3

Engineering Design Tools

The engineer utilizes many technical skills when designing a device, product, or system. Prototyping, breadboarding, estimation, modeling, simulation, computer analysis, and testing are all part of the engineer's tool kit. An engineer also must have numerous nontechnical skills, including the ability to work in a team, generate new ideas, make sketches, keep good documentation, make approximations, and predict outcomes. Seldom does an engineer simply sit down and get right to work on the technical details of a project. Before beginning work in earnest, he or she spends much time planning, conducting feasibility studies, reviewing results of other projects, doing approximate calculations, interacting with other engineers, and defining the approach to the problem. This chapter introduces several of the skills—both technical and nontechnical—that an engineer uses as part of the design process.

SECTIONS

OBJECTIVES

In this chapter, you will learn about

- Design tools available to the engineer.
- Brainstorming, documentation, estimation, prototyping, and project management.
- Establishing foundations for good engineering design.

3.1 TEAMWORK AS A DESIGN TOOL

The spirit of rugged individualism persists as a theme in books, movies, and television. The image of a lone hero or heroine who strives for truth and justice against insurmountable odds may appeal to our sense of adventure and daring. The dream of becoming a sole entrepreneur who endures economic and technical hardship, eventually prevailing with an award-winning product leading to riches, arouses our pioneering spirit. Yet, in the real world, engineers seldom work alone. Most engineering problems are interdisciplinary, and true progress requires teamwork, cooperation, and the contributions of many individuals. This concept is easy to understand in the context of designing large structures, such as bridges and buildings, or world-wide computer networks. Likewise, complicated devices, such as automobiles, video players, medical implants, network routers, copy machines, and ink-jet printers, cannot be designed by one person alone. Some of the great accomplishments in space exploration of the 20th century, such as the Apollo moon landing, the Mir space station, and the Hubble telescope, required hundreds, if not thousands, of engineers working in cooperation with each other and teams of physicists, chemists, astronomers, material scientists, medical specialists, and mathematicians. Teamwork is an important skill, and you should learn it as part of your engineering education. (See Figure 3.1) Working in a team requires that you speak clearly, write efficiently, and have acquired the ability to see another person's point of view. Each member of a team must understand how his or her task relates to the responsibilities of the team as a whole.

Many engineering firms offer team building workshops as part of their employee training programs, and self-help books on the subject of teamwork abound. You'll have many opportunities to work as a team if you study engineering, and you should treat each one as a learning experience.

Effective Team Building

An effective team is one that works well together and functions at its maximum potential when solving a design problem. One key ingredient of an effective team is a good attitude toward fellow teammates and team activities. Team morale and a sense of pro-

Figure 3.1. Students working on a design project build strong team relationships.

fessionalism can be enhanced if team members agree upon a set of rules of behavior. The following set offers one possible guideline for effective team building.

1. Define Clear Roles

Each team member should understand his or her function within the organization of the team. The responsibilities of each individual should be defined *before* work begins on the project. Roles need not be mutually exclusive, but they should be defined so that all aspects of the design problem fall within the jurisdiction of at least one person. In that way, no task will "fall between the cracks."

2. Agree Upon Goals

Members of the team should agree upon the goals of the project. This consensus is not as easily achieved as you might think. One teammate may want to solve the problem using a traditional, time-tested approach, while another may want to attempt a far out, esoteric path to success. Define a realistic set of goals at the outset. If the design process brings surprises, you can always redefine your goals midway through the project.

3. Define Processes and Procedures

Teammates should agree on a set of procedures for getting things done. Everything from documentation and the ordering of parts to communication with professors, clients, and customers should follow a predetermined procedure. In that way, misunderstandings about conduct can be greatly reduced.

4. Develop Effective Interpersonal Relationships

You must learn to work with everyone on your team, even those individuals who you may personally dislike. In the real world, a client will seldom care about what conflicts may occur behind the scenes. It's a sign of engineering professionalism to be able to rise above squabbles and personality clashes as you concentrate on the job at hand. Be nice. Be professional. Forbid name calling, accusations, and assigning fault between team members.

5. Define Leadership Roles

Sometimes a team works best when a single person emerges as a clearly defined leader. Other teams work better by consensus using distributed leadership, or even no leadership at all. Regardless of your team's style, make sure that leadership roles are clearly defined and agreed upon at the start of a project.

PROFESSIONAL SUCCESS: YOU'RE THE TEAM LEADER, ONE TEAMMATE HAS DISAPPEARED, AND YOU'RE DOING ALL THE WORK

It's impossible to get along with all people all the time. When you work in close proximity to other individuals such as project teammates, personal conflicts and disagreements are inevitable. At times these personal differences occur because one team member fails to meet his or her responsibilities. Remember that however complicated your team relationships may become, your customer does not care about them. Your customer is interested in receiving a well designed product that reflects your best engineering abilities, so it's up to you to resolve team conflicts internally. At times this resolution will simply mean that you do more work than others, even if you will not be rewarded for your extra efforts. A good leader understands this tradeoff and devises a plan to work around the errant teammate. Such situations may seem frustrating and unfair, but they happen in the real engineering world all the time. Learning how to deal with them as a student is part of your engineering training.

Exercises 3.1

E1. Show how the five elements of effective team building might apply to the functioning of a basketball team.

E2. Define the roles, goals, and procedures that might apply to the design and construction of a suspension bridge.

E3. Define the roles, goals, and procedures that might apply to a team of software engineers developing a Web site for the sales catalog of a national book selling chain.

E4. Define the roles, goals, and procedures that might apply to a team of electrical and mechanical engineers developing an electric automobile.

E5. Define the roles, goals, and procedures that might apply to a team of biomedical engineers developing an artificial heart/lung machine.

3.2 BRAINSTORMING

One obvious area in which teamwork plays an important role is the generation of ideas for problem solving. When engineers gather to solve problems, they often resort to a creative process called *brainstorming*. Brainstorming requires a spontaneous mode of thinking that frees the mind from traditional boundaries. All too often, we limit our problem solving approach to obvious solutions that have worked in the past. Responsible engineering sometimes requires that we consider other design alternatives, including those previously untried. A good engineer will never settle on a solution just because it's the first one to come to mind. When engineers brainstorm, creativity proceeds spontaneously unfettered by concerns that an idea is "way out" or impractical. Hearing the ideas of others taps new ideas buried in the recesses of the brain. Ideas are discarded as unfeasible only after consideration, study, analysis, and comparison with competing ideas. Brainstorming allows the engineer to consider as many options as possible before choosing the final design path.

Brainstorming can be done informally, or it can follow one of several time-tested formal methods (See Figure 3.2). Formal methods are used in large group settings where organization is needed to avoid chaos and anarchy. Informal methods typically are used when one, two, or perhaps three people wish to generate ideas. Although they differ in execution, informal and formal brainstorming techniques share the same set of core principles. The primary goal is to foster the inhibited, free exchange of ideas by creating a friendly, nonjudgmental environment. Brainstorming is an art and requires practice, but anyone who has an open mind and some imagination can do it.

Ground Rules for Brainstorming

The ground rules for brainstorming are designed to create a friendly, nonthreatening environment that encourages the free flow of ideas. Although the specific rules may vary, depending on the procedures followed, the following list can serve as a guideline:

1. No holding back. Any idea may be brought to the floor at any time.
2. No boundaries. An idea is never too outrageous or "way out" to mention.
3. No criticizing. An idea may not be criticized until the final discussion phase.
4. No dismissing. An idea may not be discounted until after group discussion.
5. No limit. There is no such thing as having too many ideas: the more the better.
6. No restrictions. Participants may generate ideas from any field of expertise.
7. No shame. A participant should never feel embarrassed about bringing up a stupid idea.

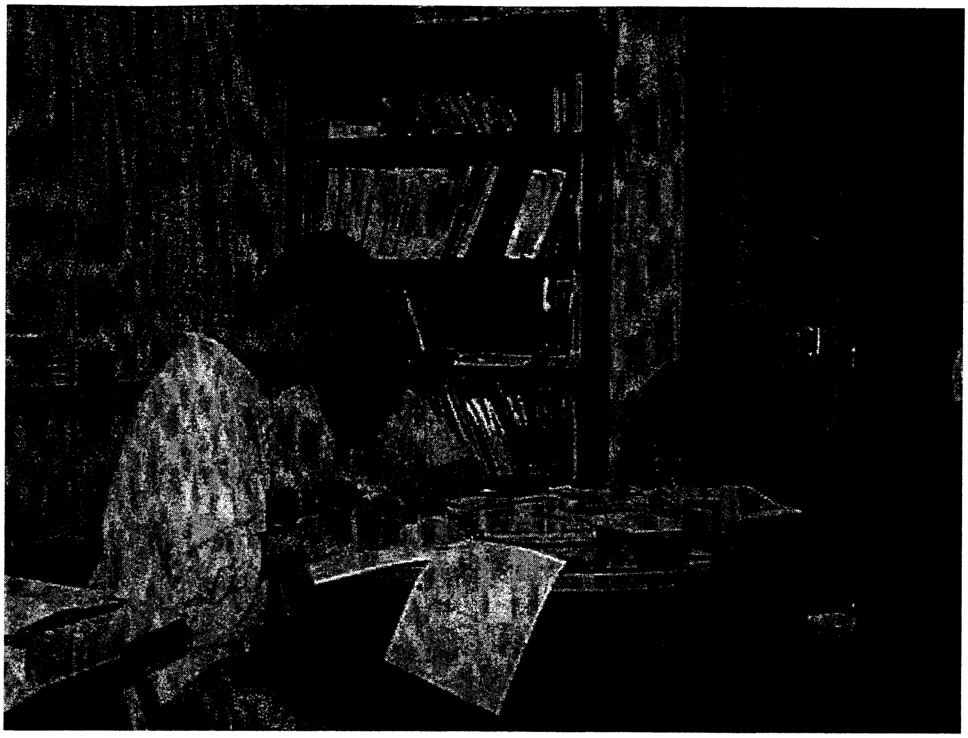


Figure 3.2. Students engage in an idea trigger session.

When a brainstorming session is in progress, one person should act as the facilitator, and another should record everyone's ideas. It's also possible to use video or audio tape in lieu of a human secretary.

Formal Brainstorming Method

When a large group gets together to brainstorm, some sort of formal structure is needed. Without such a structure, a flood of competing ideas, all brought to the floor simultaneously, can create chaos. Instead of thinking creatively, participants become confrontational as they strive to be heard and gain a voice in the conversation. With so many randomly competing opinions, each person's creative process is inhibited, and the brainstorming session becomes counterproductive. This effect is sometimes called "idea chaos." Adding formal structure to the brainstorming session restricts the flow of ideas to a manageable rate without restricting the number of ideas generated. In fact, the addition of formal structure can enhance the brain's creative process in large group settings by preventing aggressive individuals from dominating the conversation and by providing time for people to think.

Of the many formal brainstorming techniques that exist, the *idea trigger* method has been well tested and is used often by brainstorming specialists in large group settings. The idea trigger method is based on the work of psychologists* and has been shown to enhance the brain's creative process. It may seem contrived at first, but it's been well tested and has been shown to be effective. It relies on a process of alternating tension and relaxation that taps the brain's creative potential. By listening to the ideas of others, receiving the foreign stimulus of other people's spoken ideas, and being forced

*G. H. Muller, *The Idea Trigger Session Primer,* Ann Arbor, MI: A.I.R. Foundation, 1973. S. F. Love, *Mastery and Management of Time,* Englewood Cliffs, NJ: Prentice-Hall, 1981.

to respond with counter ideas, a participant's habitual behavior patterns, personality traits, and narrow modes of thinking, which often serve as barriers that stifle creativity, can momentarily be broken, allowing ideas hidden in the recesses of the brain to come to the foreground. A participant who is shy, for example, and reluctant to offer seemingly silly ideas will be more willing to do so under the alternating tension and relaxation of the purge-trigger sequence.

The idea trigger method requires a leader, at least four participants, and a printed form, such as the one shown in Figure 3.3. The procedure has three phases, as follows.**

Phase 1: Idea Purge Phase The problem or design issue is summarized by the leader. Each person is given a blank copy of the form shown in Figure 3.3. Without talking, each participant writes down in rapid succession as many ideas or solutions as possible. These entries are placed under Column 1. Key words suffice; whole sentences are not necessary. During the idea generation phase, participants open their minds, consider many alternatives, and do not worry if ideas seem too trivial or ridiculous. "Pie in the sky" types of ideas that may seem radical or impossible should also be included. In short, participants write down *anything* that comes to mind that may be relevant to the

Figure 3.3. Blank form for the idea trigger session.

IDEA TRIGGER SESSION

COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4
120 MINUTES			
60 SECONDS			

CONTRIBUTOR:

**C. Lovas, *Integrating Design Into the Engineering Curriculum,* Dallas, TX: Engineering Design Services Short Course and Workshop, October 1995.

problem. The fact that ideas are written down silently removes the element of intimidation from the idea generation process.

After the first two minutes of the session, the group takes a break and then attempts to write down additional ideas under Column 1 for another sixty seconds. This *tension and relaxation* sequence has been shown to enhance creativity. It helps to completely extract all ideas from the brain's subconscious memory, much like squeezing and releasing a sponge several times to extract all the water.

Phase 2: Idea Trigger Phase After the idea generation phase, the leader calls upon all members of the group. Each participant takes a turn reading his or her entries from Column 1. As each person recites Column-1 entries, others silently cross out the duplicates on their own lists. Hearing the ideas of others will trigger new ideas, which each person should enter under Column 2 as soon as they emerge. This process is called *idea triggering*. Hearing the remarks and ideas of others while pausing from the act of speaking causes the hidden thoughts stored in the subconscious to surface. The purpose of the idea trigger phase is not to discount the ideas from Column 1, but rather to amplify them, modify them, or generate new ideas.

After all members have read their Column-1 entries and have completed their Column-2 entries, the idea trigger process is repeated again. This time, entries from Column 2 are read, and any new ideas triggered are entered under Column 3. The process is repeated, with entries added to Columns 4, 5, etc., until *all* ideas are exhausted. Complex problems may require as many as five rounds of idea trigger phase.

The entries that appear under the second and third columns (and the fourth and fifth columns if the problem is complex) are usually the most creative. Such richness is thought to result from several factors. Often participants are secretly angered at having had their ideas stolen by another and are self-motivated to move on to new, unexplored territory. Simple competitive pressure can also propel a person toward new, original ideas. Conversely, seeing that one's ideas have not been duplicated by others can provide positive reenforcement, pushing the participant to come up with even better or more refined ideas. Some individuals may respond to their own nonduplicated entries with a desire to produce more as a way of hoarding the good ideas. Yet others may subconsciously think that augmenting previously discussed ideas fosters group cooperation.

Phase 3: Compilation Phase When the idea trigger phase has been completed, it's the job of the leader to compile everyone's sheets and make one master list of all the ideas that have been generated. The group then proceeds to discuss all ideas, discarding the ones that probably will not work, and deciding which of the remaining ideas are appropriate for further consideration and development.

