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# Introductory Engineering Design: A Projects-Based Approach

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## **NOTES**

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# Introduction

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The primary objective of the introductory engineering projects course is to provide an overview of engineering careers, primarily through open-ended, hands-on design experiences. This text and reference book is designed to support those experiences by providing guidance on course activities and information about the principles, methods and professional skills that are essential to engineering design.

In introductory engineering projects courses, the full cycle of engineering design is experienced. It begins with specification of design objectives and constraints, continues through development, documentation and analysis of design ideas, and ends with the process of building and testing the solution. Throughout the cycle, engineering design follows a logical process involving careful documentation and quantitative analysis using mathematical tools and scientific principles.

During the design process, experience will be gained in developing and working in interdisciplinary teams. Written and oral communication skills will be honed, both through formal communications with classmates, instructors and clients, and through informal communication within teams. Because engineering communication utilizes graphics, in addition to words, proficiency with engineering drawing and graphical presentation of data is developed.

The first few chapters of this book cover three course activities: the Mystery Artifact Challenge, the Design Loop and Reverse Engineering, which are intended to emphasize various critical skills or elements of the design process. Each of these chapters provide information on the skills or elements addressed by the activity and gives guidance on how to successfully complete it.

Chapter 2 provides guidance on completing the Mystery Artifact Challenge. This activity is designed to cultivate investigative skills and resourcefulness, as well as to begin the process of evolving work groups into effective teams. The investigative skills required for the Mystery Artifact Challenge are in fact vital to all engineers, and include the ability to make detailed observations, to formulate and test hypotheses based on observations, and to assess how characteristics and properties of an artifact correlate to its function.

Chapter 3 describes the Design Loop, a design exercise that emphasizes the iterative nature of the design process. The Design Loop introduces the role of measurements and testing in the design process and provides experience with measurements, spreadsheets and engineering drawing.

Reverse Engineering is covered in Chapter 4. This activity provides an opportunity to learn about how engineering products are designed and manufactured by carefully dissecting an existing product. Reverse Engineering emphasizes analysis and quantitative testing, and challenges participants to make product improvements in function, appearance, manufacturability, environmental impact and universal accessibility.

The remaining chapters of the book explore professional skills essential to design courses; these will be further developed throughout subsequent college coursework and used throughout an engineering career. These skills include the ability to make ethical judgments; to work effectively in teams; to communicate technical information using words and graphics; and to apply the fundamentals of engineering mechanics, measurements and instrumentation to engineering design.

One of the defining characteristics of the engineering profession is its code of ethics, which consists of standards of conduct that are necessary because of society's reliance on engineering expertise. The introduction to engineering ethics presented in Chapter 5 is intended to assist with the recognition of ethical conflicts when they arise and provide practice in making ethical judgments. Moving from societal interactions to interpersonal dynamics, Chapter 6 deals with teamwork. Teams, not individuals, are now widely recognized as the fundamental unit in most engineering organizations. Chapter 6 outlines practical tools for effective team building and maintenance.

Chapter 7 describes the design process, detailing the essential stages of the process and describing tools and concepts that are useful for negotiating each stage. The chapter presents tools for scheduling, project management, ideation, analysis and evaluation of engineering designs. The chapter also provides background information for all engineering design courses. Chapter 8 provides suggestions and guidance for the creation of products that are aesthetically pleasing as well as functional.

Chapters 9-13 deal with effective communication of technical information. Data presentation and engineering drawing are covered in Chapters 9 and 10, respectively. Modes of communication—written reports, oral reports and poster presentations—are discussed in turn in Chapters 11, 12 and 13. Each of these chapters begins with the principles of effective communication in the respective mode and provides straightforward guidance on organization, format and delivery.

Chapter 14 presents fundamental concepts of engineering mechanics. In future courses, students in aerospace, civil and mechanical engineering will study this topic in more depth. However, a basic understanding is valuable for all engineers engaged in design of physical artifacts, because strength and stiffness are factors in the design of most objects. Chapter 15 introduces techniques and instrumentation for making measurements that are commonly required for analysis and testing of design projects. As with engineering mechanics, most students will learn more about measurements and instrumentation in future courses, building on the basic information presented here.

Since analysis is the essence of engineering, Chapter 16 provides a review of engineering analysis to engender appreciation of the role analytical assessment plays in the design process.

Chapter 17 introduces electronics and circuits and provides enough information to recognize electronic components and their role in a simple circuit, read an electronic schematic circuit design, and make basic calculations to create a safe functioning circuit.

# Mystery Artifact Challenge

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## **INTRODUCTION**

Past mystery artifacts have taken a number of forms: a complete, working device; a sub-component of a system; or a prototype of some leading-edge technology. An artifact is chosen to illustrate an engineering principle or to represent an engineered object. The challenge, using all resources available, is to develop, test and defend hypotheses for the functioning of selected artifacts. Only the artifact donors, and perhaps one other coordinating professor, know the identity and function of the objects.

This exercise is used as an introduction to the design process and reverse engineering. It provides an initial opportunity for team members to work together to solve an open-ended problem.

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## **MYSTERY ARTIFACT LEARNING GOALS**

The learning objectives of the mystery artifact challenge include the following:

- ◆ Solidify team dynamics in a short-term exercise.
- ◆ Help students learn to work effectively in a team activity.
- ◆ Provide an introduction to reverse engineering.
- ◆ Disperse teams throughout the community to meet and talk with a variety of faculty members and be introduced to available resources.
- ◆ Cultivate investigative skills.
- ◆ Increase resourcefulness in seeking out information.
- ◆ Encourage the habit of making detailed observations correlating aspects to functions.
- ◆ Introduce the formulation and testing of hypotheses, drawing and supporting conclusions.
- ◆ Provide practice of communication skills.
- ◆ Ease entrance into engineering.

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## **THE ORIGINS OF ARTIFACTS**

An artifact is never used more than once. This is to insure that the exercise remains an engineering exercise and does not degrade into an effort of searching for students in prior classes or old assignments for answers. In other words, the goal is to create engineers not historians. In the past, artifacts have come from a variety of sources, including:

- ◆ Professors
- ◆ Alumnae
- ◆ Technological pack rats
- ◆ Local commercial and government laboratories
- ◆ Other universities
- ◆ Antique stores and museums
- ◆ New materials or prototype devices
- ◆ Surrounding engineered objects

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## **EXAMPLES OF PAST ARTIFACTS**

Examples of past mystery artifacts indicate the broad range of devices and materials presented for analysis. Past artifacts include:

- ◆ Muscle wire
- ◆ Section of a floor mat from an engineering building
- ◆ A plastic that changes color when exposed to ultraviolet light
- ◆ An optical coupler for transferring movie film to video
- ◆ Components of a pressure sensor for detecting nuclear explosions
- ◆ A device used by scientists for capturing insects
- ◆ Wind noise reducer for a microphone
- ◆ Replica of an ancient Chinese seismometer
- ◆ Staple dispenser from a copy machine
- ◆ Thermostat from a refrigerator
- ◆ Adjustable pressure switch
- ◆ Radio beacon
- ◆ Helmholtz resonator

This is only a small sample of the artifacts used to date. Teams can expect to encounter practically anything. The mystery artifacts have represented all disciplines and included complete devices, materials and sub-components. Quantitative testing and analysis of data obtained to determine function was possible for many students. One example, emphasizing the importance of paying attention

to small clues, is the student who was investigating the radio beacon. While holding the artifact, which looked like a bomb (a sealed, small plastic case with a fuse-like appendage), he noticed strange interference on a nearby television. Following up on this clue the team was able to determine most of the beacon properties.

---

## THE MYSTERY ARTIFACT EXERCISE

During one class meeting, the instructor reviews the background and learning goals, presents examples of past artifacts and runs through the exercise in capsule form. The original information for the example devices is provided for each artifact. After each team has inspected the example devices, students are asked to make quick guesses concerning their function. After this “guessing game,” the solutions to the example are presented.

Next, students are introduced to a selection of unknown artifacts to be investigated. An information sheet taped to the table in front of each artifact provides a modest amount of background information. Also at each table there is a sheet for written questions and answers. Student teams choose three artifacts on which to report. For one of these three, each team prepares a detailed report and presentation; the team produces short summaries for the other two artifacts. There is a sign-out sheet if a team wishes to take an artifact from the classroom *during their class period* for testing or consultation. Teams should be aware that other students also require access, and the artifacts must be returned on time.

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## EXAMPLES OF ARTIFACT INFORMATION PROVIDED

Four samples of past artifacts appear below. The information that was originally provided to students appears with each artifact. Without actually physically inspecting and testing, deducing functions and purpose is close to impossible. The purpose here, however, is to capture the sequence of events involved in the process. Solutions to these artifacts appear at the end of this chapter.

### Artifact A: Clear Box with Red Balls

Information provided:

- ◆ This was sold by a company in quantity.
- ◆ This is not a toy.
- ◆ This is complete as is and not intended to be used with any other devices.
- ◆ This is in working order.



### Artifact B: The Rubber Thing

Information provided:

- ◆ This is made out of rubber.



### Artifact C: Gears & Levers

Information provided:

- ◆ The back of this was removed so that the mechanism can be inspected. The knobs can be moved freely to see how the various parts are linked together. Do not mess with the linkages in the back. As an exercise, try using the Working Model software program to represent a portion of the system.
- ◆ There is important information on the front. The stand is not a part of the device and was added so that the mechanism could be inspected easily. There is no important information underneath the device.
- ◆ It was purchased in a parts store for three dollars.
- ◆ Can the function be determined?
- ◆ Why was it needed?
- ◆ From what period of time does it come?
- ◆ How was it designed? By a single person? By a team?



