts at the local hobby shop. "I don't think anyone makes 9-volt motors," says

Figure 2.12. Weight of opposing vehicle on top of rear end causes car to topple over backwards.

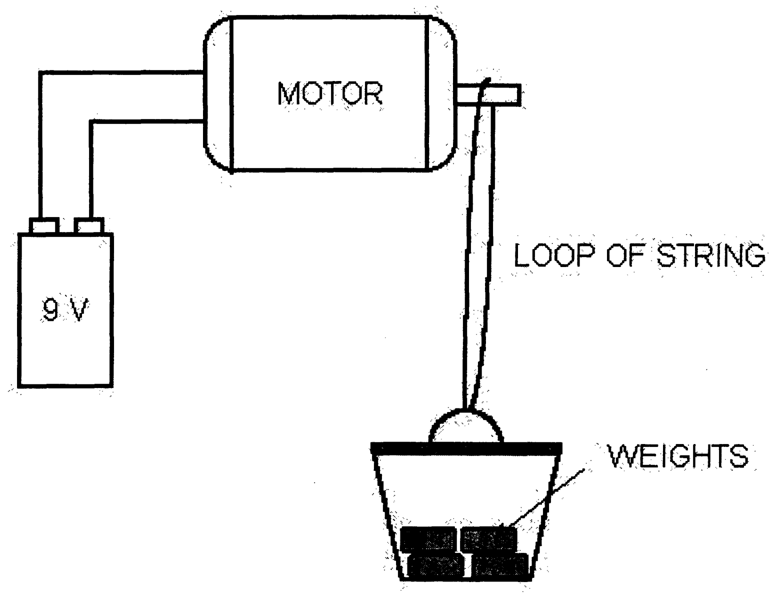


the salesperson behind the counter. You look up the Web pages of vendors*, scrutinize several catalogs , and find motors rated for 3, 6, 12, or 24 volts, but no 9-volt motors. Your professor explains that the rating of a motor specifies its operating voltage under steady-state use. If a lower-than-rated voltage is used, the maximum torque available from the motor will be reduced. If a higher-than-rated voltage is connected, the excess current will heat the windings inside the motor and possibly damage it. In the Peak Performance design competition, however, the motor will be energized only for about 15 seconds at a time. This interval may be short enough to allow a larger-than-rated voltage to be applied without harming the motor. The feasibility of this intentional overloading must be verified by testing or by contacting the motor's manufacturer.

After hearing your professor's explanation, your team decides to purchase several different motors rated at 3 volts and 6 volts. You test each one by connecting it to a variable voltage supply and measure the current flow at various applied voltages. You compute the power flow by multiplying voltage and current. You devise the apparatus shown in Figure 2.13 to measure the mechanical power delivered by the motor. Your contraption is a crude version of the industry-standard Prony brake used to measure motor torque. The frictional rubbing of the weighted loop of string applies a mechanical load to the motor. You power each of your motors at the same voltage and add weights until the motor stalls. The motor that sustains the largest weight before stalling will have the largest torque. You check your mechanical loading measurements against your electrical measurements and use your data to determine which motor gives you the most mechanical torque when powered by 9 volts.

As suggested by your professor, you and your teammate each keep a design notebook in which you record all your design decisions and the results of all your experiments and tests. Figure 2.14, for example, shows a page from your notebook in

Figure 2.13. Simple apparatus to measure motor torque.



* See, for example, http://www.robotics.com; http://www.nwsl.com/products; http://www.morat.com; or http://www.sdp-si.com.