An Example of Formal Brainstorming

Let's illustrate the formal idea trigger method with an example. Four students, Tina, Juan, Fred, and Karin, are designing an entry for the Peak-Performance Design Competition introduced in Chapter 2. As discussed in that chapter, the overall objective is to design a self-propelled vehicle that can climb a 1.5-meter ramp, stop at the top, and prevail over an opposing vehicle climbing up the ramp from the other side. The four students recently held a formal brainstorming session based on the idea trigger method. They agreed to address all elements of the car design, including the issues of propulsion, offensive and defensive strategies, and the stopping mechanism. The following discussion chronicles their brainstorming session. Tina acted as the leader and timed the first two minutes, the break, and the subsequent 60-second idea purge phase. At the end of the purge phase, Juan's page looked like this:

JUAN	**BRAIN PURGE PHASE COLUMN 1 2 MINUTES:**
	• Support structure = wood (easy to make)
	• Use angle irons from Mechano™ (Erector™ Set)
	• Plastic body for lighter weight
	• Zinc air batteries (lightweight)
	• Wheels taken from my radio controlled car
	• Rubber band for chain drive
	• Small car will be harder for opponent to deflect.
	1 MINUTE:
	• Ramming device
	• Wedge shaped body

Juan read his entries. As Fred listened to Juan, he crossed out his own duplicate entries. When Juan was finished, Fred's first column, including crossouts, looked like this:

FRED	**BRAIN PURGE PHASE COLUMN 1 2 MINUTES:**
	• ~~No heavy batteries (use zinc air)~~
	• Larger wheels for slower turning speed
	• Gear box
	• Higher torque (harder for opponent to push backwards)
	• ~~Use plastic for body~~
	• Electronic timer for stopping mechanism
	• Rechargeable batteries
	• ~~Wedge shaped design~~
	1 MINUTE:
	• ~~Buy wheels from hobby shop for radio controlled car~~
	• Sense speed, determine distance traveled
	• Aluminum frame

Karin next read those of her entries that had not been duplicated by Juan. As Fred listened to Karin, an idea flashed into his head. *A threaded rod,* he thought, *We can make the drive shaft from a threaded rod.* Fred reasoned that they could make the drive shaft from a threaded rod and have it screw a sliding nut toward a cutoff switch. The method would not be foolproof, because slipping wheels could ruin the system's ability to track distance, but it was worth discussing. Fred wrote down "threaded rod" under his Column 2 entries.

When Karin heard Juan read his "ramming device" entry, it had made her think about using an ejected object as part of an offensive strategy. She wrote the words "ejected device" under her Column 2 entries. Tina reacted similarly to Juan's idea and wrote the words, "lob something on the track ahead of opposing car" under her Column 2 entries.

The spoken trigger phase made its way around the group. A great many ideas, some simple, some esoteric, and some very clever found their way onto peoples lists.

When everyone had finished, Tina started the process again. This time, everyone read their Column 2 entries and wrote down new ideas under Column 3. As Karin read her entry about ejected devices from Column 2, Tina got another idea. The idea of an ejected object brought to her a fleeting image from the Herman Melville novel *Moby Dick*. She imagined a flying spear with a barbed tip shot ahead of the vehicle over the top of the hill. *After hitting the carpet in front of the opposing vehicle,* she thought, *the barbed tip will dig into the carpet, blocking the other car, and be very difficult to dislodge.* Tina wrote down "harpoon" under her Column 3 entries.

The second idea trigger round progressed, and Tina started yet another one. After about 45 minutes, the entire Phase 2 session was finished. Tina suggested a break so that she could compile everyone's lists of ideas. Her combined list of entries from everyone's three columns looked like this:

COMPLETE LIST OF IDEAS FROM EVERYONE'S SHEETS

SHAPE:

- Small car = harder for opponent to deflect
- Wedge shaped vehicle having same width as track
- Rolling can design
- Snow plow shaped wedge

STRUCTURE:

- Support structure = wood (easy to make)
- Aluminum frame
- Plastic body for light weight.
- Use angle irons from Mechano™ (Erector™ Set)
- Hot melt glue balsa wood

POWER:

- Zinc air batteries (lightweight)
- Rechargeable batteries
- Change batteries after every run
- Electronic timer for stopping mechanism
- Microprocessor-controlled car with onboard sensors
- Sense speed, determine distance traveled from microprocessor software

PROPULSION:

- Wheels from radio-controlled car purchased at hobby shop
- Large wheels
- Rubber band for chain drive
- Plastic linked chain from junked radio-controlled car chassis.
- Single large mousetrap with mechanical links
- Wind up large rubber band

STRATEGIES:

- Ramming device
- Flying barbed harpoon
- Pick up arm
- Throw jacks in front of oncoming opponent
- Roll over opponent with large roller

After the break, Tina reconvened the team to discuss the list of ideas. They weeded out the ones that did not seem feasible and compared ideas that looked promising. They combined multiple ideas and converged on a slow-moving, wedge-shaped vehicle concept for the prototype stage. They also decided to try out Tina's offensive strategy of a flying harpoon designed to dig into the carpet and block the path of the opposing vehicle.

Informal Brainstorming

The formal brainstorming method discussed in the previous section requires organization and planning. In contrast, informal brainstorming can be done anywhere. Have you ever had a thinking session with a fellow student, friend, or colleague? If so, you probably engaged in informal brainstorming. You need not have discussed a technical issue. The conversation might have revolved around something as mundane as a social get-together. Suppose, for example, that you tried to figure out transportation arrangements for a trip to a show at the science museum. The conversation might have proceeded as follows:

You: "I've called the Science Museum, and the 11- and 1-o'clock shows are sold out. We can get seats for 3, 5, and 7 o'clock. What do you think?"

Friend: "Okay, it's 10 o'clock now. If we aim for the 5-o'clock show, we can head for dinner afterwards."

You: "How about asking Pat to join us?"

Friend: "Great!"

You to friend (after phoning Pat): "Well, Pat wants to come but has another appointment at six. Will that give us enough time to see the 5-o'clock show? "

Friend: "Not really."

You: "How about this: We eat an early lunch, go with Pat to the three-o'clock show, and see as much of the general exhibits as we can before Pat has to leave? We can stay on until the Museum closes at nine if we like."

Friend: "Sure, sounds fine. Give Pat a call."

You (with Pat on hold): "It's okay with Pat. What time is the next bus?"

Friend: "Ten thirty. But, if we take the commuter train, we can meet Pat at the museum and eat at the museum cafeteria."

You: "Yes, but the food's not great there. Too healthy!"

Friend: "How about if we stop at Mo and Jo's Submarine Palace, buy sandwiches for three, and eat them at the museum?"

You: "Better yet, we can have a picnic on the lawn in back."

Friend: "Good idea. Ask Pat if that idea works."

You and your friends engaged in informal brainstorming over a very ordinary, everyday topic: going to the museum. This commonplace discussion had in it the same features that one would find in a technical brainstorming session. The problem had many solutions, and arriving at the final choice involved iteration and testing. By trading thoughts, bringing several ideas to the table, discarding those that were judged not feasible, and building upon those that were, you eventually arrived at a plan of action.

Informal Brainstorming: An Engineering Example

The informal brainstorming technique can be used to solve technical problems that arise during the design process. As a technique for engineering design, informal brainstorming in a round table format is appropriate for small groups of people. Ideas are contributed in random order by any participant. The flow of ideas need not be logical, and new proposals can be offered whenever they come to mind.

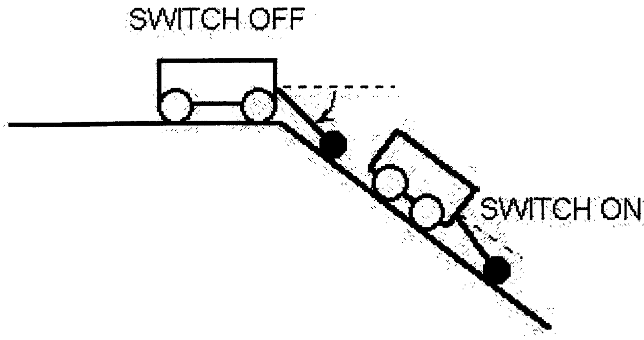


Figure 3.4. Juan's idea for a stopping switch.

The following conversation provides an example of an informal brainstorming session involving a technical topic. It chronicles again an imaginary discussion that took place between two students attempting to design an entry for the Peak-Performance Design Competition introduced in Chapter 2. Two of the students from the previous example, Tina and Juan, discuss the issue of how to make the vehicle stop when it arrives at the top of the ramp. Take note of the flow of ideas and the way in which the design concept evolves with the conversation. Tina and Juan do not settle on the first idea that comes to mind, but instead allow the flow of ideas to lead them to better solution.

Tina: "I think we can use a switch of some kind to turn off the electric motor when the car arrives at the top."

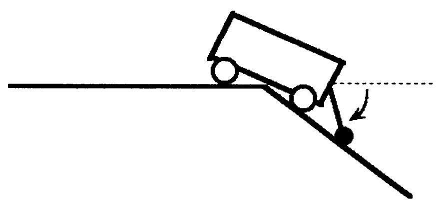
Juan: "Yes, that's one possibility." (*He thought for a while*) "We also could modify the switch so that it trails behind and is spring loaded in the closed position. Putting the car on a flat surface will press the lever arm against the spring, closing the switch and connecting the battery to the motor. When the car reaches the top, the switch arm will stay on the slope, allowing the spring to force the arm downward. The switch will open, disconnecting the battery from the motor and stopping the car." (*Juan drew the sketch of Figure 3.4.*)

Tina: "It *might* work, but I'm afraid that the switch might open before the car gets to the top of the ramp. Unless we measure and construct everything perfectly, the switch may open prematurely when the car just starts to go over the transition to the top of the hill." (*She drew the sketch shown in Figure 3.5.*)

Juan: "Yes, premature switch opening may be a problem. We could try it out."

Tina: "Here's another idea: We could connect a long screw thread to the drive shaft of the car and put some sort of sliding nut along the shaft. As the shaft turns, it will move the nut toward a stationary, normally closed switch, opening it after just the right

Figure 3.5. Premature opening of the switch.



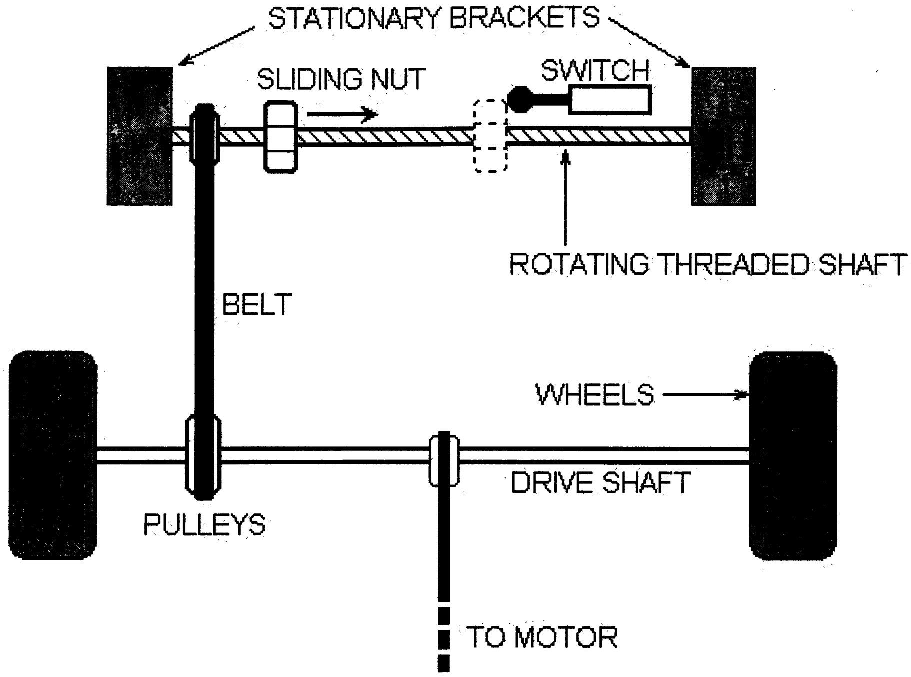


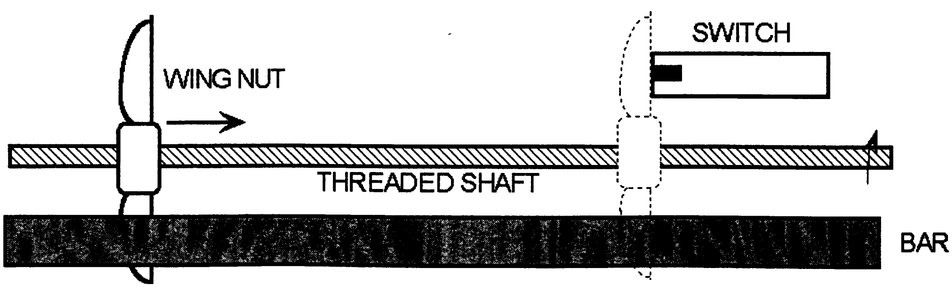
Figure 3.6. Non-turning nut moves along a rotating, threaded shaft.

amount of distance traveled. It might look something like this:" (*She drew the sketch shown in Figure 3.6 and presented it to Juan.*)

Juan: "Yes! We could self-calibrate it before each run by placing the car on the top of the hill with the nut in the 'off' position against the switch and then manually roll the car *backwards* to the starting point. As the nut traveled back along the threaded rod, it would arrive in just the right position for the start." (*He thought a moment more.*) "How about a butterfly wing nut on the rotating shaft? We could buy one at the hardware store instead of having to make our own. One wing of the nut could ride against the car frame and prevent the nut from turning as the shaft turns. In this way, the nut would be screwed down along the threaded shaft. The other wing could be used to press the switch." (*Juan drew the sketch shown in Figure 3.7.*)

Tina: "Yes, we could use one of those switches that has three contacts: normally open (NO), normally closed (NC), and common (COM)." (See Figure 3.8.) "The switch remains in the closed position, thereby connecting COM to NC, until it is pressed. When it's pressed, it switches COM to the NO contact."

Figure 3.7. The wing nut concept.



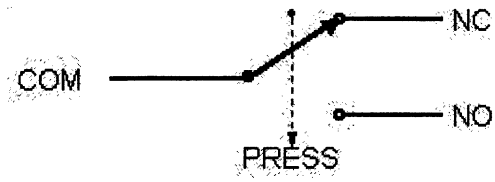


Figure 3.8. Switch showing normally open (NO) and normally closed (NC) contacts. The normal state of the switch refers to the condition where no force is applied to its pushbutton or lever arm.

After some thought, Tina continued, saying, "You know, we don't have to run a separate threaded rod from the drive shaft. We can make the actual drive shaft *be* a threaded rod, like this." (*Tina drew the sketch shown in Figure 3.9 and presented it to Juan.*)

"That way, we'll have a simpler design, reduce frictional loss, and provide an easy way to attach the wheels to the drive shaft with locking nuts."

Juan: "I like this new idea much better than our first switch idea. I think it's a lot more foolproof."

Tina: "On the other hand, if we use the threaded-rod idea and the wheels slip at all, the wing nut will still be threaded down the turning shaft, but the car won't be moving, and it will stop prematurely, short of the top of the hill."