F



B

### Artifact D: The Blue Box

Information provided:

- ◆ This is a “one of a kind” object. It was built to illustrate a concept and resulted in the Federal Aviation Administration funding a multi-year program at well over a million dollars.
- ◆ An Italian TV personality (in-depth news show) brought a crew to Boulder, Colorado, and video was taken of him carrying this device out of an elevator.
- ◆ This is in full working order.
- ◆ Feel free to take it out of the case. Do not disconnect any wires or tubes. There seem to be two circuits: one electrical and one pneumatic. Trace these out if desired.
- ◆ What is it? How does it work?



### WRITTEN QUESTION / ANSWER FORMAT

In most cases, only one or two people associated with this course know the functions of the mystery artifacts. This places everyone (students, TAs, professors and other faculty) on an even playing field. Professors and TAs are free to make suggestions and answer questions. To provide everyone with the same information, once a day, someone “in the know” visits the question/answer sheets and provides answers. This way, everyone receives the same feedback. Although this process would work over the Internet, taping the sheets to the tables in front of the artifacts permits efficient information updates. The written question/answer format has proven fair and efficient.

### WHAT QUESTIONS CAN BE ASKED AND HOW?

Any questions can be asked. However, keep in mind that the spirit of the exercise is to apply analytical skills; it is not intended to be a “hot or cold” guessing game. Thus, there is a two-column sheet for questions and answers.

Some questions will not be answered. For others, the response will be “Zen like,” in the sense that the answer will probably be profound, but not supply anything very helpful. Feel free to write any question on the sheet. Do not be disappointed by the reply, and remember that other students will also read the Q/As.

Examples of questions that are valuable to ask (and will probably be answered) are those dealing with the following areas:



- ◆ Limits of testing: *Can it be put underwater? Can it be set on fire?*
- ◆ Historical background: *How many were made?*
- ◆ Context of use: *Was it part of a system? Is another component or device necessary for functionality?*
- ◆ Resources: *Can a pressure gauge be made available?*

For the four example artifacts listed above, the following are some typical Q/As:

<b>Questions</b>	<b>Possible Answers</b>
<b>Artifact A:</b> We put this underwater and now the balls are all stuck together. Can you fix it?	Will work on it. Low heat overnight solved the problem.
<b>Artifact A:</b> Can we test this in a microwave oven?	Please don't. There is metallic paint on one portion that will probably vaporize.
<b>Artifact B:</b> Were these used in large numbers with a long rope through the center?	Could be, or on the other hand, perhaps not.
<b>Artifact C:</b> Was this used in aircraft?	Not telling.
<b>Artifact D:</b> Why was the Italian TV personality in the elevator?	Good question.

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## **INVESTIGATIVE CONTEXT AND CONDUCT**

The process of solving a mystery artifact replicates the steps of a major reverse-engineering project, but on a short time scale. The exercise is intended to develop keen perception skills and sensitivity to subtle design features. The habit of curious questioning is a valuable trait for engineers to nurture, and solving and exploring an interesting mystery can be a satisfying experience. The following suggestions for solving mystery artifacts emphasize the need to be organized, analytical and open minded. Rarely, a team member may have special knowledge concerning an artifact. Should this happen, please keep this knowledge within the team, and be aware that there is still a requirement to follow through with a complete analysis and reporting.

### **Suggestions for Solving Artifacts**

Suggested approaches for solving mystery artifacts include:

- ◆ *Inspect the artifact* with notebook in hand. Record all first impressions.
- ◆ *Record the details* of the device or material (color, shape, weight, dimensions, etc.) in journal entries. Make sketches as part of this process.
- ◆ *Summarize all information* provided including Q/A information. Pose questions that arise.
- ◆ *Meet as a team and brainstorm* the function of each object. Remember to include guidance from team dynamics experiences and record non-judgmental suggestions for future discussion.

- ◆ *Develop a plan* for further investigation, quantitative testing and analysis. Some artifacts are especially suited to exploration by measurement. At this point, an artifact may particularly intrigue one team member; it may be effective for that person to explore the artifact and then report back to the team.
- ◆ *Start the testing and analysis.* Through this period, it is wise to remain open-minded to new clues and information. Any resource developed or thought of can be applied (e.g., Internet and patent searches, visiting various faculty, visiting local laboratories). Resourcefulness and persistence are also valuable traits for engineers. Many people in the scientific and business community have assisted teams with advice and information.
- ◆ At some point, it is effective to *make a priority list of hypotheses*, and start to work on the presentation and report. The time to start collecting information with a report and presentation in mind is from the very beginning. Factual sections can be written early in the process, while sections on deductions are developed later when tests and analyses are complete.
- ◆ Teams should meet to decide how best to do this. In the past, some teams have divided the various artifact sub-tasks between members, while other teams have elected to do all the work as a group. Everyone should be involved in the process and do their fair share of work. Teamwork is important because the effectiveness of a team as a whole is a model for the rest of the semester. It is imperative to address potential problems within the team as early as possible and solve these issues before the team “falls apart.”
- ◆ *Plan the presentation* and report so that everyone has an opportunity and is contributing.
- ◆ After the mystery artifact exercise is over, meet as a team and *discuss the overall team’s efforts*. Should the approach and methodology change in the future? Provide feedback comments to faculty and TAs.

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## **PROJECT CLOSURE**

Project solutions are only provided when all sections of the course have completed their presentations. This means that some classes will have to wait several days before the solutions are disclosed. Often, faculty members who have been contacted concerning a particular artifact will come to a class to find out the artifact’s function. For some artifacts, a simple demonstration of use will be possible. If time permits, a summary of suggested solutions from various sections will be provided. The variety of reasonable hypotheses advanced is amazing.

Solutions to the mystery artifacts presented earlier appear below in the same format usually followed. Some artifact solutions are accompanied by additional detail:

- ◆ manufacturer’s specifications/manuals
- ◆ technical properties
- ◆ advertisements
- ◆ historical background
- ◆ analytical calculations

**Solutions*****Artifact A: Clear Box with Red Balls***

The transparent plastic container with the little red balls floating in air was sold briefly in large quantities during the cold war. The device is a nuclear radiation detector. When radiation is present, it ionizes the air inside the container, allowing the static charges to leak off and the balls to fall.

***Artifact B: The Rubber Thing***

This artifact is a part of a large bus suspension system. The main rear suspension for large buses, such as those used on main bus routes, uses large air springs to provide “springiness” under normal driving conditions; but the rubber things (of which there are two) come into play if a large bump in the road is encountered. They stiffen the spring rate of the suspension and prevent metal-to-metal contact between the suspension and the frame of the bus. Some teams tested this in a civil engineering lab under compression loads of up to 10,000 pounds.

***Artifact C: Gears & Levers***

This is an analog computer that was used during the Second World War for setting the timing on the fuses of anti-aircraft shells. The complex set of interacting parameters, and the need for speed and accuracy, made this device a valuable resource in the absence of electronic computers.

***Artifact D: The Blue Box***

This is a prototype of a pressure jump detector designed to respond to the pressure increase that occurs at the leading edge of thunderstorm outflow boundaries and other sources of wind shear causing aircraft flight hazards. When a pressure increase occurs fast enough, the switch will close, setting off an alarm. Teams tested this by taking it down in an elevator until the alarm went off, using the pressure change with altitude to investigate the response.

# The Design Loop

## INTRODUCTION

Obtaining a viable solution to an engineering problem requires thought and action coordinated in a specific, iterative pattern. The method enables engineers to evaluate and refine potential solutions. Each step defines a specific action that propels the project forward to the next step. This process is shown in Figure 3.1.

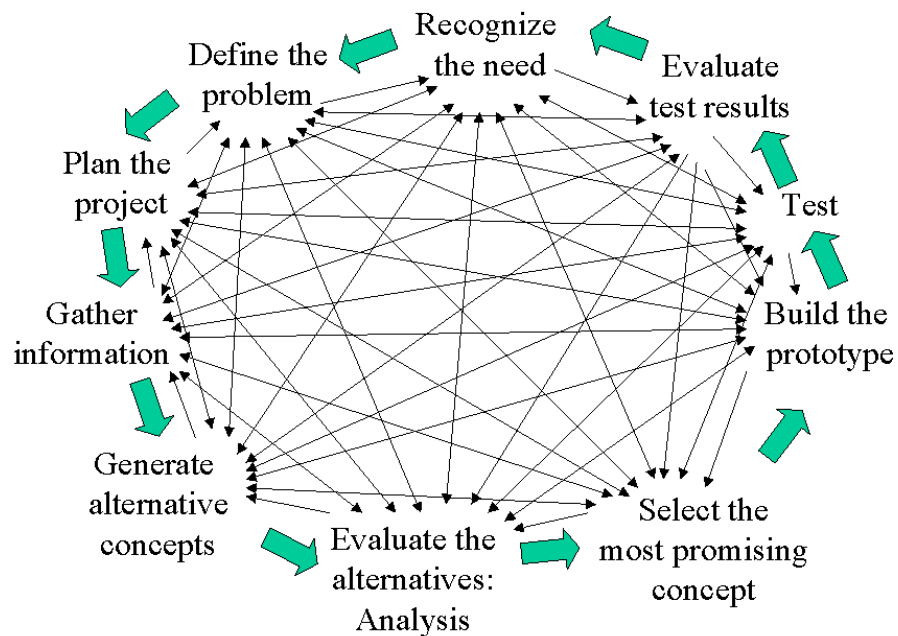


Figure 3.1. Schematic of the design process.

The process begins when a design engineer recognizes the need for a solution to a problem. A brief examination of the problem leads to defining and determining the requirements of the project. Although the full scope of the solution is still undefined, the design team begins to plan the project by

estimating how much time each stage of the project should take. The team then gathers information to refine the objectives of the project.