MOTOR A: TC-254

# weights	V(volts)	I (amps)
0	9.0	0.02
1	8.9	0.05
2	8.9	0.07
3	8.8	0.1
4	8.7	0.2
5	8.0	0.5

MOTOR B: RS-257-234

# weights	V(volts)	I (amps)
0	9.0	0.05
1	8.8	0.1
2	8.7	0.17
3	8.5	0.23
4	8.0	0.3
5	7.6	0.7

MOTOR C: BOD-37A

# weights	V(volts)	I (amps)
0	9.0	0.01
1	8.9	0.04
2	8.9	0.05
3	8.8	0.1
4	8.7	0.25
5	8.0	0.52

MOTOR D: TOSH-7954

# weights	V(volts)	I (amps)
0	9.0	0.01
1	8.9	0.11
2	8.9	0.21
3	8.8	0.31
4	8.7	0.41
5	8.7	0.51

Figure 2.14. Page from lab notebook that documents mechanical loading tests on various motors.

which you've recorded a list of your motor collection plus the results of the mechanical loading tests. You've also sketched the loading apparatus of Figure 2.13 in your notebook. It's important to record the characteristics of the motors you *do not* use in case your design needs change and you need to reconsider one of the rejected motors. As your design proceeds, you record all calculations, specifications, and sketches pertinent to the drive train, including gear ratios, electrical power consumption, wheel diameters, weight of each part, and construction techniques. Your objective is to have a complete record of your design activities by the time you enter the vehicle competition.

Exercises 2.3

E13. Make a two-column list that outlines the advantages of the various power sources for the Peak Performance Design Competition.

E14. Make a list of additional propulsion mechanisms not mentioned in this section that could be used to drive a Peak Performance vehicle.

E15. Make a two-column list that outlines the advantages of using gravity versus friction as a stopping mechanism for the Peak Performance Design Competition.

E16. Determine the minimum energy needed to lift a Peak Performance vehicle of maximum allowed weight from the bottom to the top of the ramp.

E17. How much electrical energy (in joules) is needed to exert 1 N of force over a distance of 1 meter?

E18. How much electrical power (in watts) is needed to exert 1 N of force on a body over a distance of 1 meter for 10 seconds?

E19. Determine the number of turns per cm of wheel diameter that will be required to move a vehicle from the bottom to the top of the ramp in the Peak Performance Design Competition.

E20. Determine the diameter of the wheels needed to move a vehicle from the bottom to the top of the ramp in the Peak Performance Design Competition with 50 turns of the drive axle.

SUMMARY

This chapter has outlined the essential elements of design at a very basic level. Design differs from analysis and reproduction because it involves multiple paths to solution, decision making, evaluation, and testing. The *design cycle* is an important part of engineering problem solving, as are knowledge, experience, and intuition. Documentation is critical to the success of a product and should be an integral part of the design process.

The chapters that follow examine several aspects of design in more detail using the Peak Performance Design Competition as a continuing example. Some of the topics to be presented include teamwork, brainstorming, documentation, estimation, modeling, prototyping, project organization, and the use of computers in engineering design.

KEY TERMS

Design	Analysis	Design cycle

Problems

The following problem statements can be used to practice problem solving and idea generation. Some of them involve paper designs, while others are suitable for actual fabrication and testing.

1. Develop a design concept for a mechanism to allow hands-free operation of a telephone. Outline its basic form, key features, proposed method of construction, and prototyping plan. Consider size, weight, shape, safety factors, and ease of use.
2. Design a device for securing a coffee cup near the driver's seat of an automobile. The device should prevent the cup from spilling and should not interfere with the proper operation of the car. It should be universally adaptable to a wide variety of vehicles. Address safety and liability issues as part of your design.
3. Design a device for carrying a cellular telephone on a bicycle. Your contraption should allow the rider to converse while holding on to the handlebars with both hands.
4. Develop at least three design concepts for a nonlethal mousetrap. Is your device cost effective compared with an ordinary, spring bale mousetrap? Is your trap more humane, and is it worth any added cost?
5. Devise a concept for a device that can dig holes in the ground for the installation of fence posts. Develop a prototype and test plan for your design concept.
6. Design a device that will allow the inside and outside surfaces of windows to be cleaned from the inside only. Compare projected cost with that of a simple, handheld, squeegee-type window cleaner.
7. Design a system for feeding aquarium fish automatically when the owner is out of town.
8. Develop a design concept for a spill-free coffee cup.
9. Design a device for carrying bricks to the top of a house for chimney repair. The alternative is to carry them up a ladder by hand.
10. Design at least three different systems for measuring the height of a tall building. If resources permit, try out your designs on a nearby building and compare results.
11. Design a system that will enable a self-propelled lawn mower to cut the grass in a yard unattended.
12. Design a system for minimizing the number of red lights encountered by cars traveling east and west through a major city. The system should not unnecessarily impede north-south traffic flow.