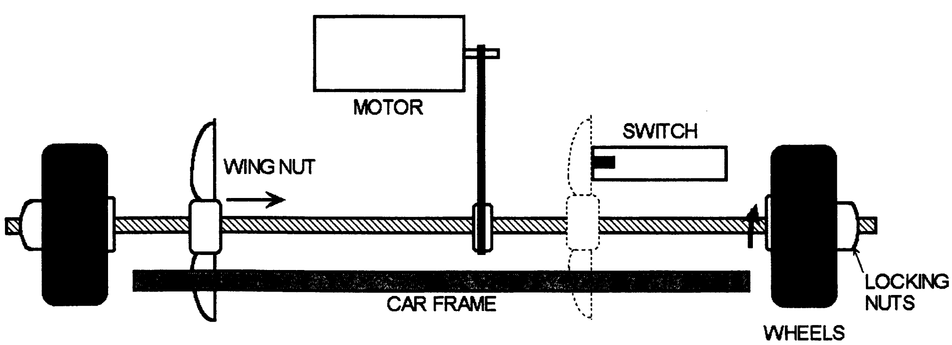
Juan: "We could go back to our separate shaft idea and lubricate the shaft very well to reduce friction."

Tina: "No, that still won't solve the problem of the slipping wheels."

Juan: "Well, then, I have another idea. We could use a threaded shaft that is separate from the drive shaft and have it be turned by two idler wheels, rather than by the motor. Idler wheels will run along the track and turn the wing nut shaft but will be much less likely to slip because they won't be driven by the motor and thus will experience a much smaller torque." (*Juan drew the sketch shown in Figure 3.10.*)

"The idler wheels won't be connected in any way to the drive shaft or driven wheels. The only way that the idler wheels can turn is if the car is moving. If the idlers themselves get stuck, they'll drag along the track and *not* move the nut by the correct amount. But if the mechanism is well lubricated, stuck idler wheels should not be a problem."

Figure 3.9. Threaded rod also serves the function of a drive shaft.



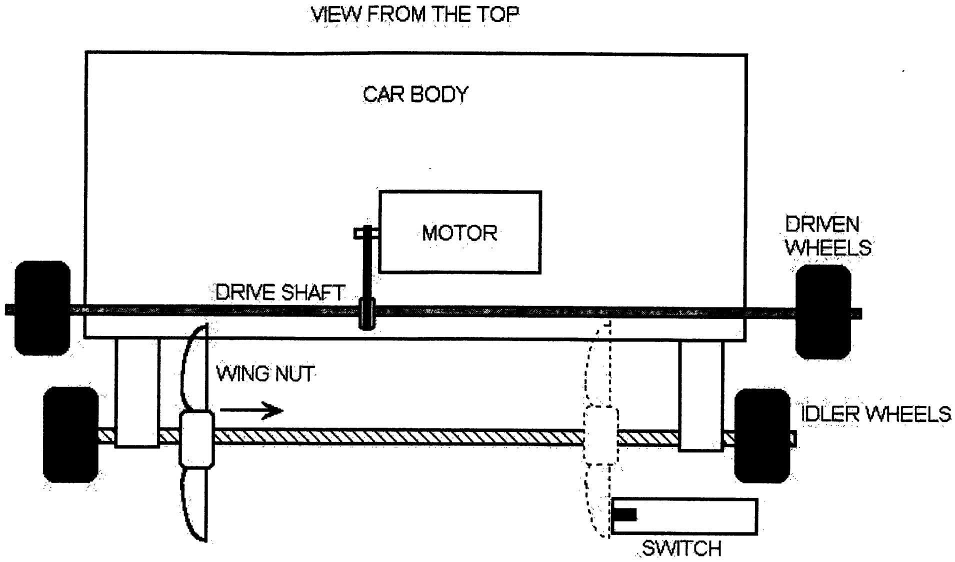


Figure 3.10. Idler wheels turn the threaded rod which is not driven by the motor

Tina: "We've got some ideas to try, but I'd like us also to consider an electronic timer that keeps the motor turned on for a fixed amount of time. We could experiment with the car and determine the exact amount of time needed for it to get to the top."

Juan: "Or how about an altimeter that measures the height of the car off the floor?"

Tina: "Or maybe a string that hooks to the base of the ramp, unwinds as the car goes up, and pulls a switch to the off position when the car arrives at the top?"

Juan: "That's not allowed by the rules. All parts of the car have to lie inside the one-meter marks at the end of the fifteen-second time interval."

Tina checked the rules and confirmed that Juan was correct. They both considered the altimeter idea and decided that it was not feasible. *If* they could find one at all, an altimeter with a resolution in the one-meter range would be an expensive (and heavy) instrument indeed. Neither student wanted to design an altimeter from scratch. Their primary desire was to focus on the design of the vehicle itself. They also decided against the electronic timer idea for now. They were afraid that the car might travel at increasingly slower speeds from run to run as the battery ran down, and they remembered from their electronics class that the speed of the typical electronic timer is independent of its power supply voltage.

With their preliminary design concepts prioritized, they focused their attention on the two mechanical solutions: the trip switch and the concept of the sliding nut. They decided to build a few prototypes and try out these basic ideas.

The foregoing conversation between Tina and Juan illustrates the principles of informal brainstorming. As each person stated a new idea, the other amplified upon it and came up with new ones. In the end, the students condensed their list of ideas into one or two concepts that seemed feasible and agreed to try them out in test experiments. The flow of words between Tina and Juan was appropriate for two people and even would have worked for three or four. Had their design team been larger, a formal brainstorming method, such as the one discussed in the previous section, would have been more appropriate.

PROFESSIONAL SUCCESS: WHAT TO DO WHEN ONE INDIVIDUAL DOMINATES A BRAINSTORMING SESSION

Suppose that you are the leader of a brainstorming session and one member of your team dominates the conversation. That person may criticize participants, dismiss unconventional ideas, cut off speakers, or otherwise break the rules. When this situation occurs, it's your responsibility to keep the offender in line. Saying to the group, "Hey, we need to stick to the formal rules of brainstorming. I'm going to institute a 'don't speak until called upon' rule." This approach will usually short circuit the behavior of the dominant participant while helping to maintain harmony among team members.

Exercises 3.2

E6. Conduct a one-person mini-brainstorm session and add as many ideas as you can to the final list of ideas compiled by Tina, Juan, Fred, and Karin. Allow yourself four minutes of brainstorm time to compile your ideas.

E7. A non-engineering friend complains about a pair of eyeglasses that keeps falling off. Give yourself five minutes of brainstorming time, and compile a list of as many ideas as you can for solving your friend's problem.

E8. Over a time span of two minutes, write down as many ways as you can for safely confining a dog to your back yard.

E9. Can brainstorming be used in solving math problems? Why or why not?

3.3 DOCUMENTATION: THE IMPORTANCE OF KEEPING CAREFUL RECORDS

Engineering design is never performed in isolation. As an engineer, it's your professional responsibility to record your ideas and the results of your work. One way that engineers communicate with each other is through careful record keeping at each stage of the design process. The collection of records, drawings, reports, schematics, and test results is referred to collectively as the *documentation trail.* The documentation trail serves as a tool for passing information on to individuals who may need to repeat or verify your work, manufacture your product from a prototype, apply for patents based on your inventions, or take over your job should you be promoted or move to another job. Written records are also a good way to communicate with yourself. Many an engineer has been unable to reproduce design accomplishments or confirm test results due to sloppy record keeping. Indeed, one of the marks of a professional engineer is the discipline necessary to keep accurate, neat, and up-to-date records. Documentation should never be performed as an afterthought. If a project is dropped by one engineer, the state of documentation should *always* be such that another engineer can resume the project without delay. As a student of engineering, you should learn the art of record keeping and develop good documentation habits early in your career. Most companies, laboratories, and other technical institutions require their employees to keep records that document the results of their engineering efforts.

Paper versus Electronic Documentation

Nowadays just about every piece of engineering documentation, with the exception of the engineer's notebook described in the next section, is generated on a computer.

Examples include word processing, spreadsheets, schematics, drawings, and simulated test results. All of this documentation must be preserved. Some engineers prefer to preserve documentation by printing out everything on paper and storing the documents in a file cabinet. Others prefer to store information on disk so that it can be viewed on screen and printed out only as needed. Whichever method you choose, you should follow the following two important guidelines:

1. *Organize your information:* It's important to store documentation in an organized and logical manner. If the project is small, its documentation should be stored in a single folder (paper *or* electronic). Larger projects may require a group of folders, each relating to different aspects of the project. The folders should be labeled and dated with informative titles such as "The XYZ Project" and kept in a place that will be easy to find should another authorized person need to find it.
2. *Back up your information:* It's equally important to store a duplicate copy of all documentation. This guideline applies to written as well as electronic information. Fire, flood, theft, misplacement, and the all-too-common disk crash all can lead to the loss of a project's documentation trail. Archival storage of records in a different physical location will help to keep a project on track if one of these catastrophes should occur.

The Engineers's Logbook

One important vehicle for record keeping is the *engineer's logbook,* sometimes called the *engineer's notebook.* A well-maintained logbook serves as a permanent record that includes all ideas, calculations, innovations, and test results that emerge from the design process. When a project is brought to completion, all related logbooks are placed in an archive and remain the property of the company. An engineering notebook thus serves as an archival record of new ideas and engineering research achievements *whether or not they lead to commercial use.* A complete logbook serves as evidence of inventorship, establishes the date of conception and "reduction to practice" of a new idea, and shows that the inventor (you!) has used diligence in advancing the invention to completion. In this respect, the engineer's logbook is more than just a simple lab notebook. It serves as a valuable document that has legal implications. When you work as an engineer, you have a professional responsibility to your employer, your colleagues, and to the integrity of your job to keep a good logbook.

The notebook shown in Figure 3.11 is typical of many used in industry, government labs, and research institutions. It has permanently bound and numbered pages, a cardboard cover, and quadrille lines that form a coarse grid pattern. A label fixed to the front cover uniquely identifies the notebook and its contents. The company, laboratory, or project name is printed at the top, and the notebook is assigned a unique number by the user. In some companies and large research labs, a central office assigns notebook numbers to its employees when the notebook is signed out.

The techniques for logbook use are different from the procedures applied to simple lab notebooks, such as those found in your science classes in school. In many courses, instructors encourage students to write things down first on scratch paper and then to recopy relevant items from loose sheets into a neat notebook. This procedure is bad practice for an engineer. Although notebooks prepared in this way are easier for instructors to grade, the finished notebook seldom resembles a running record of what went on in the laboratory and is not especially useful for engineering design projects. Design is as much a *process* as it is a final product, and the act of writing things down as they happen helps you with your thinking and creativity. Also, keeping a record of what

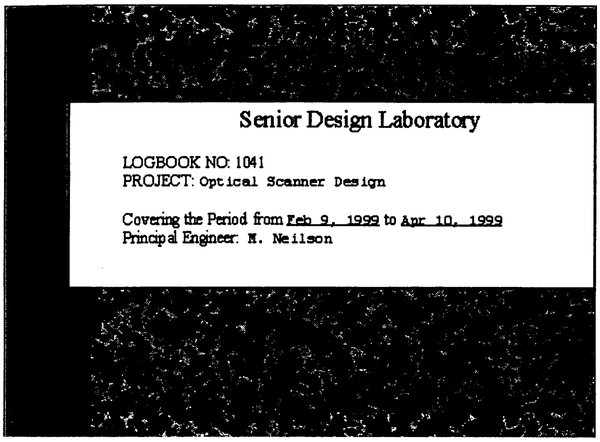


Figure 3.11. Cover label of a typical engineers logbook.

did *not* work is just as important as recording what did, so that mistakes will not be repeated in the future.

Logbook Format

An engineering logbook should be used as an design *tool.* Enter everything into your logbook, no matter how seemingly irrelevant. Write down ideas as you think of them, even if you have no immediate plans to pursue them. Keep an ongoing record of successes and failures. Record the results of every mechanical, structural, electrical, system, flight, or performance test, even if the results are not used in the final design. Stopping to write things down will take discipline but will be worth the trouble at later stages in the design process. All-important information, including some you may have forgotten along the way, will have been entered into your logbook and will be at your fingertips to use as needed. Any format that meets your needs is suitable, as long as it forms a permanent record of the design process. Ban loose paper from the laboratory. It is easily lost, misplaced, or spilled upon. Resist the temptation to reach for the closest piece of loose paper when you need to do a calculation, record information, draw a sketch, or discuss an idea. Take the time to open your logbook, and use its pages for writing. You'll be glad you did when those numbers and sketches you need are readily available. Unbound paper used for anything other than doodling has no place in an engineering laboratory.

Using Your Engineer's Logbook

As the chief author of your logbook, you have the freedom to set your own objectives for its use. The following guidelines, however, are typical of those used by many engineers:

1. Each person working on a project should keep a separate logbook specifically for that project. All relevant data should be entered. When the logbook is full, it should be stored in a safe place specifically designated for logbook storage. In that way, everyone will know where to find the logbook when it's needed.
2. All ideas, calculations, experiments, tests, mechanical sketches, flow charts, circuit diagrams, etc. related the project should be entered into the logbook. Entries should be dated and written in ink. Pencil has a nasty habit of smudging or wearing away over time when pages rub against one another.
3. Logbook entries should outline the problem addressed, tests performed, calculations made, and so forth, but subjective conclusions about the success of

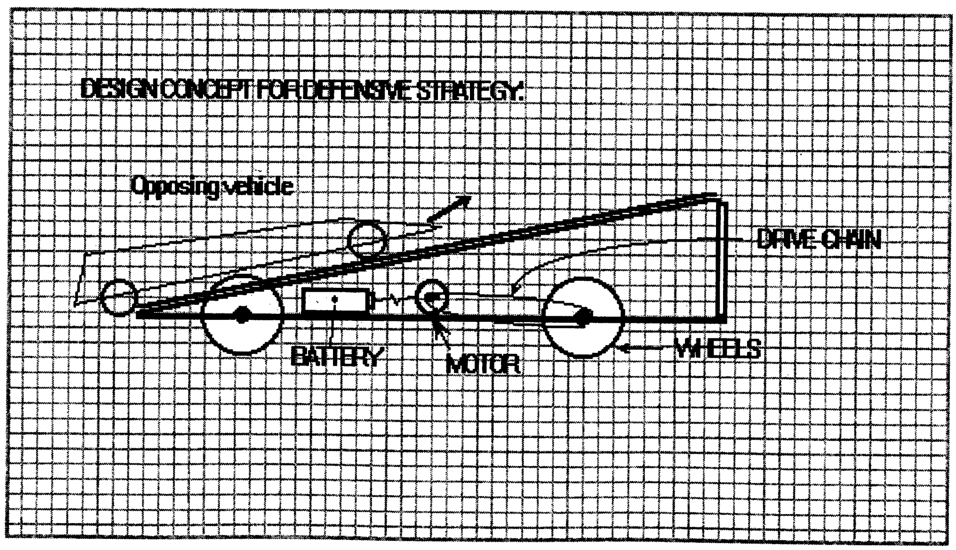
the tests (e.g., I believe . . .) should be avoided. The facts should speak for themselves. Logbook entries should not be a tape recording of your opinions.