Throughout these first stages of the design process, ideas for potential solutions representing alternative concepts will be generated. These concepts must be analyzed, so that an informed decision selecting the most promising concept can be made. These important analyses take the process out of the realm of pure “trial and error” into an “engineered” solution. Next a *prototype*, or first model, is constructed. The prototype is then tested to see if it fulfills the requirements. The outcome of the test is evaluated to determine whether modifications are needed or if new problems have been created. If so, the loop is started over (iterated). If not, the original problem has been solved.

This is an idealized model of the design process. In reality, events rarely proceed so smoothly. Instead, stages occur simultaneously, shortcuts around the loop are often taken, and sometimes the process goes in reverse. The following example illustrates some possibilities: the column on the right identifies the design process stages as they occur in the example.

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**EXAMPLE: DESIGN OF A CUP HEATER**

Suppose that your small design team at Sunbeam Inc. was given the following task: *Design a better cup heater to heat 250 ml of tap water to boiling in 2 minutes.*

First, notice how simple—yet general—the problem statement is. There are no guidelines for the size or type of heater, except that it must fit inside a cup. Also, the shape of the heater is unclear. Your team also asks the questions: “To what is the heater compared? Better than what?” Your supervisor says that the heater should perform better than a microwave oven and plug into an electric wall socket. Then, your supervisor mentions that you have only one week to complete the design.

“One week!” Your team quickly realizes that the preliminary design must be completed today, and tested and refined tomorrow.

These first observations and questions are written in your design journal, but they remain unanswered. What is the next step in assessing the problem? A quick look in a physics textbook helps to further define the problem. Your team finds that it is possible to generate heat by passing a current through a wire.

⇐ Problem statement

⇐ Problem definition

⇐ Planning

⇐ Information gathering

Now the ideas start to flow. One team member remembers that her mother uses a small electric heater to heat cups of water. You remark that electric space heaters basically are made of long sections of thick wire, too. A suggestion is made to purchase a tea cup heater. Many team members speak at once. Someone suggests, obviously in jest, building a pocket-sized nuclear weapon. Another idea is to use the chemical packet that warms up feet in ski boots. All of these ideas are documented in your journal.

Your supervisor then requests that the heater be constructed from specialty wire located in the warehouse. You wonder what is so special about this particular wire. You wonder if the supervisor will continue to add more parameters.

Since heating wire is now required, your team decides to evaluate that concept further. A sketch is drawn in your design journal. The potential set-up looks something like the drawing in Figure 3.2.

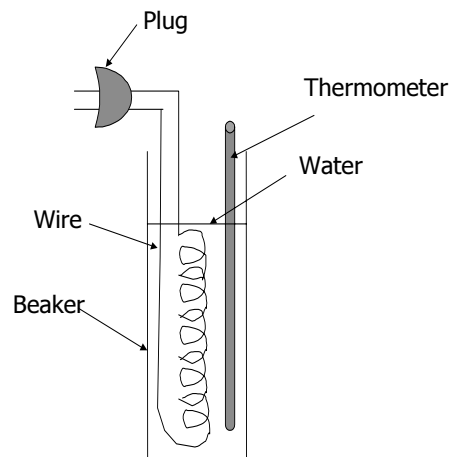


Figure 3.2. Design journal sketch.

A parts list prepared from the sketch includes wire, beaker, water and thermometer. Two team members state that they are ready to build the heater—but *are* they? Some members of the team want to build the heater immediately, but you say that the team needs more information before beginning. Another member returns from

⇐ Brainstorming: generating alternative concepts

⇐ Additional problem definition

⇐ Selection

⇐ Information gathering

the warehouse with a spool of the specialty wire. The label states that the material is NiCr, that the wire diameter is 22 gauge and that the resistance is 1.6  $\Omega$  per foot. One team member notes the thinness of the wire. Another team member says that the symbol " $\Omega$ " stands for the word "ohm." How does the value of 1.6  $\Omega$  per foot relate to the heating of water? Your team realizes that it must perform an *engineering analysis* of the problem to understand the relationship between the heating wire and the temperature of the water.

Together you discuss how a heater performs. Current flowing through the wire causes the wire to heat. The heat is transferred to the water. Your team estimates that the temperature of the water must be raised a maximum of 100°C, if the temperature comes out of the tap at close to 0°C (as a worst case scenario). How much heat is required to perform this feat? What equations apply to heating water? Someone digs out a first-year chemistry book, and the team finds that the heat absorbed by a volume of water is related to its heat capacity according to the following energy equation:

$$Q = C_p \Delta T,$$

where  $Q$  is the energy or heat absorbed by the water in watts, and  $\Delta T = (T_2 - T_1)$ , the difference between the beginning and ending water temperatures.

The reference tables in the back of the chemistry book give a value for  $C_p$  of water as approximately 1 cal/cc/°C.

$$Q = \left(1 \frac{\text{cal}}{\text{cc} \cdot ^\circ\text{C}}\right) (100^\circ\text{C} - 0^\circ\text{C}) \left(1 \frac{\text{cc}}{\text{ml}}\right) \left(4.1868 \frac{\text{Joules}}{\text{cal}}\right) \left(1 \frac{\text{Watt} \cdot \text{sec}}{\text{Joule}}\right)$$

$$Q = 418.69 \frac{\text{Watts} \cdot \text{sec}}{\text{ml}}$$

This is the amount of energy needed to heat one ml of water 100°C. Heating a cup of water (250 ml) in 2 minutes

$$\text{will take } \frac{\left(418.68 \frac{\text{Watt} \cdot \text{sec}}{\text{ml}}\right) (250 \text{ml})}{(2 \text{min}) \left(60 \frac{\text{sec}}{\text{min}}\right)} = 873 \text{Watts} .$$

⇐ Information gathering (cont.'d)

⇐ Engineering analysis

This value,  $Q = \frac{dQ}{dt} = 873 \text{ Watts}$  is the energy per unit time, or power, required. At this point, you perform a reality check. "If this were a light bulb, it would be pretty bright. Some hair dryers are only 800 watts. Some microwaves are around 1000 watts, but it does take a lot of energy to heat water."

Your next move is to determine how much wire is needed. The physics text states that for any material conducting electricity, Ohm's Law is given by the following formula:

$$V = IR,$$

where V is volts, I is current in amps, and R is resistance in ohms. You also read that the power P dissipated by the wire is given by this formula:

$$P = I^2 R = IV$$

Now, by using the above power equation, your team finds the current that is carried by the wire. The heater is to be plugged into a socket supplying common household electricity that has a voltage of 110 volts. From the power equation, the following expression is obtained for I:

$$I = \frac{P}{V} = \frac{873 \text{ Watts}}{110 \text{ V}} = 8 \text{ amps}$$

The required wire resistance is calculated from Ohm's Law:

$$R = \frac{V}{I} = \frac{110 \text{ V}}{8 \text{ amps}} = 14 \Omega$$

Now, the length of the wire can be estimated. The length is found from the resistance characteristic stated on the label, or 1.6  $\Omega$  per foot, and the required resistance value for the heater, or 14  $\Omega$ :

$$\text{Length} = 14 \Omega / 1.6 \Omega \text{ per foot} = 8.75 \text{ feet.}$$

This seems like a reasonable amount to coil up in a coffee cup, since the wire is so thin.

Your team decides that the analysis supports the original design concept shown in Figure 3.1 and chooses to build it. The team gathers in the lab and locates a glass beaker, an alcohol thermometer, a pair of wire snips and an unwired electrical plug. One team member suggests using a 10-amp fuse "just in case." The wire is wound



neatly around a 1-inch rod, and the ends of the wire are attached to the plug and the fuse. After filling the beaker with water, the coil of wire is submerged. You are ready to record the amount of time to heat the water while another team member prepares to record the temperature rise, and a third snaps a photograph of the experimental set-up. The plug is placed into the outlet.

Everyone watches as the plug smokes and they hear the snap of the fuse. What happened to heater? Why has it shorted out?

The team evaluates the test procedure. The bare wire was placed in the beaker of water. The fuse is attached to one end of the wire. The other wire end and the fuse end were connected to the plug. A team member comments, "Doesn't water conduct electricity?"

All of you simultaneously recognize that the water created a short circuit around the wire because the wire was not insulated from the water.

Your team decides to modify the configuration so that the wire is electrically insulated from the water. Scouting around the supplies in the warehouse, the team notices thin, small diameter tubing called shrink tubing. The tubing slides over uninsulated wire. A heat gun is used to shrink the tubing until a snug fit is obtained.

You apply the shrink tubing and then start the test again. After four minutes the temperature of the water reaches 50°C.

After eight minutes the temperature is only 90°C. It takes 11 minutes to heat the water to boiling.

The team evaluates the data by plotting the temperature rise as a function of time (see Figure 3.3). Why does it take so long to heat the water to boiling?

One team member muses on the possibility of the insulation affecting the rate of heat dissipating from the wire. You suggest that the plastic tubing acts as electrical and thermal insulation. The team decides that only electrical insulation is necessary. How can the design be changed to obtain the correct amount of heat transfer?

⇐ Engineering analysis (cont.'d)

⇐ Testing

⇐ Evaluation of test results

⇐ Problem re-definition

⇐ Concept selection

⇐ Prototype fabrication

⇐ Testing

⇐ Evaluation of test results

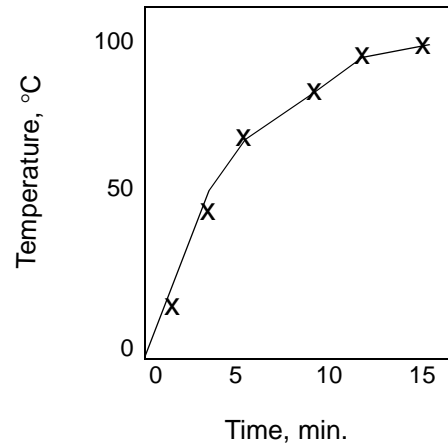


Figure 3.3. Plot of temperature vs. time.