13. Devise a method for managing the flow of two-way railroad traffic on a one-track system. The single line of track has a parallel spur track located every five kilometers. These parallel sections of track allow one train to wait as another passes by in the opposite direction.
14. Design a public transportation system in which every traveler can ride a private vehicle on demand from any one station to another.
15. Develop a design concept for a system to measure the speed of a passing train.
16. Design a system for automatically turning off a small electric baking oven when a cake inside is done.
17. Design an electric switch that will turn off lights if the room is vacated.
18. Design a device that will enable a quadriplegic to change the channels on a television set.
19. Devise a system for turning on security lights at dusk and turning them off at dawn. These lights are to be installed throughout a large factory. You system should have a single master override for all lights.
20. Design a warning system for your home freezer that will alert you to abrupt changes in temperature.
21. Design a system for keeping a satellite's solar panels pointed at the sun.
22. Design a system that will automatically water houseplants when they are in need of moisture.
23. Design a device that will allow a one-armed individual to properly use dental floss.
24. Design a method for counting the number of people who attend a football game.
25. Design a lamp post that will break away when struck by an errant automobile.
26. Design an irrigation system that will bring water from a nearby pond to your vegetable garden.
27. Design a system that can aerate the pond in a city park so that algae growth will not overtake other forms of wildlife.
28. Design a system for automatically steering a ship along a desired compass heading.
29. Design an apparatus that will keep a telescope pointed at a distant star despite the rotation of the earth.
30. Devise a system for painting car bodies automatically by robot. You must include a method for training the robot for each painting task.
31. Devise a plan for a campus-wide information system that will allow any professor to access the grades of any student, while maintaining the privacy of the system to other users. A student also should be able to obtain his or her own grades, but not those of others.
32. Design an electric pencil sharpener that will turn off when the pencil has been properly sharpened.
33. Develop a design concept for a device that will turn on a car's windshield wipers automatically when rain falls. The wipers should come on only momentarily when rainfall is light but should be on all the time when the rainfall is moderate to heavy.
34. One of the problems with recycling of post-consumer waste is the sorting of materials. Consumers and homeowners cannot always be relied upon to sort correctly, yet one erroneously placed container can ruin a batch of recycled material. At the present time, most municipalities resort to manual labor to sort recyclable materials. Devise a concept that will sort metal cans, plastic bottles, and plastic containers at a recycling plant. Develop a plan for modeling and testing your system.
35. Design a concept for a voice-synthesized prompting system that can provide cues for an individual who must take medication on a strict regimen. The device need not be pocket sized, but should be portable and battery operated.
36. Design a system consisting of several panic buttons that will be installed at each of several workshop fabrication stations on a factory floor. Pressing any one of these buttons would activate a signal at a central control console and identify the location of the activated button. Ideally, voice communication over the system would be a desirable feature. One matter to consider is whether a wired or a wireless system is better.

37. An elementary school teacher needs a calendar-teaching system to help students learn about dates, appointments, and scheduling events. Your professor has asked you to develop a design concept. The basic system should be a large pad over which a monthly calendar can be placed. The underlying pad should have touch-sensitive sensors that can detect a finger placed on each day block in the calendar. The entire unit should interface with a desktop computer which will run a question-and-answer game or program. The typical types of questions to be asked might include, "You have scheduled a dentist appointment two weeks from today. Point to the day on the calendar on which you should go to the dentist," or "Sara's birthday is on February 11. Point to that day on the calendar." An appropriate reward, either visual, auditory, or both, should be issued by the computer for correct answers. A nonintimidating signal should be issued for incorrect answers. Outline the key features of your system and devise a development plan.