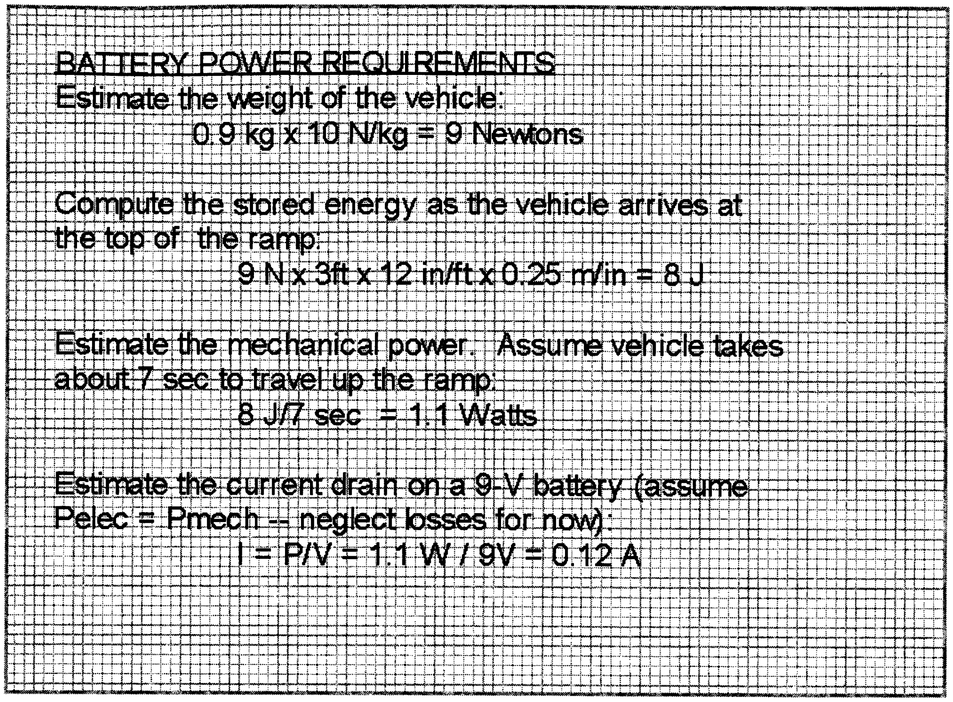
4. The voice of the logbook should speak to a third-party reader. Assume that your logbook will be read by your boss, co-worker, or perhaps someone from marketing, who will review your work at some future date.
5. In company, corporate, or government settings the concluding page of each section or laboratory session should be dated and, where appropriate, signed. This practice eliminates all ambiguity with regard to the dates of invention and disclosure. Important entries should be periodically and routinely witnessed by at least one other person, preferably two. Witnesses should endorse and date the relevant pages with the words, "witnessed and understood."
6. Logbook pages should not be left blank. If a portion of a page must be left blank, a vertical or slanted line should be drawn through it. Pages should be numbered consecutively and not be torn out.
7. Relevant computer-generated plots, graphics, schematics, or photos printed on loose paper should be pasted or taped onto bound logbook pages. This procedure will help prevent loss of important data.
8. Do not make changes by using correction fluid. Cross out instead. This precaution will prevent you from creating obscure or questionable entries should your logbook be entered as legal evidence in patent or liability actions. Although this precaution probably won't be relevant to logbooks you keep for college design courses, it's a good idea to make the procedure a habit at an early point in your training.

Logbook Example

The following example illustrates proper use of an engineering logbook. Imagine that the pages to follow outline the design of your vehicle for the Peak Performance Design Competition introduced in Chapter 2. The first page shows a preliminary sketch of a basic concept for the vehicle based on a simple moving wedge. (See Figure 3.12.) The second page contains some calculations that estimate the battery drain as the vehicle

Figure 3.12. Logbook entry: Moving wedge concept for competition vehicle.




BATTERY POWER REQUIREMENTS
Estimate the weight of the vehicle:
0.9 kg x 10 N/kg = 9 Newtons

Compute the stored energy as the vehicle arrives at the top of the ramp:
9 N x 3ft x 12 in/ft x 0.25 m/in = 8 J

Estimate the mechanical power. Assume vehicle takes about 7 sec to travel up the ramp:
8 J/7 sec = 1.1 Watts

Estimate the current drain on a 9-V battery (assume Pelec = Pmech -- neglect losses for now):
I = P/V = 1.1 W / 9V = 0.12 A

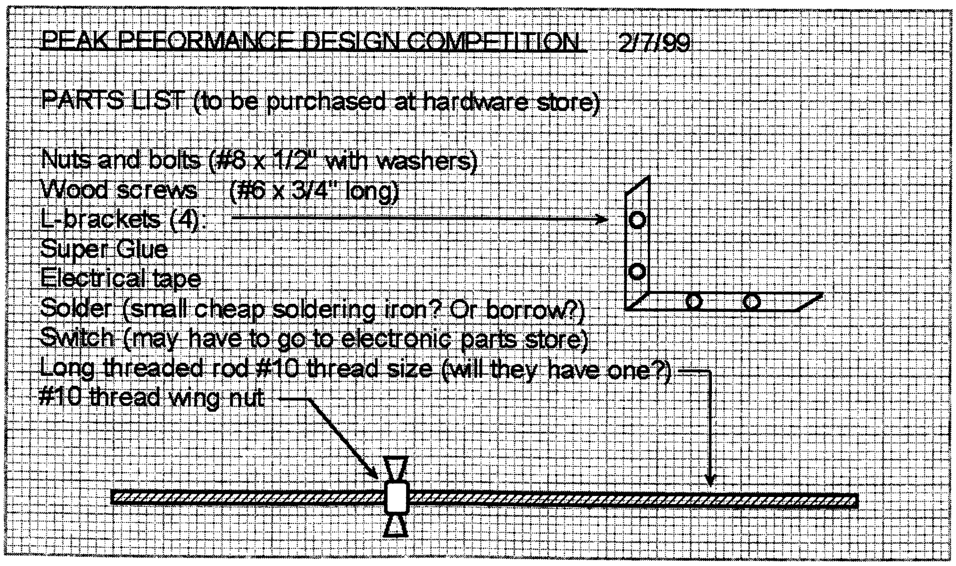
Figure 3.13. Logbook entry: Power consumption calculations.

moves up the contest ramp. (See Figure 3.13.) The entries on the third page show a list of materials and parts to be purchased at the hardware store. (See Figure 3.14.) These parts will allow you to build a prototype and test your vehicle's ability to climb the ramp.

Dimensions and Tolerance

The sketch shown in Figure 3.15 shows the main chassis of the vehicle. Suppose that you were to have a machinist fabricate this part from a single, 0.4-cm-thick aluminum

Figure 3.14. Logbook entry: List of parts to be purchased at the hardware store.


PEAK PEFORMANCE DESIGN COMPETITION 2/7/99

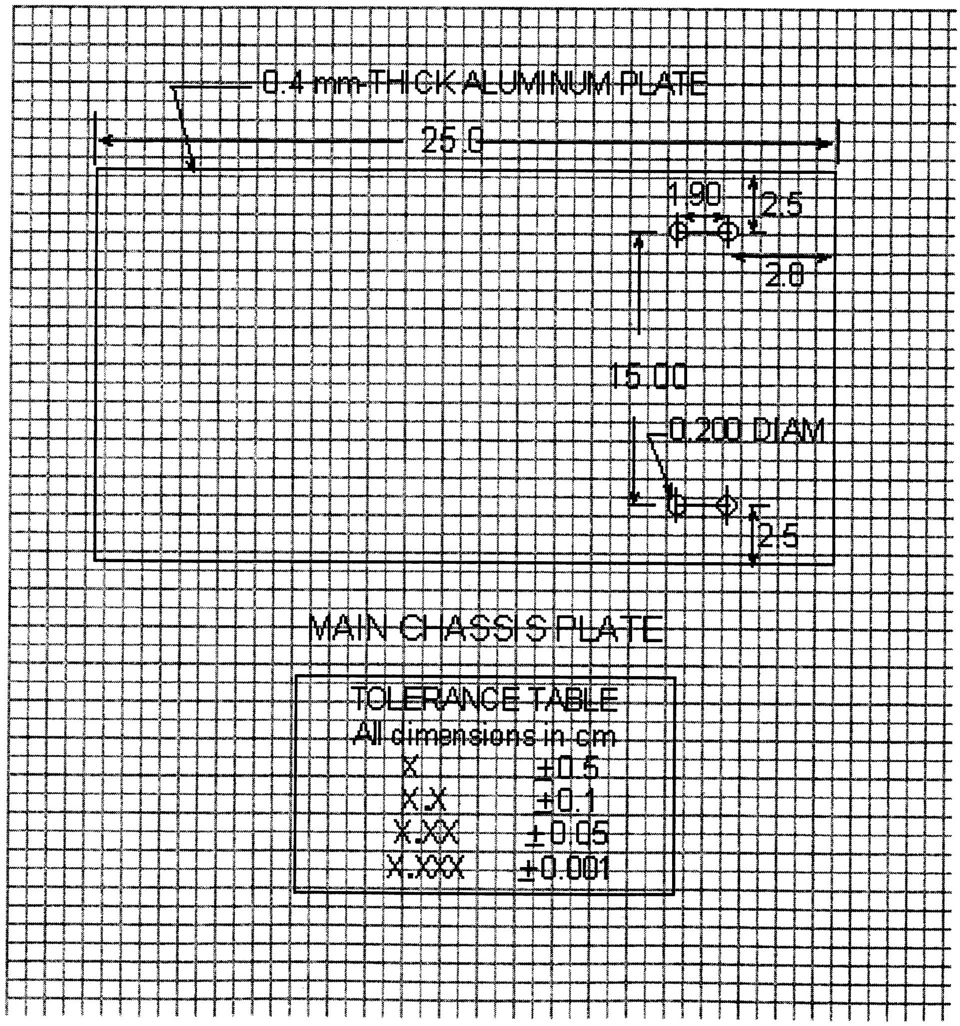
PARTS LIST (to be purchased at hardware store)

Nuts and bolts (#8 x 1/2" with washers)
Wood screws (#6 x 3/4" long)
L-brackets (4):
Super Glue
Electrical tape
Solder (small cheap soldering iron? Or borrow?)
Switch (may have to go to electronic parts store)
Long threaded rod #10 thread size (will they have one?)
#10 thread wing nut

plate. Such a job requires specialized tools, including a *milling machine*, a *drill press*, and a *tap set*. Carefully note the labeled dimensions shown in Figure 3.15. These numbers communicate to the machinist the acceptable deviation, or *tolerance*, for each of the plate's various dimensions. No part can ever be made to *exact* dimensions, because machine tools do not cut perfectly. A cutting tool wanders about its intended position during the machining process. Similarly, changes in temperature, humidity, or vibration during the cutting process can cause the tool to follow a less-than-perfect path. The tolerance of each dimension shown in the drawing specifies the degree of error that will be acceptable for the finished product. As a rule, creating parts with tight tolerances involves the use of more expensive machining equipment and more time, because material cuts must be made more slowly. These features add considerable expense to the finished part. As the designer, you must decide which dimensions are truly critical.

The numbers on the drawing in Figure 3.15 have precise meaning for any machinist who reads the tolerance table. In this case, only the holes that will hold the axle mounts are especially critical. The length of the chassis base, for example, is 25 cm. The numbers 25.0, 25.00, and 25.000, though all mathematically equivalent, would mean

Figure 3.15. Main chassis plate with dimensions and tolerance table.



different things to the machinist. According to the tolerance table, the number 25.0, with one digit after the decimal point, should be interpreted by the machinist to mean 25 ± 0.1 cm. A chassis plate with a finished width diameter anywhere between 25.1 and 24.9 cm would be deemed acceptable. Similarly, the location of the holes that will hold the axle mounts are specified as lying 15.00 cm apart, implying a machined tolerance of 15 ± 0.05 cm. The minimum and maximum tolerance limits for the hole centers as machined would be between 15.05 cm and 14.95 cm. According to the tolerance table, the most stringent dimensions of all are those of the holes themselves. Because they will hold pins inserted by a friction fit, their diameters are specified to three decimal points, implying a strict machining tolerance of 0.200 ± 0.001 cm.

Significant Figures

The accuracy of any number used in technical calculations is specified by the number of *significant figures* that it contains. A significant figure is any nonzero digit or any leading zero that does not serve to locate the decimal point. A number cannot be interpreted as being any more accurate than its least significant digit, nor should a quantity be specified with more digits than justifiable by its measured accuracy. The numbers 128.1, 1.5, and 5.4, for example, imply numbers that have known accuracies of ±0.1, but the first is specified to four significant figures, while the second and third are specified to only two. If trailing zeros are placed *after* the decimal point, they carry the weight of significant figures. Thus the number 1.000 means 1 ± 0.001.

The accuracy of any computation can only be deemed as accurate as the *least* accurate number entering into the computation, and the number of significant figures that can be claimed for the result should be set accordingly. For example, the product 128.1 × 1.5 × 5.4 entered into a calculator produces the result 345.87. But because 1.5 and 5.4 are specified to only two significant figures, the rounded-off result of the multiplication must be recorded as 350, also with two significant figures. Note that a digit is rounded *up* if the digit to its right is 5 or more; if the digit to its right is less than 5, the digit is rounded down.

Technical Reports and Memoranda

Logbooks provide but one method of keeping a good documentation trail. Engineers also communicate information by writing technical reports at the significant milestones of a design project. A technical report describes a particular accomplishment, perhaps providing some project history or background material before explaining the details of what was achieved. The report may contain theory, data, test results, calculations, design parameters, or fabrication dimensions. Technical reports help form the backbone of a company's or laboratory's technical database and typically are stored in archival format, each with its own title and catalog number. Information for a technical report is gathered easily from a logbook this is accurate and up to date. When the time comes to write a journal paper, patent application, or product application note, the technical report becomes an indispensable reference tool. Techniques for writing technical reports in a clear and concise manner are presented in Chapter 7.

A technical report is also an appropriate way to explain why a particular idea did not work or was not attempted. Taking the time to write a technical report about a negative result or design failure can save considerable time later on should a design concept be revisited or attempted by engineers who were not present when the original project took place.

Schematics and Drawings

Documentation does not always appear in the form of text. Graphical records, such as drawings, circuit schematics, photographs, and plots, also become part of the documentation trail. These items are typically created with the help of computer software tools.

If paper is chosen as the storage medium, then graphical output should be printed on paper and kept in a folder along with other written records. If an electronic storage medium is preferred, then all files related to a particular project should be stored on disk in a logical hierarchy. Some engineers choose to keep all files for a project in a single file folder on the computer. Others prefer to sort files by the applications that produce them (e.g., CAD drawings in one folder, spreadsheet files in another, etc.) Yet other engineers like to transfer all the computer files related to a given project to a single removable disk that can be stored in a physical file-cabinet folder. Regardless of which storage method is chosen, the information related to a particular project should be carefully preserved in a format that will prevent loss.