One person proposes that thinner shrink tubing be found. Another team member suggests using a longer wire. How much longer should the wire be? Two team members suggest using at least four times as long, while another says it should be six times as long.

After much discussion, your team decides to try using more analysis to determine an appropriate length for the wire. You review the equations and realize that you need a heat transfer model to take the thermal insulating effect of the shrink tubing into account.

⇐ Generating alternative concepts

⇐ Engineering analysis

## Conclusion

What do you think will happen in the next iteration of the design loop? The heat transfer analysis could lead to a new prototype with a much longer length of wire. Testing could show the same temperature response. Additional information gathering could reveal that a thick rod of NiCr could better heat the water. Additional brainstorming could lead the design team at Sunbeam Inc. to a completely different design. Many possibilities exist, most requiring substantial planning, problem definition, engineering analysis and testing to justify advancing a particular design choice.

The preceding example demonstrates the iterative process that a typical engineering design solution can follow. In this course your design team will find that many solution pathways can exist. Practicing the steps in the design loop will help determine the optimal solution for your design problem.



# Reverse Engineering

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## INTRODUCTION

The study of engineered objects can lead to important insights about design and, specifically, the design process. Reverse engineering involves the methodic disassembly and re-assembly of a device, taking care to document, test, analyze and report on the study of its function<sup>1</sup>.

Whereas the mystery artifact challenge is a capsule introduction to reverse engineering of assigned artifacts, the reverse-engineering project is open-ended, requiring students to choose an engineered device and perform a broad and detailed study of the factors and constraints that dictated its final form. For teams working effectively and efficiently (with members respecting and understanding each others' talents), the reverse-engineering project can provide an interesting, valuable experience and a challenge to integrate and apply one's ever-growing skills. The process of reverse engineering a well-designed product can uncover a wealth of subtle innovations that can lead to a lasting respect and wonder about seemingly "simple" objects. Often, a superficial simplicity prevents us from appreciating elegant design features.

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## PROJECT LEARNING GOALS

The reverse engineering project learning objectives are quite broad. They are to:

- ◆ Document design
- ◆ Analyze design
- ◆ Learn about design by example
- ◆ Design and execute quantitative tests
- ◆ Discover design principles by understanding the design attributes producing its functions

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1. Stanford University [1] offers a mechanical dissection course based upon this concept.

- ♦ Analyze device users
- ♦ Create an advertisement or television commercial (being sensitive to the elements of a product marketed for a specific audience)
- ♦ Design for manufacturing
- ♦ Create packaging for customers
- ♦ Improve design, making enhancements
- ♦ Think green: can it be redesigned to be more environmentally friendly?
- ♦ Design universally: can it be redesigned to be accessible to all people?
- ♦ Reinforce lessons learned from course design experiences
- ♦ Apply tools, techniques and team methodologies developed during courses

Responding to the project challenges will provide a range of valuable experiences. The fact that the objects usually represent evolutionary designs means that an object in its present form is not only analyzed, but that the dynamics which cause design changes with time are also studied. Additionally, the need for testing and analyzing challenges teams to invent methods for study, within the constraints of time and available resources.

Reverse engineering brings to bear the skills of analysis and the design of investigative approaches. Methodological testing, documentation, data retrieval, spread sheet use, graphical representation and creative design are equally important. This is accomplished in a framework of sensitivity to manufacturing and marketing factors.

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## **CHOOSING PROJECT DEVICES**

The fact that the choice of the object to be reverse engineered is open-ended encourages responses to a natural curiosity about an artifact. If this project immediately follows a “forward” engineering project, team members should be sensitive to design issues (problems, challenges and solutions). In this exercise, teams ask and answer their own questions.

Typically, the project starts with a simple question: How does this work? This leads to an ensemble of other questions and challenges to which responses are needed. These questions include:

- ♦ How will the team perform the investigation?
- ♦ What constraints have to be dealt with in analyzing the artifact?
- ♦ What plan will best unravel the artifact's function and design features?
- ♦ What types of plots or graphical displays will best communicate discoveries about the object's function?
- ♦ How was it manufactured?
- ♦ What is the consumer population?
- ♦ Are design improvements possible?
- ♦ What kind of an ad or commercial will be suited for the object?

If the team feels comfortable with the challenge of responding to these questions, then the object is probably suitable for reverse engineering. The following sections provide some examples of past reverse-engineered devices and also make specific suggestions about potential objects.

Another approach to choosing an object is to first define the reverse-engineering goals and methodology. Some teams decide that they want to exercise a particular approach and then choose a suitable object. For example, teams may consider any of the following:

- ◆ Non-destructive dissection
- ◆ Destructive dissection
- ◆ Destructive dissection and creation of a metamorph<sup>2</sup>
- ◆ Analysis and testing

Examples of devices involving non-destructive dissection include an expensive tennis racquet or a pitot (pronounced pea-toe) tube. In the case of the tennis racquet, the critical components are exposed, and the challenge is to develop a reliable testing methodology. Similarly, the details of a pitot tube are easily documented without dissection, but there is a need to analyze and test.

There is a wealth of surrounding opportunity to discover devices. It is important to find an object that is intriguing to help ensure that reverse-engineering experiences are fun and rewarding. Many places are overflowing with great objects to reverse engineer and provide inspiration. These include:

- |                       |                      |
|-----------------------|----------------------|
| ◆ Dorm rooms          | ◆ Electronic stores  |
| ◆ Automobiles         | ◆ Second-hand stores |
| ◆ Universities        | ◆ Garage sales       |
| ◆ Army surplus stores | ◆ Toy stores         |
| ◆ Hardware stores     |                      |

A continuous stream of new, innovative toys appear on store shelves, many of which are very sophisticated. Often, these toys provide feedback loops and decision-making sub-components that are quite interesting to study.

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## EXAMPLES OF REVERSE-ENGINEERED DEVICES

Examples of reverse-engineering projects include a great variety of devices, of which some were quite complex (e.g., a portable CD player). Others, however, at first seemed quite simple (e.g., a fly swatter), yet turned out to be very interesting. The listing below indicates the range of objects that can be studied and disciplines that can be represented.

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2. A metamorph is a melding of the essences of two distinct objects to create an object with new or enhanced functions [2]. For example, destructive dissection of a “weed whacker” and a lawn mower could lead to a combined system that would trim difficult edges evenly while the lawn was being cut, eliminating the need for a two-stage process.

- ♦ Frisbee
- ♦ Aluminum can
- ♦ Wind-up toy robot
- ♦ Disposable camera
- ♦ Stapler
- ♦ Climbing rope
- ♦ Coffee maker
- ♦ Thermos
- ♦ Harmonica
- ♦ Golf ball dimples (comparative study)
- ♦ Speed reducing geared motor
- ♦ Etch-a-Sketch toy
- ♦ Light bulb
- ♦ Carabiners (comparative study)
- ♦ Hovercraft
- ♦ Lock and key
- ♦ Ski binding
- ♦ Water gun
- ♦ Lighter
- ♦ Match
- ♦ Bicycle light system
- ♦ Audio speakers
- ♦ Shop vac
- ♦ Electric and battery-powered pencil sharpeners
- ♦ Running shoes (Nike vs. Reebok comparative study)
- ♦ Shock absorber
- ♦ Bouncing balls (comparative study)
- ♦ Velcro vs. zipper (comparative study)
- ♦ Alarm clock

An interesting exercise is to sit in a familiar room and look around analytically. How many objects are interesting, but have puzzling functionality? This is an opportunity to reverse engineer an object and satisfy one's curiosity at the same time.

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## **PROJECT EXERCISE PROCESS**

Usually, five two-hour lab periods are available for the reverse-engineering project. Past teams have produced excellent reverse-engineering projects working within this block of time.

During one class meeting, student teams propose the object that they wish to reverse engineer. Discussions involving the instructor, TAs and teams address issues concerning the proposed device (e.g., safety, practicality, timeliness, resources required, etc.). Usually the proposed reverse-engineering project is accepted, and only occasionally is an alternate proposal requested.

Once the project goal is defined, teams usually purchase the device; however, donations of objects frequently occur (especially when non-destructive dissection is involved). Next, teams submit a one-page reverse-engineering plan and begin analysis.

At the completion of the exercise, teams make a presentation of their results, show their video commercial or ad, and submit their report. Teams are encouraged—and many elect—to construct a poster to summarize their work.

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## **PREVIOUS PROJECTS**

A book by H. Petroski [3], *Invention by Design*, reviews several simple objects from a reverse engineering perspective. The design history of the simple paper clip emphasizes that when engi-

neers study an object, they tend to see the imperfections and also potential design improvements and solutions to problems. There have been several hundred patents issued for bent wire paper clips during the past century. The author challenges readers to reverse engineer a Gem paper clip, design an improved clip, and objectively measure the gripping forces.

A second object studied by Petroski is the pencil. He points out that often it is the analysis of design failures or limitations that leads to improved products. Such a failure analysis study based upon reverse engineering of a spectrum of manufactured pencils led to significant design improvements.

The zipper is another object reviewed. Its design history is developed, including the discovery of Velcro by the Swiss inventor George de Mestral and the development of resealable plastic bags. This book also covers aluminum cans, the 777 aircraft and a variety of structures.

The National Transportation Safety Board has teams available to be dispatched at a moment's notice to the scene of a transportation accident. These teams apply a reverse engineering approach to work backwards from the evidence at a crash site to determine the cause. Numerous design weaknesses uncovered in this way have helped make transportation systems safer. Similarly, forensic atmospheric science is used to analyze the aftermath of destructive severe weather events (e.g., hurricanes and tornadoes) to estimate the magnitude and structure of the wind fields causing damage. These analyses have led to improved building codes to help mitigate future damage.