The following three projects involve devices that will assist the professor running the Peak Performance Design Competition introduced in Section 2.5:

38. The rules of the Peak-Performance Design Competition state that each vehicle must be placed behind a starting line located 30 cm up the side of a 1.5-m ramp. After the starting signal is given from the judge, contestants must release their vehicles, which then have 15 seconds to acquire and maintain a dominant position on top of the ramp. Any vehicle that travels over the 30-cm starting line prior to the "go" signal loses the run. Currently, the starting sequence is initiated orally by the judge and timed by stopwatch. This system leads to much variability between judges, as many use different starting signals (e.g., "on your mark, get set, go" or "one, two, three, go"), and one may be lax in timing or checking for starting line violations.

    Design a system consisting of starting-line sensors, a start signal, a 15-second interval signal, and starting-line violation signals for each side of the ramp. The judge should have a button that initiates the start sequence. A series of periodic beeps that mimic the words, "ready, set, go!" should sound, with the final "go" being a loud and clearly distinguishable tone or buzzer. In addition, a green light or LED should illuminate when the "go" signal is sounded. The system should time for 15 seconds, then sound another tone or buzzer to indicate the end of the 15-second time interval. If a vehicle crosses the starting line prior to the "go" signal, a red light should go on for the violating vehicle's side of the ramp, and a special "violation" signal should be sounded to alert the judge.

39. Teams in the Peak-Performance Design Competition are called to the floor when it is their turn to compete. After the initial call, each team has three minutes to arrive at its starting line. A team that does not show up at the starting line after three minutes loses that run. Warnings are supposed to be given two minutes and one minute before the deadline. Traditionally, the announcer has called the teams and issued these warnings orally. With three races running simultaneously, all starting at different times, and with only some teams requiring the full three minutes to arrive, the proper issuing of these cues has been lax. The judges have asked that you design an automated system that will inform a given team how much of its three-minute sequence has elapsed. The system must send an appropriate signal, oral, auditory, or visual, to only the affected team, and the timing sequence must be initiated from the judges bench. As many as eighty teams may compete on a given day, and each is assigned one work table from a large array of 3 × 8-ft. tables where the competition is held. Typically, the team being called is delayed, because it is repairing or modifying its vehicle.

    One of the key design issues is whether a wireless or wired system is the better system, given the logistic constraints of the competition environment. As the event operates on a strict budget, ultimate cost is also an important factor.

40. Vehicles entering the Peak-Performance Design Competition must meet several constraints, including a maximum battery-voltage limit. Each vehicle is checked once with a voltmeter at the start of the day by the head judge. Having a standardized voltage-checking device would shorten the time for voltage checking. Design a unit that has a rotary (or other type of)

switch that can select a predetermined battery voltage. If the measured battery falls within the acceptable range, a green light should come on. If the voltage falls below or above the range, yellow and red lights, respectively, should come on.

41. A local company employs several workers who sort and package small (1 to 2 cm) parts in the 10–100 gm range. A typical operation might consist of putting ten small parts in a polyethylene bag for subsequent packaging. As part of a course design project, your professor has asked you to design a mechanical sorting apparatus for dispensing these parts one at time so that the employees do not have to pick them up by hand. Develop an outline for how such a system might work, and draw a sketch of your proposed apparatus.

42. Ace Cleaning Services employs custodians performing a variety of cleaning tasks at four major building in the downtown area. Many of these individuals have poor cognitive abilities and are unable to generalize the cleaning skills they have been taught. They cannot perform a supervisor-demonstrated office-cleaning task in a different office, even if a similar operation is involved. As a result, their cleaning job performance is often poor. Many of the employees rely on supervisor cues to repeatedly perform to acceptable standards the same task in different locations.