Software Documentation

Of all design endeavors, the writing of software is one most prone to poor documentation. The revision loop of a software design cycle can be extremely rapid, because the typical software development tool allows the programmer to make small changes and test their effects immediately. This rapid-fire method of development invites poor documentation habits. Seldom does the software engineer find a good time to stop and document the flow of a program, because most pauses are short and change is frequent. As a result, the documentation for many software programs is added after the fact, if at all.

If you find yourself writing software, get into the habit of including documentation in your program as you go along. All software development tools provide a means for adding comment lines right inside the program code. Add them frequently to explain why you've taken a certain approach or written a particular section of program code. Explain the meaning of object names and program variables. Outline the flow of the program and the format of input data, output data, and graphical interfaces. Your in-program documentation should enable another engineer to completely understand and take over the writing of your program simply by reading the comment lines. Good in-program documentation will also be invaluable to you should you need to modify your program at a later time. It's amazing how quickly a programmer can forget the internal logic of a program after setting it aside for only a short time.

If your program is destined for commercial sale, then good internal documentation will easily translate into an instruction manual for the software. Better yet, write the instruction manual as you write the program code. You can change the instruction manual at the same time that you make major changes in the program code. The abundance of commercial software packages with pathetic or poorly written instruction manuals is testimony to generations of software engineers who have perpetuated a tendency toward poor documentation habits. If you master the skill of documenting software, your software products will be better utilized and more successful than those with poor documentation.

PROFESSIONAL SUCCESS: HOW TO KEEP GOOD RECORDS ALL THE TIME

If you want to keep a good documentation trail, get into the habit of carrying your logbook with you wherever you go. In that way it will be available whenever you have a thought or idea related to your project. Buy a medium sized notebook that can fit easily into your backpack if you carry one. Clip a pen right inside the binding. Be sure to write your name and contact information on the cover in case you misplace your logbook. A tiny [illegible] pocket notebook [illegible] because it will readily fit into your pocket [illegible] Although writing space will be [illegible] smaller size, you'll be more apt to [illegible] with you when an idea comes [illegible]

Exercises 3.3

E10. Refer to the logbook calculations of Figure 3.13. Revise the estimate of the current drain on the battery if the vehicle weight is 1.7 kg.

E11. Refer to the logbook calculations of Figure 3.13. Convert all quantities to metric units and rewrite the logbook page.

E12. Refer to the logbook calculations of Figure 3.13. Revise the estimate of the current drain on the battery if the ramp height is 2 m and its length is 4 m.

E13. Refer to the tolerance table on the logbook page shown in Figure 3.15. Compute the difference between the maximum and minimum permissible physical values for dimensions specified by the following numbers: 10.0 cm, 7.55 cm, 1 cm, 2.375 cm, 0.005 cm.

3.4 ESTIMATION AS AN ENGINEERING DESIGN TOOL

Engineering design and estimation go hand in hand. When beginning any new design task, it's always a good idea to test for feasibility by doing rough calculations of important quantities and parameters. A paper-and-pencil analysis of a proposed strategy may eliminate fatal flaws before the actual construction process begins. The calculations need not be elaborate or precise. In the age of calculators and computers, students sometimes feel that an answer with lots of digits implies a better or more accurate answer. In many cases, however, "back of the envelope" calculations done by hand (recorded in your logbook, of course!) are all that are required to determine the soundness of a design strategy.

An Estimation Example

The following example, based on the Peak-Performance Design Competition introduced in Chapter 2, illustrates the usefulness of estimation as a design tool. Suppose that you and your teammate have decided to build a car that is battery operated and propelled by an electric motor. In an effort to conserve weight, you have decided to operate the vehicle from a single 9-V "transistor radio" battery, if possible. This design choice takes advantage of the fact that each run up the ramp is short in duration (around 15 seconds), and teams are allowed to change batteries between runs. Your strategy will be to heavily tax each battery to its maximum output and change it between each run up the ramp. In order to determine whether such a strategy is feasible, you must estimate the power to be delivered by the battery as the vehicle travels up the ramp. If this required power exceeds the amount available from a single battery, you will need to alter your design strategy and use two or more batteries.

Calculating the Power Required from the Battery

A simple calculation will reveal the power flow required from the battery as the vehicle travels up the ramp. The competition rules specify a maximum weight of 2 kg (about $4^1/_2$ pounds), but you hope to limit your vehicle weight to less than half that amount, or 0.9 kg (about 2 pounds). Of course, when you actually build your vehicle, you will need to determine whether your maximum weight target has been met.

Mechanical power for the vehicle will ultimately come from the battery. The motor has the job of converting electrical power into mechanical power. The electrical power going into the motor will have to equal the mechanical power transmitted to the wheels plus any electrical or mechanical losses in the drive train. This power–flow relationship is illustrated in Figure 3.16. Computing the mechanical power needed to

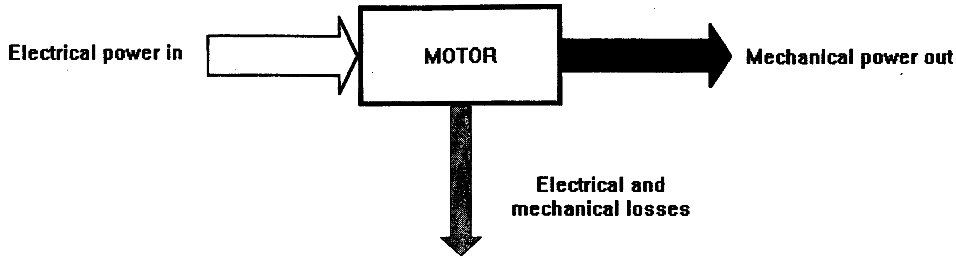


Figure 3.16. Power flow diagram.

propel the vehicle up the ramp will allow you to estimate the electric power flow required from the battery. You first compute the gravitational force on the vehicle:

Gravitational Force (Weight) Equals Mass Times Gravitational Constant

Newton's law states that

$$\mathbf{F} = m\mathbf{g},$$

where **g**, the gravitational constant, is downward directed and has a magnitude of about 10 Newtons per kilogram. The weight of a 0.9-kg vehicle will be (0.9 kg)(10 N/kg) = 9 Newtons.

Energy Equals Force Times Distance

As the car is propelled to the top of the ramp, the mechanical energy supplied by the wheels will be equal to the net gain in the car's stored potential energy. This quantity will be equal to the magnitude of the gravitational force on the vehicle times the vertical distance traveled. The top of the hill lies 90 cm above the floor, hence the net gain in potential energy becomes

$$E = \|\mathbf{F}\|\Delta y = (9\text{ N})(90\text{ cm} \times 0.01\text{ m/cm}) \approx 8\text{ Joules.}^{*}$$

Mechanical Power Equals Energy Per Unit Time

The quantity *power*, or flow of energy per unit time, is measured in joules per second. Assuming, for estimation purposes, that the run up the ramp lasts about 7 seconds, or half the allotted run time of 15 seconds, the mechanical power supplied by the wheels can be estimated by dividing the stored energy by the time required to climb the ramp:

$$P_{\text{mech}} = E/t = (8\text{ J})/(7\text{ s}) = 1.1\text{ watts}$$

*The net gain in potential energy also can be expressed as the vector *dot product* of the vertically directed force and the trajectory *s* of the vehicle along the angle of the ramp. The ramp is inclined at an angle θ relative to the vertical, where θ can be computed from the ramp specifications. As shown in Figure 2.5, the vertical rise of the ramp is 90 cm, and the path length traveled by the vehicle is 30 cm + 120 cm = 150 cm. Hence,

$$\cos\theta = (\text{height})/(\text{path length}) = (90\text{cm})/(150\text{ cm}) = 0.6$$

$$\Rightarrow \theta = \cos^{-1} 0.6 \approx 53^\circ$$

The potential energy stored in the vehicle then becomes

$$E = \mathbf{F} \cdot \mathbf{s} = (9\text{ N})(150\text{ cm} \times 0.01\text{ m/cm}) \times \cos 53^\circ \approx 8\text{ joules.}$$

This result is the same one computed from $\|\mathbf{F}\|\Delta y$.

A calculation such as this one should always be examined to make sure that the answer is reasonable. As a basis for comparison, consider a small plug-in night-light that draws about 4 watts. Expecting the car to draw about one quarter of that amount for 7 seconds indeed seems reasonable; the answer is believable.

Electrical Power Equals Current Times Voltage

The electrical power supplied to the motor must be equal to the mechanical power supplied to the wheels plus any losses that occur in the motor and drive train (e.g., the gears, belts, pulleys, bearings, and axle mounts). Neglecting these losses, one arrives at the simple conclusion that $P_{elec} = P_{mech}$. The electrical power supplied by the battery will be equal to the product of its voltage and its current, i.e., $P_{elec} = VI$. Hence, at a fixed voltage of 9 V, a power drain of 1.1 W will require a battery current of

$$I = P/V = (1.1 \text{ W})/(9 \text{ V}) \approx 120 \text{ mA}.$$

You next decide to obtain some information about batteries. Accessing the Duracell™ and Eveready™ Web pages* reveals that the typical 9-V battery can supply about 100 mA of current for short (1 hour or less) periods. This level of battery performance places your design specification at the border of feasibility. You can decide to use one battery only, possibly taxing it to its limit, or change your design specifications to include *two* batteries, each providing half the required power. For the moment, you decide that one battery is the better choice from the size and weight points of view. The 100 mA battery capacity is a general guideline, not an absolute limit. If you stick with your strategy of replacing the battery after every run, it might perform adequately. Also, if you increase the run time to 10 seconds, the power required will be reduced to 0.8 W, and the current required will be reduced to 90 mA.

On Second Thought

After reviewing your calculations and assumptions, you and your teammate realize that you have neglected all losses in the system. In reality, the conversion efficiency from electrical to mechanical power will be far from perfect. According to your professor, one might expect a power conversion efficiency of up to 90% from a well-designed, expensive motor, but you've decided to buy an inexpensive motor from a local electronic parts store to save money. Similarly, no more than about 60 percent of the converted mechanical power supplied by the motor shaft will show up at the wheels, because of frictional losses in the gears, drive belts, and axle mounts, leaving only about 50 percent of the power taken from the battery to actually propel the vehicle. The two-battery approach seems to be the more reasonable choice after taking losses into account.

Another Estimation Example (Not Related to the Peak-Performance Design Competition)

Imagine that you work for a company that makes automobiles. The head of manufacturing thinks that the company could save a lot of money by adopting a finishing process that impregnates color right into the body material during manufacturing using an electrostatic powder coating and baking technique. You are trying to convince your boss that the paint does not cost that much compared to the cost of making the rest of the car.

*http://www.duracell.com, http://www.eveready.com

The comparison is a tough call, because labor and equipment depreciation, not materials, are the main costs involved in most manufacturing processes. The overhead at a typical fabrication facility, including benefits, insurance, physical plant (the cost of keeping the factory open so that workers can do their jobs), and depreciation can run anywhere from 60 percent to 200 percent of salaries and other direct costs. Alternatively, the car could be painted by robot as are many large consumer items. In that case, labor costs would be eliminated, and a comparison between the powder and paint coating mechanisms is valid, because the cost of materials becomes the primary issue. The head of manufacturing has asked you, a manufacturing engineer, to estimate the total cost of conventional paint needed to cover the vehicle. How can you arrive at such an estimate? The steps required are outlined in the following discussion:

Draw a Rough Sketch of the Surfaces to Be Painted

The first step should be to draw a rough sketch of the car body on paper. One such sketch that depicts the various car surfaces is shown in Figure 3.17. The largest areas to be painted include the hood, trunk, roof, and both side fenders. The paint required to cover the posts of the window frames is negligible.

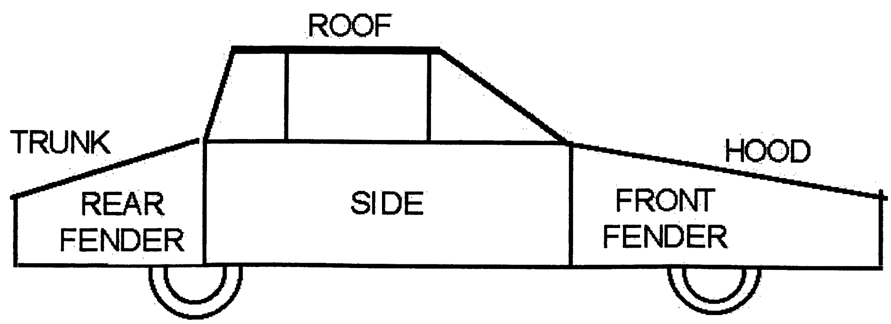
Estimate the Area of Each Section

Next estimate the area of each separate section of the car. The hood forms an approximate 1.2 m × 1.2 m square for a total area of about 1.4 square meters. The trunk is also nearly rectangular, measuring about 1.2 m × 1.5 m, for an additional 1.8 square meters. The doors are about 1 m long by 0.8 m tall, for a total area of 0.8 square meter each. The dimensions of the roof are about 1.4 m long by 1.2 m wide, for total of 1.7 square meters. For estimation purposes, each of the fenders can be modeled by one of the shapes shown in Figure 3.18. The surface area of the windows need not be counted, because they are not painted. The area of each fender can be calculated from the area formula for a trapezoid:

$$A = bc + c(a - b)/2.$$

If we assume reasonable numbers for the dimensions of the fenders, for example $a \approx 0.8$ m, $b \approx 0.4$ m, and $c \approx 1.5$ m for the front, and $a \approx 0.8$ m, $b \approx 0.4$ m, and $c \approx 1$ m for the rear, then we can compute the individual area estimates and add them to obtain an estimate for the total surface area of the car:

Figure 3.17. Rough sketch of car body.



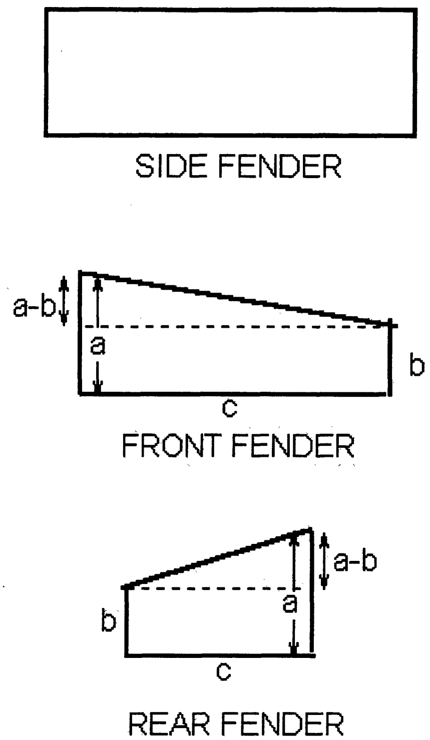


Figure 3.18. Estimated shape of side fenders.