The following examples of methods and findings from previous student projects may serve to guide team design approaches.

### Aluminum Can

Procedure	Results/Conclusions
Measured dimensions, weight, flow rates (wide mouth, narrow mouth), force (required to open) and load (to deform and to explode). The deformation force defines the critical axial buckling load.	<ul style="list-style-type: none"> <li>◆ Requires 550 to 600 pounds to deform.</li> <li>◆ Requires 725 to 790 pounds to explode.</li> <li>◆ Wide mouth takes 8.3 seconds to empty.</li> <li>◆ Narrow mouth takes 13.6 seconds to empty.</li> <li>◆ Ease of recycling is a big advantage.</li> <li>◆ 617 cans can be stacked high without damaging the bottom can. This is important for storage and shipping.</li> </ul>



## The Match

Procedure	Results/Conclusions
Studied history. Measured the burn time of matches of different lengths as a function of angle, the critical angle to hold a match in the wind (a fan was used) and the striking force and match angle (an air track was used).	<ul style="list-style-type: none"> <li>◆ Held horizontally, a short match burned about 1.7 inches in 30 seconds.</li> <li>◆ Held at 45°, a short match burned about 1.4 inches in 12 seconds.</li> <li>◆ In wind, it is best to point a match straight down.</li> <li>◆ The best striking angle was between 35 - 40° from the surface.</li> </ul>

## Fly Swatter

Procedure	Results/Conclusions
Conducted comparative tests of a variety of fly swatters. Measured the pressures on an impact surface from a “swat” (used a sensitive pressure gage connected to a hole in a flat plate).	<ul style="list-style-type: none"> <li>◆ The larger swatters and the ones with a few smaller or no holes produce the largest air pressure changes and will actually warn a fly before swatting.</li> <li>◆ It is better to use a smaller swatter with a porous surface.</li> </ul>

## Horner Harmonica

Procedure	Results/Conclusions
Studied history. Measured frequencies of blowholes in which a spectrum analyzer was used. Measured the minimum pressure required to produce a clear note (used a simple U-tube water manometer).	<ul style="list-style-type: none"> <li>◆ Frequency is inversely proportional to the length of the metal strips.</li> <li>◆ The low- and high-frequency notes require the most pressure.</li> <li>◆ The range of pressures required is from 1 to 2.5 inches of water.</li> </ul>

## The Toaster

Procedure	Results/Conclusions
Dissected object and measured dimensions. Measured temperature and time at each setting. Measured electrical resistance.	<ul style="list-style-type: none"> <li>◆ The time for toasting ranges with settings from 20 to 34 seconds, if the toaster is cooled between tests.</li> <li>◆ The time for toasting ranges with settings from 4.7 to 11.7 seconds, if the toaster is <i>not</i> cooled between tests. Hence, for a quick response, let the toaster go through a heat cycle before initially toasting.</li> <li>◆ The toast compartments taper in width from top to bottom. The team theorized that this permits smaller, thicker items to be toasted without falling to the bottom of the toaster.</li> </ul>

An additional reverse-engineering project, a comparative study of the “sweet spots” of tennis racquets, comes to mind because of the elegant simplicity of the test method. Video film was taken of tennis balls (marked with chalk) dropped from a fixed height. The heights of the ball bounces after impact on the tennis racquets were measured as a function of the impact position. A three-dimensional plot of the data vividly displayed the forms of the very complex sweet spots of the tennis racquets.

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## **STUDENT PROJECT PRODUCTS**

The products for the reverse-engineering project include a number of required elements. Although many of these products should be contained in the final report, team notebooks should contain sufficient detail and background to answer questions that may arise. Include the following elements or answers to questions:

- ◆ Documentation of background, including:
  - Areas of use and a characterization of typical users.
  - Where did it come from?
  - Was there an evolution with time? Were there distinct transitions of form or use?
- ◆ Description of the typical function.
- ◆ Summary of any documentation provided.
- ◆ A definition of goals and methodology.
- ◆ Documentation of the test methodology created.
- ◆ Documentation of systematic analysis, including:
  - A list of major components.
  - Definition of the dissection sequence (if required).
  - Description of interactions between components.
  - Summary of working guesses concerning functions.
  - Summary of equations or physical processes that determine the function.
- ◆ Documentation of procedures.
- ◆ Summary of results and recommendations.
- ◆ Identification of a market and marketing approach.
- ◆ Creation of an advertisement or a User’s Manual.

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## **PRESENTATION AND REPORT**

Teams turn in a final report at the time of the presentation. The suggested following outline covers the key topic areas. The report should contain a combination of drawings and photos covering key functions.

### **Reverse Engineering Project Report**

1. *Background:* Describe what need the device fulfills. Give a brief history of the design. Include any accompanying literature as an appendix.
2. *Project Goals:* List the goals for performing the reverse-engineering study; i.e., what will be learned from the study?
3. *Test and Analysis Procedures:* Describe the procedures used to address the above goals. How was the device and its components evaluated? Document test data obtained.
4. *Dissection Details:* Describe (using drawings, photos and/or video where appropriate) the key components and how they function.
5. *Results:* Describe what was learned about this device's design and functionality. Provide suggestions for changes that would improve its function or make it more cost effective to produce. Provide suggestions for any changes that would make it "greener" or more universally available.
6. *Marketing:* Include either an advertisement (in print) or a video or radio commercial, marketing this artifact to an identified target group of potential customers.

### **Ad or Commercial**

Typically, examples of past student advertisements or commercials are shown to introduce a reverse-engineering exercise. Although most teams produce television commercials, others create radio ads or flyers. The key to the creation of a successful ad—regardless of its medium—is to have a good understanding of the product, as well as the intended market. With this knowledge, marketing efforts can appeal to the desires of consumers, emphasizing the strengths of the product. The ability to communicate effectively with marketing experts in a company can be critical to the success or failure of a product and is an important skill for engineers to nurture. In the ad presentation, include a clear definition of the target customer population and an assessment of the desired product characteristics.

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### **REFERENCES**

1. Sheppard, S.D., *Mechanical Dissection: An Experience in How Things Work*, Proceedings, Engineering Education Curriculum Innovation and Integration, January 6-10, 1992, Santa Barbara, CA.
2. Sheppard, S.D., *Personnel Communication*, 1993.
3. Petroski, H., *Invention by Design: How Engineers Get from Thought to Thing*, Harvard University Press, 242 pp, 1996.

## INTRODUCTION

On January 28, 1986, seven astronauts were killed when the space shuttle Challenger exploded. Millions of people will never forget the awful sight of the NASA shuttle disappearing in a plume of white smoke, which was played over and over again on national television. The investigation following the disaster traced the cause of the explosion to the failure of the O-rings in the shuttle's solid rocket booster, which had been designed by the Morton-Thiokol Company. The O-rings were not seated properly, which allowed the combustion gases to leak out, burn through an external fuel tank and cause the explosion.

The night before the launch, Roger Boisjoly and another engineer working for Morton-Thiokol participated in a teleconference with managers from Morton-Thiokol and NASA. Temperatures at launch time were forecast to be close to 20°F, unusually cold for the Florida launch site. The teleconference was set up to discuss the engineers' long-standing concerns about the solid rocket booster design, specifically whether the O-rings would seat properly at such cold temperatures. The NASA managers challenged the engineers' arguments, ultimately leading the managers at Morton-Thiokol to override their engineers' recommendation. That night, temperatures at the launch site dropped to 8°F, raising additional safety concerns beyond those about the O-ring performance. Nevertheless, NASA waived low-temperature restrictions and proceeded with the launch. The shuttle exploded just over 70 seconds into the flight.

Roger Boisjoly first expressed his concern about the O-ring seal in the solid rocket boosters a year before the Challenger launch. He was vigilant in his efforts to avert the risk the problem potentially posed. His actions during the year leading up to the launch are widely recognized as exemplifying the highest standards of engineering ethics. Despite his best efforts, however, NASA managers were persuaded by political and economic pressures to go ahead and launch the Challenger on January 28, 1986 [1].

The space shuttle Challenger was a complex technological system. Technical considerations—as well as political and economic interests—shaped its design. In fact, engineers usually practice

their technical skills on projects that are heavily influenced by complicated and competing interests of the public, government and private sector employers or clients. Decisions that appear correct from a technical perspective are often challenged or rejected for other reasons. And, competing interests often create ethical dilemmas for engineers.

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## **PROFESSIONAL ETHICS**

Why raise the issue of ethics in an introductory engineering design course? The answer lies in the professional status of engineering. Engineering shares several defining characteristics with other professions such as nursing, law and accounting [2]. As with the other professions, engineering:

- ◆ requires extensive, specialized training
- ◆ provides knowledge and skills that are vital to society
- ◆ has a monopoly on practice of these skills (e.g., only licensed engineers are allowed to design highway bridges)
- ◆ has autonomy in practice (i.e., technical judgments in engineering are reviewed by other engineers, but not by medical doctors)
- ◆ is regulated by ethical standards above and beyond laws and personal morals

The last characteristic listed follows from the previous four. Special ethical standards are required of professions because society relies on the special skills and training of their members; because society grants them a monopoly on the practice of those skills; and because society grants

Harris et al. [3] define professional ethics as:

"Special morally permissible standards of conduct that, ideally, every member of a profession wants every other member to follow, even if that means having to do the same" and which apply "to members of a group simply because they are members of that group."

them autonomy to police themselves with respect to the technical aspects of their practice.

Members of the engineering profession want all other engineers to behave ethically, because their behavior reflects on the profession as a whole. Conversely, by accepting professional status, individual engineers agree to behave ethically, recognizing that their behavior has implications for all other engineers.

The purpose of introducing professional ethical standards in this course is to help students recognize ethical conflicts when they arise, and provide the opportunity to practice making judgments about such conflicts. Moreover, as illustrated by some of the cases presented below, professional ethics relate to situations that routinely arise in college, as well as in engineering practice.