    A crew from Ace has been assigned to a 22-story office building with over 500,000 sq. ft. of space that requires cleaning. Approximately thirty employees service this building between 6:00 am and 10:00 pm with a staffing pattern of nine people. Workers are dispersed throughout the building to perform their daily cleaning routines. Supervisors are responsible for training and for checking that the work has been performed to acceptable standards. Many of the supervisors also perform direct labor and hence cannot consistently provide prompting or cues to the rest of the employees all the time. What is needed is a communication system that can provide on-the-job cues to the cleaning staff. One system is needed for individuals who are literate and another for individuals who are not. Your task in this project is to design a modular system of either type. The system must be designed so that additional units can be reproduced at low cost. As part of a project in your engineering design class, your professor has asked you to devise a system for providing recorded cues to Ace's employees. Develop a concept for the system, draw a sketch of one implementation, and outline how such a system might work.

43. A teacher at the nearby Carver School teaches a student who has severe developmental delays. This student is highly motivated by the "Wheel of Fortune™" TV game show. The teacher currently has a four-foot-diameter, wall-mounted, colorfully painted cardboard circle that spins and simulates the real game. Use of this wheel is supplemented by video clips of the game played on a VCR. The teacher would like a more elaborate, electronically interfaced version of the game that enables the spinning dial to activate lights, voice, and the VCR clips. Despite the circus-like nature of this project, it is a top priority of the Carver school system. The customer is in need of an imaginative and creative response to this problem, and your engineering professor has asked you for ideas. Sketch several versions of the system, highlighting the advantages and disadvantages of each approach. How would you test the success of your design?

44. A teacher wants a clock system that can help students to learn the relationship between time displayed by digital clocks and time displayed by analog clocks. The system should have a console that contains a large analog clock face, as well as a digital clock display with large digits. In operation, the teacher will set either clock, then ask the student to set the other clock to the same time. If the student sets the time correctly, the unit should signal the student appropriately. If the student fails to set the time correctly, the unit should also issue an appropriate response. Outline the salient features of such a system.

45. Your school has been asked by an individual confined to a wheelchair to build a small motorized flagpole that can be raised and lowered by pressing buttons. The person needs such a device to hold a bright orange flag to provide visibility outdoors while navigating busy city streets and sidewalks. The flag must be lowered when the individual enters buildings so that the pole does not interfere with doorways and low ceilings. Here is a copy of the letter received by your school:

East Crescent Residence Facility
11 Hastings Drive
West Walworth, MA 02100

Prof. Hugo Gomez
College of Engineering
Canton University
44 Cummington St.
Canton, MA 02215

RE: Retractable Flag for Wheelchair

Dear Professor Gomez,

I am the supervisor of a residence facility that services adults with special needs. One of our residents is confined to a wheelchair and spends a great deal of time traveling throughout the community, often on busy streets, in a motorized wheelchair. Although a flag on a long pole would increase her safety, she is reluctant to install one on her wheelchair, because it becomes a problem in restaurants, crowded stores, and on public buses. I was wondering if you might have some students who could design an electrically retractable flag, possibly with visual enhancement (e.g., a flashing light) that could be raised or lowered by the individual on demand. The flag deployment mechanism could operate from either the wheelchair's existing automobile-type storage battery or its own self-contained battery. If such a device is possible, could you give me a call? I would appreciate any assistance that you might be able to offer.

Sincerely yours,

Liz DeWalt
Director

Prof. Gomez has asked you to try to build such a device for Ms. DeWalt. How would you approach such a task? Such a seemingly simple device actually can be more complicated to design than you might think. Draw a sketch of the wheelchair device, then devise a design plan for building and testing several designs. Include a list of possible safety hazards to bystanders and the user. How can you include the user in the design process, and why is it advisable to do so? Also write a report of your preliminary findings for Prof. Gomez. Your design strategy should begin with a conceptional drawing of the device that you can send to Ms. DeWalt for comments. Generate a specification list and general drawing of the apparatus as well as a cover letter to Ms. DeWalt.

Design Considerations One goal of your design might be to make a flag device that can be mounted on *any* wheelchair, not just on that of Ms. DeWalt's client. Because many wheelchairs are custom designed for the user, your device must be easily adaptable for mounting on different wheelchair styles. Not all wheelchairs are motorized, hence your device must operate from its own batteries to accommodate hand-pushed wheelchairs. Another consideration in favor of separate battery power is that motorized wheelchair manufacturers usually specify that no other electrical or electronic equipment be connected to the primary motor battery for reasons of safety, reliability, and power integrity.