Hood: $1.2 \text{ m} \times 1.2 \text{ m} \approx 1.4 \text{ m}^2$

Trunk: $1.2 \text{ m} \times 1.5 \text{ m} \approx 1.8 \text{ m}^2$

Doors: $2 \times 1 \text{ m} \times 0.8 \text{ m} \approx 1.6 \text{ m}^2$

Roof: $1.4 \text{ m} \times 1.2 \text{ m} \approx 1.7 \text{ m}^2$

Front fenders: $2 \times [(0.4 \text{ m})(1.5 \text{ m}) + (1.5 \text{ m})(0.8 \text{ m} - 0.4 \text{ m})] = 2.4 \text{ m}^2$

Rear fenders: $2 \times [(0.4 \text{ m})(1 \text{ m}) + (1.5 \text{ m})(0.8 \text{ m} - 0.4 \text{ m})] = 2 \text{ m}^2$

Total area: $1.4 \text{ m}^2 + 1.8 \text{ m}^2 + 1.6 \text{ m}^2 + 1.7 \text{ m}^2 + 2.4 \text{ m}^2 + 2 \text{ m}^2 = 10.9 \text{ m}^2$

The result is equal to about 10 square meters. Round numbers are appropriate because only a rough estimate is required.

Multiply by the Thickness of the Paint

We next estimate the volume of paint required to cover the car by multiplying its surface area by the paint thickness. Paint thicknesses are usually measured in mils (1 mil = 0.001 inch $\equiv$ 0.025 mm = 25×10^{-6} m.) A very light coating of paint is typically about 0.5 to 1 mil thick, while a very heavy coating might be as thick as 7 or 8 mils. The choice of thickness for estimation purposes will depend on the paint application and whether we want the estimate to be on the high side or the low side of the actual value. Let's choose an average value of 4 mils. For this thickness, the volume of paint required to coat the car can easily be calculated:

Volume = area $\times$ thickness $\approx (10 \text{ m}^2) \times (4 \text{ mils}) \times (25 \times 10^{-6} \text{ m/mil}) = 0.001 \text{ m}^3$, or about one liter.

Exercises 3.4

E14. Determine the power required of the battery for the Peak Performance vehicle if the ramp is only two thirds as high as the value specified in the competition guidelines presented in Chapter 2.

E15. Determine the power required of the battery for the Peak Performance vehicle if a set of four 1.5-V AAA cells is used instead of a single 9-V battery.

E16. How much mechanical power can be derived from a 6-V electric motor that is 85% efficient if its maximum allowed current is 1 A?

E17. How much internal heat will be generated by an electric motor that is 60% efficient if it provides 20 kW of mechanical power to an external load?

E18. Estimate the amount of paint required to cover a single wooden pencil.

E19. Estimate the length of a 90 minute audio cassette tape.

E20. Estimate the number of platforms needed to build a scaffolding shell that encircles the Washington Monument.

E21. Estimate the volume of water contained within the supply pipes of a one-story, single family house.

3.5 PROTOTYPING AND BREADBOARDING: COMMON DESIGN TOOLS

Designing anything for the first time requires careful planning and forethought. As discussed in previous sections, the design process should begin with an exhaustive consideration of all possible alternatives and an effort to assess feasibility through preliminary estimations, sketches, and approximations. In some cases, a computer simulation of the design may be in order. (See Chapter 4.) After these initial phases of the design effort, it's time to proceed to the prototyping phase. A *prototype* is a mock-up of the finished product that embodies all its salient features but omits nonessential elements, such as a finished appearance or features not critical to the device's fundamental operation. Figure 3.19, for example, shows the prototype of a payload for a NASA rocket experiment.

If the product is an electronic circuit, it can be built up on a *breadboard.* A breadboard allows an engineer to wire together the various components of a circuit, such as resistors, capacitors, and integrated circuits, by plugging them into holes aligned with spring loaded clips located inside the breadboard. The clips make the electrical connections between components. In the prototype development stage, a breadboard readily permits changes and alterations to a circuit. A well-laid-out electronic breadboard is shown in Figure 3.20.

In production, the finished circuit is permanently soldered onto a printed wire board, such as those found inside computers, radios, and TVs. This form of circuit construction provides a durable, reliable finished product. An example of printed wire board construction is shown in Figure 3.21.

If the product is mechanical, its prototype should be fabricated from an easy-to-machine material that will permit testing, but perhaps not be as durable or visually attractive as the finished product. The chassis plate of Figure 3.15, for example, could be made from wood for initial tests of vehicle performance. Wood is easily drilled and formed, but is much less durable than metal for demanding applications. Mechanical prototypes can also be fabricated from various forms of angle iron and similar construction materials. One example is illustrated in Figure 3.22. The pieces of angle iron used to build this structure have holes in numerous places to allow for rapid construction and protyping.

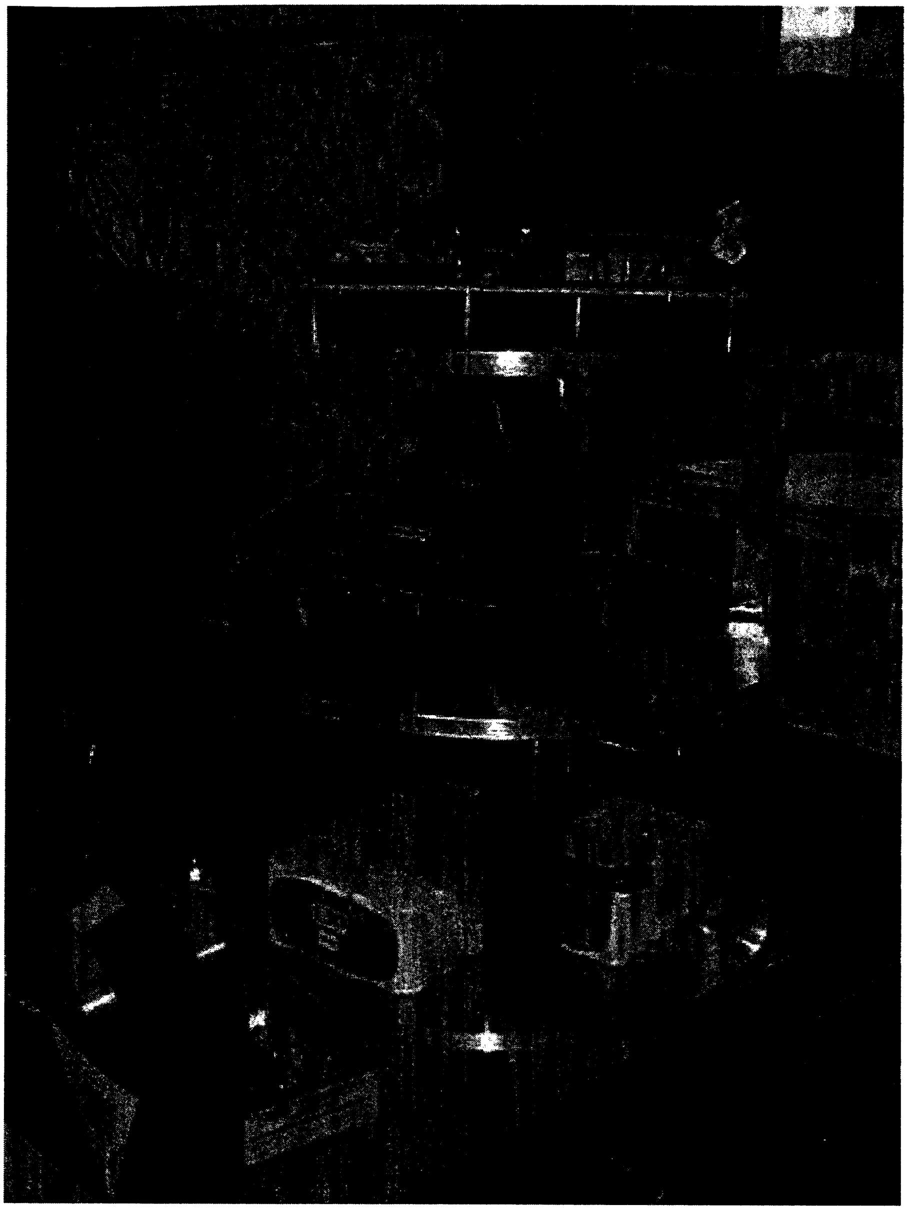


Figure 3.19. Prototype of the payload for a NASA rocket experiment.

Engineers and architects who design large structures, such as buildings, bridges, and dams, face a handicap not encountered by other engineers. It's virtually impossible to build a full-size prototype of these structures for testing purposes. It's not feasible, for example, to build the frame of a large sky scraper in some remote desert location to determine its maximum sustainable wind speed before collapse. Engineers who build large structures rely on *scale modeling* to guide them through the prototyping phase. Scale modeling relies on dimensional similarity to extrapolate observations made on a model of reduced size to the full-sized structure. Effects such as structural loading, wind loading, temperature, and large-scale motion are readily scaled and extrapolated. Wind tunnels are widely used to test scale models for aerodynamic effects. Vibration, combustion, and wave phenomena do not scale well because these effects are governed by

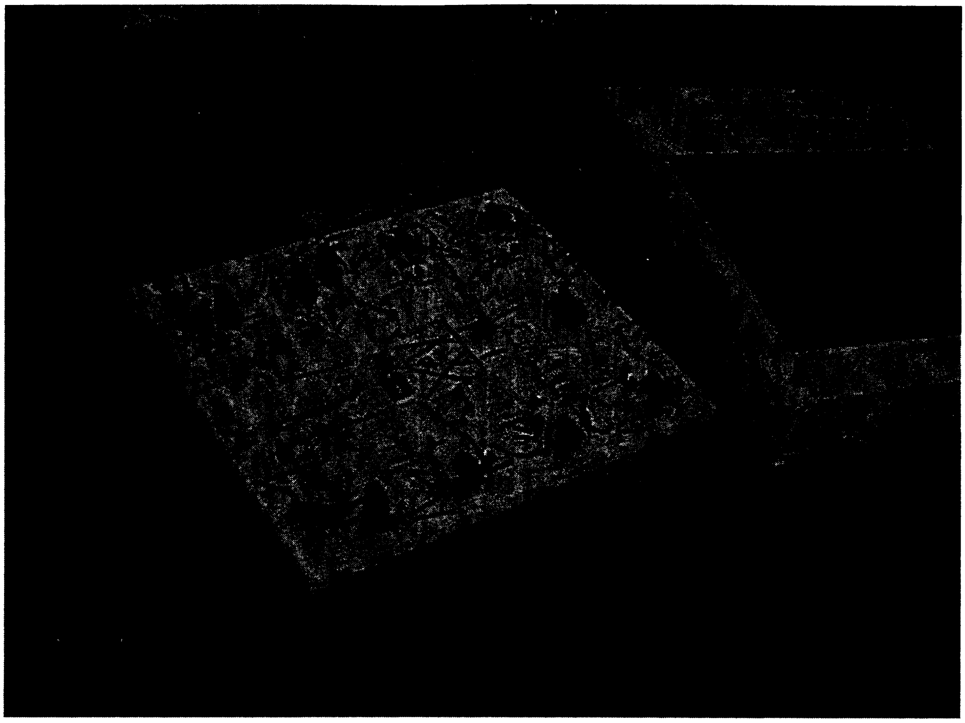


Figure 3.20. A well laid circuit on an electronic breadboard connected to two benchtop power supplies.

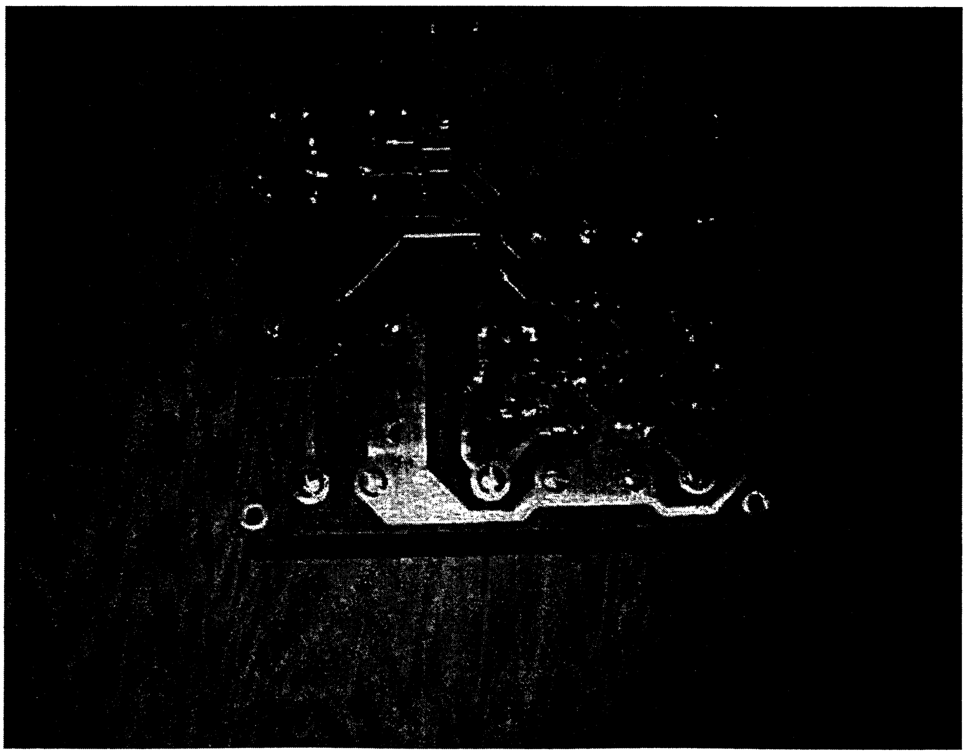


Figure 3.21. Underside view of a circuit fabricated on a printed wire board.

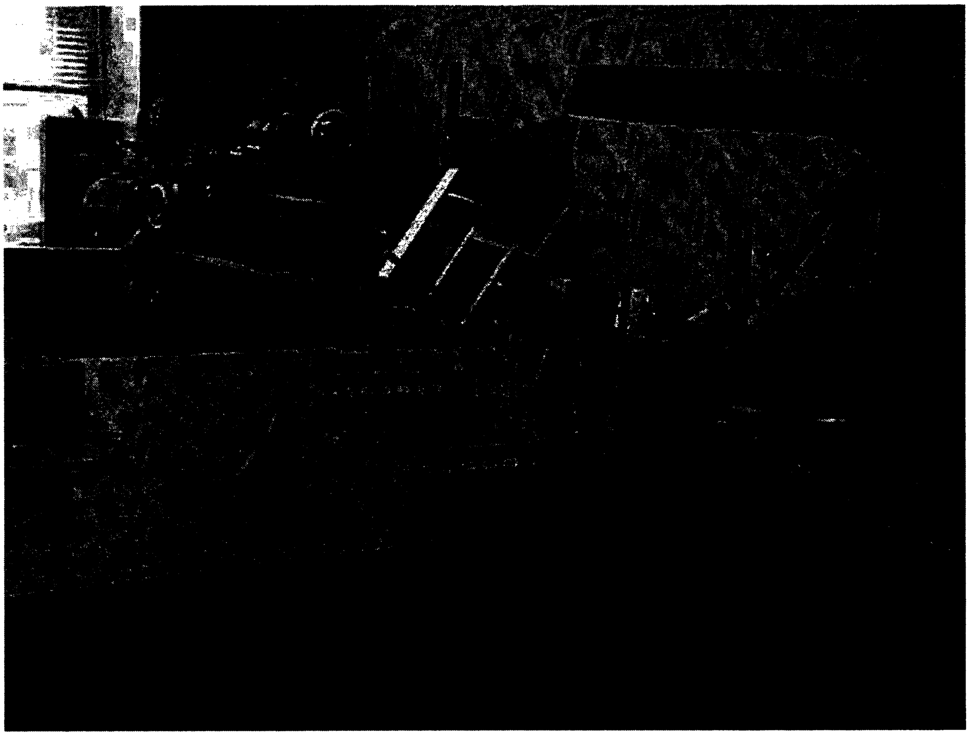


Figure 3.22. A prototype for testing an electrostatic chuck. The prototype has been fabricated from angle iron, plywood, and other simple materials.

physical parameters that are fixed regardless of the frame of reference. (That's one reason why movie scenes involving ships at sea or burning buildings often look unrealistic.)