So, what are these professional ethical standards? Professional engineering societies, including the American Institute of Chemical Engineers (AIChE), the American Society of Mechanical Engineers (ASME), the American Society of Civil Engineers (ASCE), and the Institute of Electrical and Electronics Engineers (IEEE), have codes of ethics that articulate their members' consensus on what the ethical standards should be. Although these codes change from time to time and differ somewhat from one society to another, the basic principles do not change. The Code of Ethics of the Accreditation Board for Engineering and Technology (ABET) includes these basic tenants that are common to all of the codes [2]:

## Principles

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

1. Using their knowledge and skill for the enhancement of human welfare;
2. Being honest and impartial, and serving with fidelity the public, their employers and clients;
3. Striving to increase the competence and prestige of the engineering profession.

## Canons

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

The ABET Code of Ethics [2] highlights *integrity* and *competence* as essential characteristics of ethical behavior. It emphasizes that *service* (to the public, employers and clients) *is the primary role of the engineering profession*, identifying the safety, health and welfare of the public as a paramount concern. These critical aspects of engineering ethics are explored further in the following sections.

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## RESPONSIBILITY FOR SAFETY, HEALTH AND WELFARE OF THE PUBLIC

In the Challenger disaster, the safety of the astronauts came into conflict with other pressures faced by NASA and the aerospace companies involved in the design, production and operation of the space shuttle fleet. Such is often the case with safety concerns in engineering design. It is often prohibitively expensive—if not impossible—to eliminate the possibility of injury from even simple devices, let alone from complex systems such as the space shuttle. Hazards are often difficult to anticipate, in part because it is hard to predict how and under what conditions a device will be used. Nevertheless, engineers have an ethical responsibility to protect the public from injury or harm that could be caused by the artifacts they design and produce. Engineers and the firms that employ them also bear legal liability, subject to both civil and criminal penalties, for injury due to negligent or incompetent designs, construction or production.

**Case A: The Hyatt Regency Walkway**

On July 17, 1981, two suspended walkways at the Hyatt Regency Hotel in Kansas City, Missouri, collapsed, killing 114 people and injuring more than 200 others. The victims were in the hotel atrium and on the walkways suspended above it. The connections tying in the hanger rods that held up the walkways were unable to support the load; consequently they failed, sending the walkways crashing onto the crowded atrium floor.

To simplify the process of constructing the walkways, the fabricator of the atrium structure installed hanger rods and connections that were different than those specified by the structural engineering designers. The design engineer approved the change during his review of the shop drawings, despite the fact that the new connections could have been predicted to fail under the load applied at the time of failure. After an investigation, the principal engineers involved in the case were found guilty of gross negligence and misconduct, and lost their licenses to practice engineering in Missouri.

The Hyatt Regency walkway case [4] illustrates the legal and professional responsibility that engineers bear for ensuring the safety of their designs. This responsibility includes ensuring that design specifications are followed during construction. From a legal perspective, the status of engineers as skilled professionals subjects them to a high standard of responsibility for their actions.

**Case B: Good Intentions (A Hypothetical Case)**

A group of four senior engineering students designed and built a water slide, with an innovative water circulation system, for a local elementary school. The students designed the slide to support three 70-lb children, which they thought was a reasonable load. However, the slide collapsed when ten unsupervised children crowded on at once; several children suffered broken bones. What ethical responsibility do the engineering students bear for the accident? Could they be held legally liable for it? Does it matter that the children who were injured were misusing the slide?

Regardless of their best intentions, legal liability is something that engineers must consider. Like physicians, private engineering firms often must carry liability insurance. The insurance premiums typically cost a few percent of a firm's annual income. Liability for injuries or damage is usually tried in civil cases under Tort law, which deals with injuries that one person or entity causes another. The standard applied under Tort law is that the injury was caused by the defendant, either through error or neglect. That is, the defendant's act or omission was the "proximate cause" of the injury.

With respect to legal liability, Case B actually represents a special situation. In fact, the students would probably have some protection from legal liability through a contractual agreement between the university and the school, or possibly through "sovereign immunity" if the university were a public institution [5]. Sovereign immunity is a legal principle that applies in some states to limit the liability of the government and its agents (i.e., the students in this case) for acts of negligence. Neither sover-

eign immunity nor contractual agreements can shield engineers from ethical responsibility, however. And, if the situation involved engineers in private practice, rather than engineering students, they might well face legal liability.

### **Case C: TWA Flight 800**

At 8:30 p.m. eastern time on July 17, 1996, TWA Flight 800 crashed into the Atlantic Ocean soon after taking off from John F. Kennedy International Airport. Early investigations considered the possibility that the plane, a Boeing 747-100, was accidentally shot down by the US Navy or blown up by an onboard explosive. However, recent National Transportation Safety Board investigations indicate that faulty fuel sensor wiring is likely to blame. On this particular flight, the center fuel tank was nearly empty. Prior to takeoff, heat from nearby air conditioning units vaporized the remaining fuel, which then mixed with the air in the center tank, resulting in a flammable mixture. Examination of wires leading to the fuel probe show that the insulation had degraded, and thus the wires may have provided an ignition source. This plane was one of the first few hundred that Boeing built, and was approximately 25 years old. Examination of the probe wiring was not part of normal maintenance, because no one ever thought that it would be necessary over the projected lifetime of the plane.

Since the TWA Flight 800 crash, greater attention is being paid to wiring inspections as part of routine aircraft maintenance. To date, no legal liability has been found in this case, nor have investigators accused Boeing's engineers of behaving unethically. Nevertheless, the case points out that an ethical regard for safety must go beyond the design stage of a product's life cycle, carrying through to its operation and maintenance.

A number of things can go wrong with a design, and possibly lead to injury. An operator can overload a device, as in the water slide case. The performance of parts can degrade over time, as in the case of Flight 800. Parts may not be made to specification in the first place, as in the Hyatt case. How can an engineer protect public safety in light of all these uncertainties? As discussed in this textbook's chapter on the Design Process, engineering designs typically incorporate a *safety factor*. The design is created not only to meet requirements, but also to exceed them by factors of safety. For example, if a beam, perhaps the joist beneath your kitchen floor, is reasonably expected to be subjected to a distributed load of 600 lbs, a safety factor of 5 means that the beam can actually withstand 3000 lbs before failure.

The appropriate size of a safety factor depends on the application. An elevator cable might be designed with a safety factor of 11 [6]. In contrast, a part for an unmanned rocket casing might have a safety factor of 2 if it is not to be tested before use, and a safety factor of only 1.25 if the part will be tested first [7]. Economics and the level of acceptable risk play a role in determining the size of the safety factor. In the case of the elevator cable, the size and weight of the cable will add to the cost of the elevator, but it will not be a major factor. The cable must be expected to last a long time, and its



wear characteristics must be taken into account. Moreover, the loss of lives of elevator passengers represents a huge potential cost of a failure. Combined, these aspects make a large safety factor worthwhile. On the other hand, in rocket design, a part with a larger factor of safety will be bigger and heavier, requiring that the entire rocket be scaled up. Costs rise rapidly with spacecraft size, and if the rocket becomes too heavy, its entire mission will fail. Thus small safety factors are required. Think carefully about a design. What factor of safety is appropriate?

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## **RESPONSIBILITY TO EMPLOYERS AND CLIENTS**

The ABET Code of Ethics recognizes responsibilities that engineers bear to their employers and clients, as well as to the public. Professional engineers have an ethical responsibility to provide competent services (including seeking assistance or declining projects that are beyond their capabilities), act in the interests of the employer or client, and maintain confidentiality concerning business matters or proprietary technical information. The Code also cites a responsibility for engineers to avoid situations in which they represent the competing interests of multiple parties. For example, an engineer representing a city in overseeing a construction project faces a clear conflict of interest if s/he is simultaneously receiving compensation from a contractor that is bidding on the project.

The ethical responsibility to serve an employer or client as a “faithful agent or trustee” does not imply that engineers should be blindly loyal. One of the toughest dilemmas that engineers may face is a conflict between their personal or professional principles and practices or activities that are undertaken by an employer or client. Such dilemmas arise in many gray areas of public safety and environmental protection; for example, in cases in which practices that comply with existing laws still pose risk.

### **Case D: A Revealing Audit (A Hypothetical Case)**

A manufacturing company hires a consulting engineer to perform an environmental audit on one of its plants, in order to identify waste minimization opportunities for reducing the use of toxic chemicals and thus lowering waste disposal costs. In the process, the engineer discovers a low-volume toxic waste stream of which the company leadership was unaware, and thus had not reported to the state environmental protection agency. The engineer notes in her report to the company that this waste stream should be reported to the state agency. However, a company manager tells her that because their waste minimization plans will soon eliminate that particular stream, they do not plan to report it. What should the engineer do?

**Case E: Side Saddle Fuel Tanks**

In the early 1980s, engineers working for General Motors were concerned about the location of the fuel tanks in its 1973-1987 Chevrolet and GMC pickup trucks. The fuel tanks were positioned outboard of the truck frame, and thus potentially exposed in the case of collisions from the side. The GM trucks met the existing government standards for side-impact collisions, which were tested at impact speeds of 20 mph. There was no legal requirement that the truck be designed to protect its occupants from side-impact collisions at higher speeds, in which company tests reportedly showed that the fuel tanks could indeed rupture [8]. Nor was the company legally required to share its in-house test results with the government.

What is the engineer's ethical responsibility in these two cases? Professional codes of ethics cite a responsibility for engineers to act as "faithful agents" towards employers or clients, meaning in part that they will not reveal privileged information without the employer's or client's consent. However, the duty to maintain confidentiality is overruled if reporting the information is required by law, or necessary to protect the health, safety or welfare of the public. Moreover, in situations like the GM truck case, significant debate comes in determining how much risk is acceptable. The trucks at issue actually had comparable or better overall safety records than their competitors, but higher risk of fatalities due to fire.