One last consideration concerns the placement of the switch needed to activate the flag. Like the flag itself, the activation switch must easily attach to structural features of the wheelchair and must be within easy reach of the user. At the same time, it must not be so obtrusive that it distracts the user when not in use and must not hurt anyone.

46. Develop a design concept for a computer-interfaced electronic display board that can be placed in the lobby of an office building to display messages of the day, announce upcoming seminars, or indicate the location of special events. The objective of the problem is to use a

matrix of addressable light-emitting diodes (LEDs) rather than a video display. The system should accept messages by wire from a remote site. One approach might be to design your display board system so that it is capable of independently connecting to a local area network via a telephone line. Alternatively, you could build a separate remote device that could be connected to a desktop computer and then brought down to the display board to load in the data. These examples are suggestions only. In general, any means for getting data to the board is acceptable, but a separate computer cannot become a dedicated part of the finished display.

47. An engineer is interested in measuring the small-valued ac magnetic fields generated by power lines and appliances. You have been asked to design a battery-powered, hand-held instrument capable of measuring the magnitude of ac magnetic fields in the range 0.1 to 10 μT (microtesla) at frequencies of 50–60 Hz. Magnetic fields of this magnitude are very small and are difficult to measure accurately. For comparison, the earth's dc magnetic field is on the order of 50 μT, and the magnetic field inside a typical electric motor is on the order of 1 T.

    Using your knowledge of physics, summarize the important features that such a device should have. Outline a design plan for its development and construction. You have several options for the primary sensor. For example, it may consist of a flat coil of wire of appropriate diameter and number of turns, or, alternatively, you might consider using a commercially available semiconductor sensor. Note that dc fields, such as those produced by the earth or any nearby permanent magnets, are not of interest. Hence, any signal produced by dc fields in your instrument should be filtered out. Ideally, your unit should have a digital or analog display device and should accommodate a remote probe if possible.

48. A friend of yours runs a residence home for individuals with mental and physical handicaps. She would like a medicine dispenser for dispensing pills at specific times. The unit is to be carried by an individual and must have sufficient capacity to hold medication for at least one day. The unit should open a cassette or compartment and should emit an audible or visual signal when it dispenses medication. The unit must be easy to load and should be easily programmable by a residence-home supervisor. Your friend has asked you to assess the feasibility of developing such a unit. Get together with up to four other students. Discuss the feasibility of the idea and develop one or more design concepts for implementation.

49. A friend or yours is an enthusiast of remote-control model airplanes. One perennial problem with radio-controlled airplanes concerns the lack of knowledge about the flight direction and orientation of the airplane when it is far from the ground-based operator. When the airplane is too far away to be seen clearly, the operator loses the ability to correctly control its motion. Develop a design concept for a roll-, pitch-, and compass-heading indicator system that can be mounted on the model airplane and used to send the information via radio back to the operator's control console. Your system should sense the pitch and roll of the airplane over the range +90 degrees to −90 degrees and be able to withstand a full 360-degree roll or loop-de-loop.

50. Your family has asked you to design a remote readout system for a vacation home to be interrogated by a remote computer over a modem and telephone line. The unit in the vacation home should answer the phone after ten rings, provide means for an entry password, and then provide the following information:

    Inside and outside temperatures,

    Presence of any running water in the house,

    Presence of any loud noises or unusual motion,

    Status of alarm switches installed on doors and windows.

    Discuss the design specifications for such a unit and develop a block diagram design for its implementation.

Engineering Ethics The following problems on ethics have no clear answers. They are included in this problem section to stimulate discussion on engineering ethics.