Products designed for medical applications are developed in the prototype stage from inexpensive materials that exhibit the same physical characteristics as the finished product. A new design for a ball-and-socket replacement hip joint, for example, might be fabricated from aluminum for testing in a cyclical loading machine. The finished product ready for implantation would likely be produced from surgical-grade titanium at ten times the cost.

Software modules also undergo a prototype phase. Most software kernels (the part of a software program that does the actual "thinking") are surrounded by a graphical user interface (GUI) that provides access to the user. A software designer typically will write and test the kernel portions of a program long before writing the GUI.

A Prototyping Scenario

Prototyping is essential for the development and testing of electrical, mechanical, structural, and software devices. The prototype phase helps engineers reveal design flaws and problems that have escaped the initial planning and estimation phases. The following scenario illustrates the importance of careful prototyping in engineering design. It describes Tina's attempt to test her motor and timing circuit concept for the Peak-Performance Design Competition of Chapter 2. Tina's original ideas were outlined in the discussion on brainstorming presented in Section 3.2.

With the help of her teammate Juan, who prepared a prototype of the car's chassis frame from plywood, Tina mounted a small breadboard containing the car's electronic timing circuit and attached the drive motor to the chassis with some duct tape. She wired up the battery and connected it to the timing circuit. When she was finished with the wiring, Tina collected some diagnostic equipment: an oscilloscope to measure the output of the timing circuit, an ammeter to measure the motor current, and a voltmeter to monitor the voltage of the battery.

With the motor disconnected, Tina powered up the timing circuit and examined its output on the oscilloscope. Most of the circuit checked out, but Tina did find a wire that she had forgotten to connect between two of the integrated circuits. After adding the wire, and correcting one other crossed wire, the circuit appeared to function as she had intended. It produced a voltage for driving the motor that lasted for about 7 seconds, the precise time (according to her estimation) needed for the car to travel up the ramp.

Satisfied with the operation of the timing circuit, Tina next connected the motor to the load side of the circuit and turned it on. With the drive belt disconnected, the motor turned nicely and stopped after 7 seconds, so she and her teammate mounted the wheels, the gearbox, and the drive shaft and connected them to the motor with a small drive belt. The motor was about the size of a large D-cell battery. Tina held the car in midair. The motor again turned at a steady speed and cut out quickly when the timer circuit finished its timing pulse.

Tina next took the prototype and tried to run it up a large plank, which served as a mockup for the competition ramp. The plank, purchased at a lumber store, had one end propped up on a chair to simulate an inclined ramp. After turning on the switch, the car prototype traveled about half a car length and then stopped. At first, Tina was discouraged by this result. Was the timer faulty, or had she overlooked some fundamental design principle that would make her approach to the competition unworkable? She decided to perform further tests on the vehicle off the ramp. She clamped the car chassis in a vise with its wheels held in midair, connected the oscilloscope to the output of the timer, and connected the voltmeter across the battery and ammeter in series with the motor. When the switch was turned on, the motor turned as before for the entire 7-second duration of the timer signal. She noticed that the current to the motor was about 40 milliamperes and that the voltage on the 9-V battery dropped to about 8.2 V when the motor was running. Suspecting a battery drain problem, Tina next applied some friction to the wheels with her hand so simulate the load on the car traveling up the ramp. The current to the motor jumped to 160 mA, and the battery voltage dropped to 3.9 V. This drop in voltage caused the timer circuit, which required a power source of at least 5 V, to cease functioning. Tina had been overloading the battery! She redesigned the layout of the chassis to accommodate a set of six 1.5-V, AAA batteries connected in series instead of a single 9-V battery. This modification was performed easily on the wooden mockup of the chassis frame. At the expense of some added weight, the additional battery capacity could provide up to 200 mA of current with a voltage drop to only 8.2 V. Tina's battery performance problem was detected in the prototype phase.

PROFESSIONAL SUCCESS: WHERE TO FIND PROTOTYPING MATERIALS

The materials needed for creating prototypes can be found in many places. For building mechanical structures, no better place exists than your local hardware store. A well-stocked hardware store sells all sorts of nuts, bolts, rods, dowels, fasteners, springs, hinges, and nails. Many common electrical parts, such as wires, [illegible]

[redacted]

3.6 REVERSE ENGINEERING

Reverse engineering refers to the process by which an engineer dissects a product to learn how it works. This design method is particularly useful if your goal is to duplicate a competitor's product or create a similar one using your own technology. Reverse engineering is practiced on a regular basis by companies worldwide. Although it may appear to be an unfair practice, in reality it can be a good way to avoid patent infringement and other legal problems by specifically avoiding an approach taken by a competitor. Reverse engineering one of your own products can be a good way to understand its operation if its documentation trail has been lost or is inadequate. Reverse engineering is encouraged in the writing of Web pages on the Internet. All of the major Web browsers provide a means to view and decipher the Hypertext Mark-up Language (HTML) code, or language used to encode the Web page, when it has been loaded onto your computer. This practice fosters the open information environment that has become the hallmark of the World Wide Web. Other forms of software, however, such as programs written in C, MATLAB, Mathematica, MathCad, or Fortran, can be particularly difficult to reverse engineer, particularly if the software has been poorly documented. The multitude of flow paths and logical junctions typical of such software programs can lead to confusion on the part of the reader and make it hard to understand how a program operates.

3.7 PROJECT MANAGEMENT

Even the simplest of design projects must be properly managed if they are to be successful. A systematic approach toward the completion of design goals is always preferable to a random, hit-or-miss approach. Project management is, like all the topics covered in this chapter, a design skill that must be learned and mastered. While the subject of project management could (and does) occupy the contents of entire books, we discuss here briefly three principal project management tools that can be used for design projects likely to be encountered by students or entry-level engineers.

Organizational Chart

When engineers gather to work as a team on a design project, some degree of hierarchy is necessary. It would be nice to approach all projects as a simple group of cooperative colleagues, but inevitably some team members will be burdened with more work than others unless everyone's responsibilities are clearly spelled out. One vehicle for specifying the management structure of a design project is the *organizational chart.* An organizational chart indicates who is responsible for each aspect of the design project, and it also describes the hierarchy of the team and those to whom the team members report. Figure 3.23 illustrates a simple organizational chart that might be used by students in the Peak Performance Design Competition. In this particular case, no student acts as team leader, but instead two independent teams work with each other and report to the

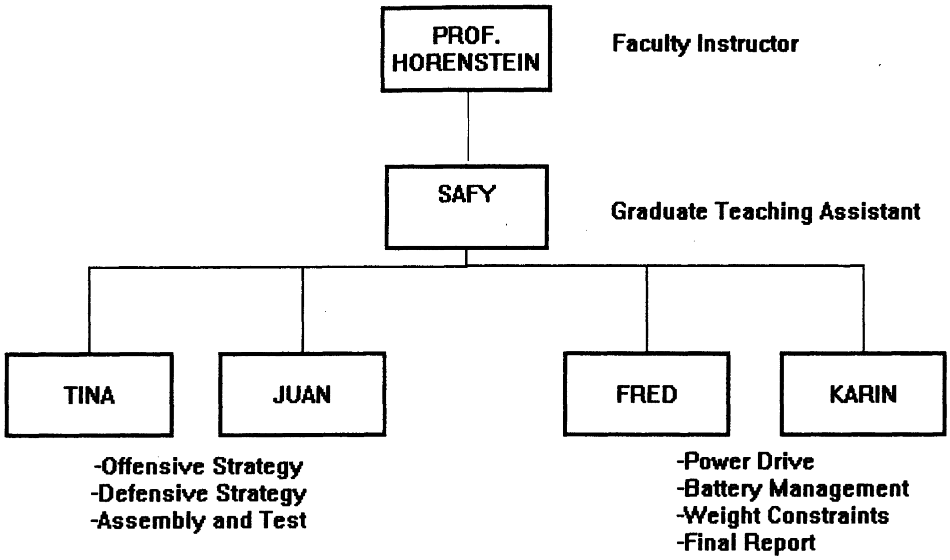


Figure 3.23. Organizational chart showing responsibilities of the Peak Performance design team.

course teaching assistant for leadership and guidance. Other teams may choose to designate one student to act as overall team leader, while others may decide that several layers of administration are best. In the corporate world, where the structuring of workers and bosses can become complex, organizational charts are essential because each employee must understand to whom he or she reports and must know how upper management layers are structured.

Time Line

Time management is critical to the successful completion of a design project. In a perfect world, a design engineer would have as much time as necessary to work on all aspects of a design project, but in the real world, deadlines, demonstrations of progress, and the pressure to "get the product out the door" require that an engineer develop a sense of how much time will be needed for the various tasks of product development. (See, for example, the success box: The Laws of Time Estimation.) A *time line* can be a valuable tool for an engineer that wants to keep a project on schedule. A time line is simply a linear plot on which each of the various phases of a design project is assigned a milestone date. If any given task is in danger of not being completed before its designated milestone date, its the job of the engineer to allocate more time, and overtime if necessary, so that the task can be completed on time. A typical time line, such as one that a student might prepare for the Peak Performance Design Competition, is shown in Figure 3.24.

Gantt Chart

When a project becomes complex and involves many people, a simple time line may be inadequate for managing all aspects of the project. Similarly, if the project's various parts are interdependent, so that the completion of one phase depends on the success of others, the *Gantt Chart* of Figure 3.25 is a more appropriate time-management tool. The Gantt chart is simply a two-dimensional plot in which the horizontal axis is time, usually measured in blocks of days, weeks, or months, and the vertical axis represents either the tasks to be completed or the individuals responsible for those tasks.

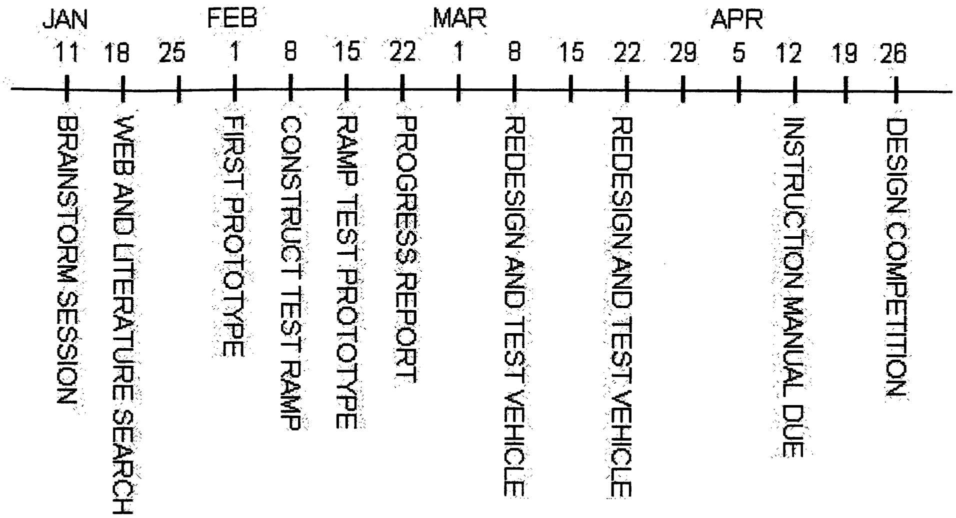


Figure 3.24. Time line for scheduling tasks for the Peak Performance design team.

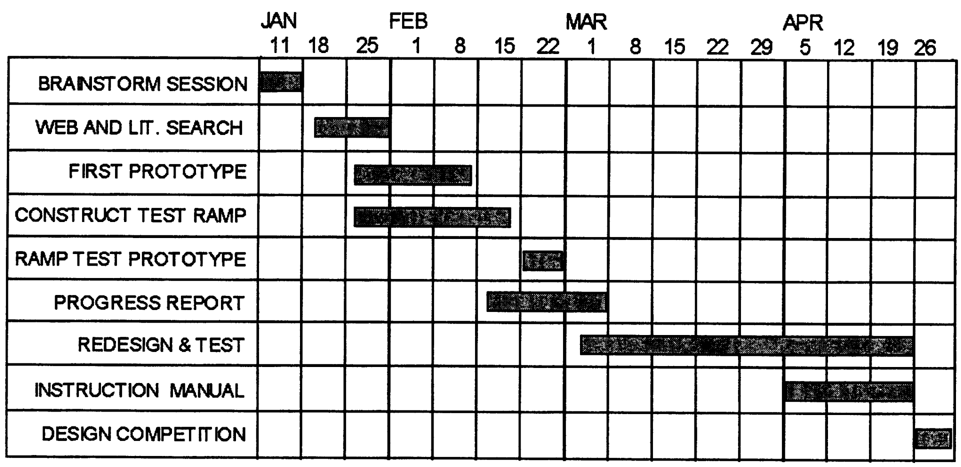


Figure 3.25. Gantt chart provides a more comprehensive, two-dimensional method of scheduling the tasks for the Peak Performance design team.

Unlike the simple one-dimensional time line, which displays only the milestone dates for each phase of the project, the Gantt chart shows *how much* time is allotted to each task. It also shows the time overlap periods that are indicative of the interdependency between the various tasks of the project. When a particular task has been completed, it can be shaded in on the Gantt chart, so that the status of the project can be determined at a glance.

Exercises 3.7

E22. Devise an organizational chart for building a float for the homecoming parade at your college or university.

E23. Develop a time line for building a float for the homecoming parade at your college or university.

E24. Develop a time line for a completing your course requirements over the time span of this semester.

E25. Develop a Gantt chart that can help you plan to host an educational conference on engineering design. Consider all needed arrangements, including food, transportation, lodging, and meeting facilities.