The tension between ethical responsibilities to employers and to the public also suggests that engineers should exhaust internal avenues for addressing their concerns before reporting them to external authorities or to the public. In fact, GM's safety engineers worked internally to change the fuel tank placement. The truck design was changed with the 1988 model year, relocating the fuel tanks inside the truck frame.

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**INTEGRITY AND INTELLECTUAL PROPERTY**

Several of the canons of the ABET Code of Ethics cite honesty and integrity as ethical responsibilities of engineers. These issues in the professional codes align closely with the issue of academic integrity. The University of Colorado's policy on academic integrity [9] states that:

"A university's intellectual reputation depends on maintaining the highest standards of intellectual honesty. Commitment to those standards is a responsibility of every student and every faculty member at the University of Colorado. Breaches of academic honesty include cheating, plagiarism, and the unauthorized possession of exams, papers, or other class materials that have not been formally released by the instructor."

Likewise, professional ethics requires that engineers respect the intellectual property of others, and represent only their own work or accomplishments as their own.

**Case F: Intellectual Property (Adapted from National Society of Professional Engineers Case No. 83-3 [10])**

Andrew, an engineer who owns his own computer support company, submits a proprietary proposal for a local area network (LAN) installation to a small business owner. An innovative preliminary design and cost information for the LAN are included in the proposal. In an effort to solicit competition, the business owner provides copies of Andrew's proposal to another prospective bidder. Katie, an engineer working for the second company, identifies some potential cost savings and revamps Andrew's design. She incorporates her version of the design in the bid that her company submits for the job. Are the small business owner's actions acceptable? Is Katie's use of Andrew's ideas ethical?

**Case G: Intellectual Contributions**

Logan is extremely annoyed because Taylor has not shown up for their group's last three design project meetings, and wants to tell the instructor about Taylor's absences. However, the two other group members, Blair and Lisa, know that Taylor is struggling with other courses and think that they should give him a break. Taylor feels that he can rely on the other group members to collectively achieve a good grade on the design project, and wants to devote more time to passing calculus and physics.

What should the group members do? Does CU's policy on academic integrity have any bearing on their dilemma? Are there parallels between this situation and Katie and Andrew's case?

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**RESPECT: DIVERSITY AND SEXUAL HARASSMENT POLICIES**

As mentioned above, the University of Colorado community views academic integrity as a responsibility of all of its students and faculty. Another ethical responsibility highlighted by the CU community is respect for diversity. The campus diversity committee adopted the following definition in 1994 [11]:

"The University of Colorado is a community in which diversity is a fundamental value. People are different and the differences among them are what we call diversity. Diversity is a natural and enriching hallmark of life. It includes, but is not limited to, ethnicity, race, gender, age, class, sexual orientation, religion and physical abilities. A climate of healthy diversity is one in which people value individual and group differences, respect the perspectives of others, and communicate openly."

Lack of respect for others can be demonstrated in many ways. Sexual harassment is one manifestation of this problem that has been particularly widespread in business and academic situations. State and federal laws prohibit sexual harassment. To ensure that violations do not occur on campus, CU uses the following definition [12]:

“Unwelcome sexual advances, requests for sexual favors, and other verbal, non-verbal or physical conduct of a sexual nature constitute sexual harassment when:

1. submission to such conduct is made either explicitly or implicitly a term or condition of an individual's employment, living conditions and/or academic evaluation;
2. submission to or rejection of such conduct by an individual is used as the basis for employment or academic decisions affecting such individual; and/or
3. such conduct has the purpose or effect of unreasonably interfering with an individual's work or academic performance or of creating an intimidating, hostile or offensive working or educational environment.”

CU policy also states that:

“Romantic/sexual relationships between faculty members (including instructors and teaching assistants) and students or between supervisors and supervisees are inappropriate when the faculty member or supervisor has direct professional responsibility for the student or the supervisee. Such situations greatly increase the chances that the faculty member or supervisor will abuse her or his power and sexually exploit the student or employee.

Moreover, others may be adversely affected by such unprofessional behavior because it places the faculty member or supervisor in a position to favor or advance one student's or employee's interest at the expense of others...”

CU's policy prohibits romantic or sexual relationships between instructors and students who they are in a position to evaluate, unless the relationship is disclosed to the instructor's supervisor and arrangements are made to eliminate potential conflicts of interest or impropriety.

#### **Case H: The Relationship (A Hypothetical Case)**

An upper-class student in electrical engineering, Chris is a second-time TA for an introductory engineering projects course. The TAs' responsibilities in the course include assisting the students with their design projects and providing input to the instructor on how the groups and individual group members are performing. During the projects course labs, Chris has especially enjoyed interacting with J.P., one of the first-year students, also an electrical engineering major. J.P. frequently goes to Chris' office hours for help with physics homework and to shoot the breeze. The relationship develops, and toward the end of the semester, J.P. and Chris start seeing each other socially. Word gets back through the grapevine to the instructor of the course. What should the instructor do?

## **ENVIRONMENTAL ETHICS**

The first canon of the ABET Code of Ethics [2] states that “Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.” What does

this imply about protection of the environment, beyond human health concerns? The “safety, health and welfare of the public” is intimately linked to the well being of the environment. However, the responsibility of engineers for broader environmental concerns such as animal rights, bio-diversity, sustainability and wilderness preservation remains controversial.

In this case, many engineers’ personal ethics may differ from those that are generally accepted by their profession. Engineers with a strong commitment to environmental protection express that commitment through lifestyle choices, volunteer activities and through their decisions about what career opportunities to pursue. Moreover, engineers from many different disciplines and in many different positions encounter and pursue on-the-job chances to conserve resources or reduce environmental impacts. The concept of “green design” encompasses many such opportunities.

**Case I: The Environmentally Conscientious Group Member**

Kelly’s group is designing an interactive model of the hydrologic cycle for a middle school classroom. He insists that the group construct the exhibit out of recycled materials and has spent several hours on the phone trying to identify a supplier of recycled plastic. The other members of Kelly’s group know he is sincere in his belief that they can encourage middle school kids to recycle by modeling the use of recycled materials in their project. However, the recycled plastic that Kelly found is twice as expensive as the alternative and is less attractive. Moreover, if they purchase the recycled plastic, the group will have to purchase a smaller pump than they deem optimal, in order to stay within budget.

What should the other members of Kelly’s group do? Does the ABET Code of Ethics provide any guidance in this situation? Is this an ethical dilemma or just a disagreement? Thinking beyond this case, in what other situations might personal, cultural or religious principles come into conflict with an engineer’s responsibilities?

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**CONCLUSION**

The professional status of engineering depends on the ethical behavior of its members. Codes of ethics for engineers require integrity, competence, and fair service in the interests of clients and employers, and commitment to protecting public health, safety and welfare. A practicing engineer inevitably encounters situations in which professional ethics are at issue. In some cases, simply knowing the ethical standards of the profession makes it obvious what action to take. In other cases, though, conflicts arise between personal and professional principles or between competing professional standards, and coming to the “right” ethical decision requires careful deliberation. Examining historical or hypothetical engineering ethics cases, and discussing the academic ethics cases encountered as a student, will help in preparation for the ethical dilemmas that will be faced in engineering careers.

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## REFERENCES

1. For more information on the Roger Boisjoly and the Challenger, see the Massachusetts Institute of Technology's ethics web site at <http://www.cwru.edu/afil/wwwethics/boisjoly>.
2. Harris, C.E. Jr., Pritchard, M.S., Rabins, M.J. (1995) *Engineering Ethics: Concepts and Cases*, Wadsworth Publishing Co., Belmont.
3. Harris, C.E. Jr., Davis, M., Pritchard, M.S., Rabins, M.J. (1996) Engineering Ethics: What? Why? How? and When?, *Journal of Engineering Education*, 85: 93-96.
4. For more information on the Hyatt Regency walkway collapse, see Texas A&M's ethics website at <http://ethics.tamu.edu/ethics/hyatt>.
5. Bintliff, B., Associate Professor, University of Colorado School of Law, Private Communication, July 1998.
6. Shigley, J.E., *Mechanical Engineering Design*, 3<sup>rd</sup> edition, p. 574. McGraw-Hill, 1963.
7. Krapfl, Z. Lockheed-Martin engineer. Private communication, June 1998.
8. Barry Meier, "Courtroom Drama Pits G.M. Against a Former Engineer" *New York Times*, January 19, 1993.
9. University of Colorado's policy on academic integrity, University of Colorado Catalog, Boulder, CO, 1997-8, p. 37.
10. National Society of Professional Engineers, Case No. 83-3, <http://www.cwru.edu/afil/wwwethics>, accessed June 1998.
11. University of Colorado's diversity committee definition, 1994, <http://www.colorado.edu/cu-diversity>, accessed July 1998.
12. The complete text of CU's sexual harassment policy is available at <http://www.colorado.edu/sacs/sexual-harassment/>.



# Teamwork and Working in Teams

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## INTRODUCTION

As industrial processes and systems have become more complex, teams—not individuals—have become the basic working unit in modern engineering organizations. Because team environments foster interaction and open communication, and create a desirable setting for generating new ideas, the ability to function effectively as a member of an interdisciplinary team has become essential. The broad range of disciplines required to move an innovative idea through product development and testing, and ultimately to the marketplace, requires that engineers, material scientists, financial analysts, artists and others collaborate to create safe products that meet the needs of consumers.