51. No mass-produced product can be made defect free 100 percent of the time. Suppose that you have the job of designing the gasoline tank for a new model of automobile. One of the problems with gas tanks is that they can rupture upon impact, leading to fire and explosion. You've determined that the cost of adding a metal baffle shield behind the gas tank to protect it in the event of a rear-end collision is approximately $50 per vehicle (including labor). The shield will add about 10 kg of weight to the vehicle, reducing its gas mileage by an average of about 0.2 percent. Your statistical models suggest that 0.1 percent of the cars sold will be involved in rear-end collisions during their product lifetime. Given that approximately 100,000 of the cars will be sold in the first model year, should you advocate for adding the protective baffle, or should you leave it out to save money and increase profit margin?

52. You have worked for eight years for Hobo Electronics designing microchips. During the past year, you helped design a state-of-the art processor that significantly surpasses the performance of your competitors' microchips. This past year also has been difficult financially for Hobo, and you are given a layoff notice. You begin searching for a new job and find a strong lead at Beta Corp as a microchip designer. During the interview, your potential boss makes it clear that you can be hired at a substantial salary increase if you are willing to bring along with you the design concepts from Hobo's new chip. Should you take the job, or do you have a professional obligation to Hobo keep their proprietary information secret?

53. You've answered an ad for a part-time job as a spreadsheet programmer. You are extremely familiar with Microsoft Excel®, and figure that you can handle the job. During the interview, you learn that your potential employer really wants someone who can code spreadsheets in Lotus 1-2-3®. Do you pretend that you know Lotus 1-2-3® because you assume it's probably similar to Excel and that you can learn it very quickly? Or do you tell the truth about your actual experience and possibly risk not being offered the job?

54. You work for a company that produces microprocessor-based systems. A customer has asked for a control module with a specific set of features. You have adapted a program from a previous job for another customer. The borrowed module meets your customer's requirements, but it also includes features that the customer did not request. You do not mention these additional features to the customer when you deliver the product.

    A few months later, the customer calls you to express satisfaction with the product and requests an updated version that includes additional features. These newly requested features are identical to the extraneous features from the original borrowed module. Do you accept the job, do virtually no additional work, and charge the customer again for the "added" features, or do you tell the customer that his present module already has the requested features?

55. In reviewing a recent exam, you notice that your professor has failed to see one of your errors and has given you too much credit for the problem. You know that you wouldn't hesitate to mention a grading error if you had been given too few points. Do you call the oversite to the attention of your professor, or do you say nothing and accept the extra points?

56. Your employer has asked you to dump a drum filled with cleaning solvent on the ground out in back of your company's manufacturing facility. You know that the town water supply is nearby, a distance of about two hundred yards. You raise your concern with your immediate boss who tells you that the company has been dumping small amounts of the chemical in the same spot for years and that no one has complained about it yet. "It's only a small amount," your boss says, "We certainly wouldn't dump any large amounts, because that would contaminate the water supply. It would cost us a fortune to have only one drum carted away by a toxic waste disposal company, though. I'm sure the solvent evaporates long before it can ever get to the water supply." Do you refuse to comply with your employer's request, or do you dump the cleaning solvent?

57. You work for a company that produces hand tools. You have designed a steel and acrylic framing hammer used to insert and remove nails. Several from the most recent lot of 20,000 have been returned from contractors with broken handles, and one caused injury when its handle broke while striking a nail. You've traced the problem to a contaminant in the acrylic resin used to make the handles and note in the production log that the problem was corrected

after the first 200 hammers. Do you suggest to your supervisor that the company issue a recall order for all 20,000 hammers, offer a free replacement for any that are returned with broken handles, or do nothing and wait to see how many are returned?

58. You've recently been given a promotion and salary increase, but a colleague and rival at work has not. You learn that your rival is making false statements about your work to your immediate superior. In particular, he claims that you falsified data on a recent benchmark test so that you could get your product out the door ahead of schedule. You discuss this problem with your supervisor who tells you to resolve the conflict with your jealous rival on your own, because if word of the discord finds its way to the company president, then your supervisor will look bad. Weeks go by, and nothing changes. Do you do nothing and assume that your reputation will win out over the false statements of your rival, do you take your problem to the president, or do you look for another job?