PROFESSIONAL SUCCESS: PROJECT MANAGEMENT—THE LAWS OF TIME ESTIMATION

How long will it take to perform a particular design task? How much time should I allot to each segment of the design cycle? The following three Laws of Time Estimation will help you to determine the time required for elements of the design process:

1. Everything takes longer than expected.
2. If you've worked on something similar before, estimate the amount of time required to fin[illegible]
3. [illegible]

KEY TERMS

Brainstorming
Prototyping
Documentation
Project management
Estimation

Problems

Brainstorming: Use brainstorming methods to generate solutions to the following problems:

1. You are given a barometer, a stop watch, and a tape measure. In how many different ways can you determine the height of the World Trade Center in New York City?
2. Design a sensing mechanism that can measure the speed of a bicycle.
3. Many international airline flights allow smoking in the rear seats of the aircraft. Design a system that will remove or deflect smoke from the front seats of the aircraft.
4. You are given an egg, some tape, and several drinking straws. Using only these materials, design a system that will prevent the egg from being broken when dropped from a height of six feet (two meters).
5. Devise as many different methods as you can for using your desktop computer to tell time.
6. Design a system for washing the inside surfaces of a large aquarium (the kind the public visits to see large sea creatures) from the outside.
7. Design a system to be used by a quadriplegic to turn the pages of a book.
8. Devise a system for automatically raising and lowering the flag at dawn and dusk each day.
9. Design a system that will automatically turn on a car's windshield wipers when needed.
10. Develop a device that can alert a blind person to the fact that water in a pot has boiled.
11. Devise a system for lining up screws on an assembly-line conveyor belt so that they are all pointing in the same direction.
12. Develop a method for detecting leaks in surgical gloves during the manufacturing process.
13. Devise a method for deriving an electrical signal from a magnetic compass so that it can be interfaced with a computer running navigational software.
14. Given a coil of rope and eight poles, devise a method to build a temporary emergency shelter in the woods.

15. Devise an alarm system to prevent an office thief from stealing the memory chips from inside a personal computer.
16. Imagine custodial workers who are in the habit of yanking on the electric cords of vacuum cleaners to unplug them from the wall. Devise a system or device to prevent damage to the plugs on the ends of the cords.
17. Develop a system for automatically dispensing medication to an elderly person who has difficulty keeping track of schedules.
18. Develop a system for reminding a business executive about meetings and appointments. The executive is always on the go, but can carry a variety of portable devices and gadgets. Feel free to use your knowledge of existing communications systems and technology, if necessary.
19. Devise a system that will agitate and circulate the water in an outdoor swimming pool so that a chlorine additive will be evenly distributed. Assume that an electrical outlet is available at the site of the pool.
20. Devise a system that will allow a truck driver to check tire air pressure without getting out of the vehicle.

Logbook and Record Keeping:

21. Begin to keep a logbook for your class activities. Enter sketches and records of design assignments, inventions, and ideas.
22. Pretend that you are Alexander Graham Bell, the inventer of the telephone. Prepare several logbook pages that describe your invention.
23. Pretend that you are Marie Curie, the discoverer of the radioactive element radium. Prepare several logbook pages that describe the activities leading to your discovery.
24. Pretend that you are Dr. Zephram Cockran, the inventor of plasma warp drive on the television and movie series Star Trek®. Prepare several logbook pages that describe your invention.
25. Imagine that you are Elias Howe, the first inventor to perfect the sewing machine by putting the eye of the needle in its tip. This innovation made possible the bobbin system still in use today. Prepare several logbook pages that describe your invention and its initial tests.
26. Reconstruct logbook pages as they might have appeared for the person inventing the common paper clip.
27. Evaluate each of the following numerical computations, expressing the result with an appropriate number of significant figures:
    a. $F = 1221 \text{ kg} \times 0.098 \text{ m/s}^2$
    b. $V = 56 \text{ A} \times 1200 \text{ ohms } (\Omega)$
    c. $x = 76.8 \text{ m/s} \times 1.000 \text{ s}$
    d. $m = 56.1 \text{ lb} + 45 \text{ lb} + 98.2 \text{ lb}$
    e. $i = 91.4 \text{ V} \div 1.0 \text{ k}\Omega$
    f. $P = (5.1 \text{ V})^2/(1.0 \text{ k}\Omega)$
28. When calculations are performed, the answer will only be as accurate as the weakest link in the chain. An answer should be expressed with the same number of significant figures as the least accurate factor in the computation. Express the result of each of the following computations with an appropriate number of significant figures:
    a. $V = (12.9 \text{ mA})(1500 \ \Omega)$
    b. $F = 2.69 \text{ kg} \times 9.8 \text{ m/s}^2$
    c. $F = -3.41 \text{ N/mm} \times 6.34 \text{ mm}$
    d. $i_B = (1.29 \text{ mA})/(100)$
    e. $Q = (6.891 \times 10^{-12} \text{ F})(2.34 \times 10^3 \text{ V})$
29. Measure the dimensions of an ordinary 3.5" computer diskette. Prepare a dimensioned sketch of the diskette, complete with tolerance table.

Estimation:

The following three problems relate to the first estimation example on page 73 concerning the amount of power required to propel the vehicle up the ramp in the Peak-Performance Design Competition:

30. For the chosen approximate run time of 7 seconds, will the battery *always* supply 1.1 W of power to the vehicle? What would be a reasonable estimate of the average power flow over the 15-second run time?
31. Suppose that smaller batteries are chosen that can supply only 50 mA of peak current. Such a decision might be made to reduce battery weight and produce a lighter vehicle. If vehicle weight is reduced to 0.5 kg, what power flow can be expected? What will be the peak battery current?
32. If motors are chosen with 95 percent efficiency, and mechanical losses are 60 percent, what will be the required battery current?

The following four problems involve vector addition. Vector manipulation is an important skill for estimating forces in mechanical systems. When adding forces or other quantities represented as vectors, the principles of vector addition must be followed. Vectors to be added are first decomposed into their respective x-, y-, and z-components. These components are added together separately, then recombined to form the total resultant vector. Sometimes it's convenient to decompose vectors into components lying on axes other than the x-, y-, and z-axes.

33. Two guy wires securing a radio antenna are connected to an eye bolt. One exerts a force of magnitude 3000 N at an angle of 10° to the vertical. The other exerts a force of 2000 N at an angle of 75° to the vertical. Find the magnitude and direction of the total force acting on the eye bolt.
34. A guy wire exerts a force on an eye bolt that is screwed into a wooden roof angled at 30° to the horizontal. The guy wire is inclined at 40° to the horizontal. If the eye bolt is rated at a maximum force of 1000 N perpendicular to the roof, how much tension can safely be applied to the guy wire?
35. A large helium-filled caricature balloon featured in a local parade is steadied by two ropes tied to its midpoint. One rope extending on one side of the balloon is inclined at 20° to the vertical. A second rope located on the other side of the balloon is inclined at 30° to the vertical. If the balloon has a buoyancy of 200 kN, what will be the tension in each of the ropes?
36. An eye bolt is fixed to a roof that is inclined at 45° relative to the x-axis. The eye bolt holds three guy wires inclined at 45°, 150°, and 195°, respectively, measured clockwise from the x-axis. These wires carry forces of 300 N, 400 N, and 225 N, respectively. What is the magnitude and direction of the total resultant force? What are the components of force measured perpendicular and parallel to the roof line?

Problems 37–54 can help you develop your design estimation skills. Discuss them with your friends, and see if you arrive at the same approximate answers.

37. Estimate the amount of paint required to paint a Boeing 747™ airplane.
38. Estimate the cost of allowing a gasoline-powered car to idle for 10 minutes.
39. Estimate the daily consumption of electrical energy by your dormitory, residence, apartment building, or home. (Check your estimate against real electric bills if any are available.)
40. Estimate the cost of leaving your computer running 24 hours per day.
41. Estimate the cost savings of installing storm windows on an average-sized four-unit apartment building.
42. Estimate the gross weight of a fully loaded eighteen-wheel tractor trailer.
43. Estimate the number of single-family houses in your home state.
44. Estimate the number of bolts required to assemble the Golden Gate Bridge.
45. Estimate the number of bricks in an average-sized house chimney.
46. Compute the surface area of all the windows in your dorm, apartment building, or house where you live.

47. Estimate the amount of carpet that it would take to cover the playing field at San Francisco's 3Com Park.
48. Estimate the total mass of air that passes through your lungs each day.
49. Estimate the time required for a stone to fall from sea level to the bottom of the lowest point in the Earth's oceans.
50. Estimate the cost of running a medium-sized refrigerator for a year.
51. Estimate the weight of a layer of shingles needed to cover a single-family, ranch-style house that has a flat roof. Revise your calculations for a pitched roof.
52. Estimate the physical length of a standard 120-minute VHS video cassette tape.
53. Estimate the number of microscopic pits on an average-sized audio compact disk (CD) or digital video disk (DVD).
54. Estimate the number of books checked out of your school library each week.

Prototyping:

55. Suppose that 100 mA of steady current flows from a 9-V battery via a timer circuit to a motor. If the controller circuit is 92 percent efficient and the motor 95 percent efficient, how much mechanical power is transferred to the motor wheels (neglecting bearing friction)?
56. Ohm's law states that the voltage across a resistor is equal to the current flowing through it times the resistor value ($V = IR$.) Calculate the current flowing through each of the following resistors if each has a measured voltage of 24 V across it: 1 Ω, 330 Ω, 1 kΩ, 560 kΩ, 1.2 MΩ (Note: 1 kΩ = 10^3 Ω; 1 MΩ = 10^6 Ω).
57. Ohm's law states that the current flowing through a resistor is equal to the voltage across it divided by the resistor value ($I = V/R$.) Calculate the voltage across each of the following resistors if each has a measured current of 10 mA: 1.2 kΩ, 4.7 kΩ, 9.1 kΩ, 560 kΩ, 1.2 MΩ. (Note: 1 mA = 10^{-3} A, 1 kΩ = 10^3 Ω, and 1 MΩ = 10^6 Ω).
58. Kirchhoff's current law states that the algebraic sum of currents flowing into a common connection, or *node,* must sum to zero. Suppose that currents of 1.2 A, –5.4 A, and 3.0 A flow on wires that enter a four-wire node. What current must flow *out* of the fourth node?
59. Kirchhoff's voltage law states that the sum of voltages around a closed path must sum to zero. Three resistors are connected in series to a 9-V battery. The measured voltages across two of the resistors are 5 V and 2.5 V, respectively.
    a. What is the voltage across the third resistor?
    b. The first two resistors have values of 100 Ω and 50 Ω, respectively. What is the current flowing through the third resistor?
60. High-power devices, such as thyristors and power transistors, are often mounted on metal *heat sinks.* A heat sink enhances the overall thermal contact between the device package and the surrounding air, leading to a cooler device and a larger power-dissipation capability. Heat removal is important, because excess heat can cause a catastrophic rise in device temperature and permanent failure. Every heat sink has a heat-transfer coefficient, or *thermal resistance,* Θ (capital Greek theta), which describes the flow of heat from the hotter sink to the cooler ambient air. The ambient air is assumed to remain at constant temperature. This thermal flow can be described by the equation $P_{therm} = (T_{sink} - T_{air})/\Theta$, where P_{therm} is the thermal power flow out of the device, T_{sink} is the temperature of the heat sink, and T_{air} the temperature of the air.
    a. A power device is mounted on a heat sink for which Θ = 4.5 °C/W. A total of 10 W is dissipated in the device. What is the device temperature if the ambient air temperature is 25°C?
    b. A device rated at 200°C maximum operating temperature is mounted on a heat sink. If the ambient air is 25°C and 25 W of power must be dissipated in the device, what is the largest thermal coefficient Θ that the heat sink can have?
61. A switch is a mechanical device that allows the user to convert its two electrical terminals from an open circuit (no connection) to a short circuit (perfect connection) by moving a

lever or sliding arm. A *switch pole* refers to a set of contacts that can be closed or opened by the mechanical action of the switch. A *single-pole, double-throw* (SPDT) switch has three terminals: a center terminal that functions as the common lead, and two outer terminals that are alternately connected to the center terminal as the position of the switch lever is changed. When one of the outer terminals is connected to the center terminal, the remaining outer terminal is disconnected from the center terminal.

a. Consider the problem of wiring the light in the stairway of a two-story house. Ideally, the occupants should be able to turn the light on or off using one of two switches. One switch is located at the top of the stairs, and the other is located at the bottom. Toggling either switch lever should make the light change state. Draw the diagram of a circuit that illustrates the stairway lighting system.

b. Now consider the problem of a *three*-story house in which the lights in the stairwell are to be turned on or off by moving the lever of any one of three switches (one located on each floor). Design an appropriate switching network using two single-pole switches and one double-pole switch. (A double-pole switch has six terminals and can be thought of as two single-pole switches in tandem, with both levers engaged simultaneously.)

62. A dc motor consists of a multipole electromagnet coil, called the *armature,* or sometimes the *rotor,* that spins inside a constant magnetic field called the *stator* field. In the small dc motors typically found in model electric cars and toys, permanent magnets are used to create the stator magnetic field. In larger, industrial-type motors, such as an automobile starter or windshield-wiper motors, the stator field is produced by a second coil winding.

Current is sent through the rotating armature coil by way of a set of contact pads and stationary brushes called the *commutator.* Each set of commutator pads on the rotor connects to a different portion of the armature coil winding. As the rotor rotates, brush contact is made to different pairs of commutator pads so that the portion of the armature coil receiving current from the brushes is constantly changed. In this way, the magnetic field produced by the rotating armature coil remains stationary and is always at right angles to the stationary stator field. The north and south poles of these fields constantly seek each other, and because they are always kept at right angles by the action of the commutator, the armature experiences a perpetual torque (rotational force). The strength of the force is proportional to the value of armature current, hence the speed of the motor under constant mechanical load is also proportional to armature current.

a. Obtain a small dc motor from a hobby or electronic parts store. Connect two D-cell batteries in series with the motor without regard to polarity. Observe the direction of rotation, and then reverse the polarity of the battery connections. Observe the results.

b. As an engineer, you are likely to encounter situations in which the rotational direction of a dc motor must be changed by a switch control. Using a double-pole, double-throw switch like the one described in the previous problem, design a circuit that can reverse the direction of the motor using a single switch.

Reverse Engineering:

63. Take apart a retractable ball point pen (the kind that has a push button on top to extend and retract the writing tip). Draw a sketch of its internal mechanism, and write a short description of how the pen works.

64. Take apart a common 3.5" floppy computer diskette. Make a sketch of inner construction, and write a short summary of its various components.

65. Take apart a standard desktop telephone. Use your investigative methods to develop a block diagram of how the phone works and connects to the outside world.

66. Suppose that you have been given the assignment to design a desktop stapler. Dissect an existing model from a competitor, draw a sketch of its mechanical construction, and create a parts list for the stapler.

67. Take apart a common flashlight, draw a sketch of its mechanical construction, and create a parts list from which you could reproduce another.

68. Imagine that you have discovered an errant, unoccupied space vehicle in an outlying field. Write a report in which you reverse engineer the spacecraft to discover elements of its technology. Examine the vehicle's propulsion system, telemetry, and sensor systems.

Project Management:

69. Suppose that you've been given the assignment to write a research paper on the history of human air flight. Develop a time line for completing this comprehensive research assignment.
70. Create a Gantt chart for your own hypothetical entry into the Peak-Performance Design Competition.
71. Imagine that you work for a company that is designing an electric car for commercial sale. Create an organizational chart for the company and a Gantt chart for designing the vehicle's drive train.
72. Choose an engineering company with which you are familiar or in which you have an interest. Develop an organizational chart for the company. Information about a company's structure and personnel often can be found on the company's Web page.
73. Imagine that you wish to start your own company to write software tools for doing business on the Web. Create an organizational chart that outlines the positions you'll need to fill to get the company started.