In the early 1980s, American industry became acutely aware of the need to better compete in the global marketplace. The shocking slippage of market share by American automobile makers focused national attention on the need to improve product quality and organizational performance. Beyond Ford and General Motors, global competition gave incentive to companies such as 3M, Motorola and Hewlett Packard to focus on improved performance through teamwork. General Motors capitalized on team design and productivity to create the Saturn Division in the mid-1980s. Motorola uses product development teams distributed throughout the world to reduce time-to-market of new products, moving the work around the globe to a different team every eight hours. Christopher Galvin, Chief Executive and Chairman of Motorola, Inc., states that there is no longer a place in Motorola for an engineer that cannot work in a team [1]. The broad acceptance of teams as an effective approach to improve performance has fundamentally changed the work environment for engineers; today's engineers must master teamwork and communication skills as never before.

Working groups and teams are *not* the same thing. Individuals working on separate parts of a project, with little collaboration between members of the group until the pieces are pulled together near or at the end, characterize working groups. Teams are a different entity; they are collaborative units of people joined together to accomplish a common goal. The output of the whole team should exceed that of the sum of the output of individual members.



"The strength of the wolf is in the pack."

- Rudyard Kipling

Teams have been variously defined; however, most definitions share common themes. Scholtes [2] defines a team simply as a group of people pooling their skills, talents and knowledge. Katzenbach and Smith [3] add the elements of commitment and mutual accountability, defining a team as a small group of people so committed to something larger than themselves that they will not be denied. For this course, a team is defined as a group of people collectively driving towards a common goal, capitalizing on and respecting the skills and knowledge of *all* individuals.

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## **CHARACTERISTICS OF EFFECTIVE TEAMS**

Effective teams are rewarding and share many common characteristics. Respect for other team members is essential for team effectiveness. Valuing the strengths of teammates, while minimizing their weaknesses, promotes team cohesion. Cooperating as a team requires trust, focusing on—and believing in—the end goal, arguing less and exploring more.

At a minimum, there are five keys to a productive team: positive interdependence, individual accountability, promotive interaction, appropriate use of social skills and group processing [4].

*Positive interdependence* is achieved when members of the team rely on each other to complete the project. They understand that their individual success is inherently linked with that of their other team members *and* with the success of the team as a whole. Group members focus on two objectives to achieve positive interdependence: maximizing their own productivity and working to maximize the productivity of all other group members.

*Individual accountability* means that each team member is held responsible for his or her contribution to the completion of the project. Team members do not "slack off" and allow other team members to assume their responsibilities.

*Promotive (face-to-face) interaction* implies that group members recognize the contribution of others in the team and give positive feedback for their accomplishments. They *encourage* and *facilitate* each other to achieve team goals, recognizing the tremendous motivational power of positive feedback.

*Appropriate use of social skills* is necessary because interpersonal and small group skills are critical to team success. Group communication skills contribute to building positive relationships between team members and promote higher achievement and productivity.

Through *group processing* techniques, team members *reflect* on how well their team is functioning and how well members are using their social skills to help *all* members of the team achieve collaborative success. The entire team is committed to team success and recognizes that effective teamwork does not just "happen"; it is the result of investment, commitment and continuous maintenance of the team.

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## **TEAM DEVELOPMENT STAGES**

Teams mature experientially and in stages; designating a group of individuals to function as a team is only the first step in team development. The development of a group of people into a team

takes time, commitment and energy. To become effective, teams must establish common goals, and their individual focus must be on those goals, ahead of personal needs. The goal of teamwork is that, with time, a highly successful team will emerge that exhibits synergy between the individual members of the team. Two models of the phases of team development follow.

## **1. The Tuckman Model**

Tuckman [5] describes four stages through which groups traverse as they mature into well-functioning teams. Not every team gets to the “performing” stage, resulting in a myriad of outcomes. The Tuckman model defines the four identifiable stages of team development as: *forming*, *storming*, *norming* and *performing*.

### ***Forming***

In this stage, members of the group are polite to each other. During this period team members assess each other and how they fit into the group; they test the limits of tolerance of their group members. Little tangible work is accomplished as people get to know each other. Productive work that can be accomplished during this time is to agree on group goals and to establish ground rules for how the team will work together. The group “being on its best behavior” characterizes the forming stage.

### ***Storming***

In the storming stage, members begin to let down their guard and argue with each other. However, if the conflict is not channeled in a productive fashion, the team is at great risk of disillusionment. Cliques that thrive on unhealthy conflict may now form within the team. In this storming phase, the group should develop strategies for encouraging constructive controversy and respecting differences of opinion. It is critical that the inevitable conflict that arises as groups begin to struggle with their differences be channeled in such a way to foster creativity and allow for the evaluation of a wide range of views. While not fun to work through conflict at the time, a group is well served by openly dealing with their differences and discussing their strategy for productive conflict resolution. Tuckman believes that groups that never learn to work through the storming phase—perhaps because they are conflict adverse and choose instead to allow one leader to set the direction for the team’s actions—are, in the end, less creative. Additionally, the team members can be divisive because they never learned to deal with their differences.

### ***Norming***

In this stage, group members accept and appreciate the differences of individuals, learn to productively work through conflict and focus on the task at hand. The risk of “group think” may be encountered if individuals “go along” with ideas to maintain harmony rather than introduce differences of opinion.

### ***Performing***

In the performing stage, group members have come to trust each other; they all reap the rewards as the group transforms into a productive, fun—and rewarding—team. During this stage, team members agree on goals; creative brainstorming is fostered; ideas, rather than personal agendas, are debated; and the team takes collective pride in their team accomplishments. Creative confrontation and innovative problem solving [6] characterize this stage.

## **2. The Cog Model**

The Cog Ladder of Group Development [7] delineates the stages through which a working group passes as it matures into a well-functioning team. Cog's model recognizes that team development is a *process*; it takes time and energy to develop a group of people into a productive team. Individuals should expect the team development process to take time to unfold. Teammates should prepare themselves for a few difficulties as the roles of individuals within the team and the personality of the team develop. The five stages of the Cog Team Development Ladder follow.

### ***Polite Stage***

This stage is characterized by politeness as people get to know each other and establish their individual identities within the group. Group members go out of their way to avoid conflict during this early phase.

### ***Why are We Here? Stage***

In this stage, members of the group ponder the purpose of the group and their own contribution to it. Members may also ask the question “Why am I here?”

### ***Bid for Power Stage***

In this stage, the traditional roles of individuals within the group emerge. The roles that have been historically comfortable for people such as leader, writer, technical expert(s), task master, morale director, mediator, creative thinker, time keeper, etc., begin to define how the team will develop. As the roles of individuals emerge, and because the team has evolved past the polite stage, power struggles between individuals may begin to surface. Also, as team members begin to have expectations of each other, they may begin to subtly *expect* teammates to perform their preferred or “natural” role.

### ***Constructive Stage***

In this stage, individuals move past performing the role that is most comfortable to them to performing the role that best complements the other members of the team. This stage is characterized by enhanced harmony as team members envision and implement strategies that promote the purpose of the team.

### ***Esprit Stage***

In this “all for one and one for all” stage, reached by few teams, members within the team experience a high interdependence; the team shares in the esteem of group goals and accomplishments. In this stage, team members clearly identify with the team; they are proud of being a team member and demonstrate genuine caring for the welfare and success of their teammates.

- ◆ What stage of development is your group or team in now?
- ◆ Do all of your teammates perceive your team to be in the same stage of development?
- ◆ What can you do to promote the movement of your team to the next higher stage of development?

Learning to be an effective team member takes time and practice; it is a *learned* skill that is mastered over time by team members committed to the end goal of achieving an effective and productive team. A key to building a well-functioning team is the process of *reflection*, whereby team members actively think about and discuss among themselves the progress of their team through the stages of team development. Open and candid communication among team members regarding the contribution of individuals to the overall success of the team may be uncomfortable in the beginning. Repeated brief discussions among the team will make the process of analyzing team performance more comfortable and natural. Through *practicing* teaming skills and *reflecting* upon ones own and others' performance as team members, student teams learn teaming skills [8].

---

## **TEAM ROLES**

Differentiation of roles within a team leads to better team organization and productivity. As team size increases, the need to differentiate between the roles of individuals increases. With time, the roles that team members naturally prefer tend to emerge. However, early in the team development process, team productivity may be promoted through the assigning and rotating of team roles. The characteristic behavior of a team member, i.e., their role, in the context of the team, defines the way other team members expect them to contribute to and advance the objectives and goals of the team. All team members are responsible for behaving in such a way as to further the objectives of the team. All are responsible for completion of a quality product, inclusion of all team members in the process, capitalizing on the strengths of all individuals and promoting an environment where all team members acquire new skills and knowledge. Each team should define the roles that will best promote their team productivity. Example roles include a team leader, a recorder/scribe, a facilitator and a liaison. Each role type is described below.

Weekly rotation of team roles allows all members to learn new skills and to appreciate the challenges inherent in each role. Some roles will be more comfortable than others. Reflection by the

team members on their experiences in the various roles strengthens team understanding and communication.

### **Team Leader**

A team leader exerts the greatest influence on the team and is responsible for the overall project scheduling and deliverables. Effective leaders must change as the needs of the team evolve. Additionally, leaders understand that their role involves both task roles (managing tasks) and responsibilities associated with nurturing the emotional or people component of the team (leading people).

It is beneficial for a team to designate a different “leader” for each meeting and rotate the leadership on a weekly basis. Team leader responsibilities include, but are not limited to:

- ◆ Preparing of the meeting agenda, to be published and distributed at least a day in advance.
- ◆ Sending a reminder of the meeting time and place to all team members.
- ◆ Ensuring that the meeting remains focused on the agenda.
- ◆ Encouraging participation by all team members.
- ◆ Establishing an environment that fosters creativity where team members are respected, take risks and feel safe expressing their ideas.
- ◆ Furthering the overall goals and objectives of the team.

### **Recorder / Scribe**

A recorder/scribe captures the team’s discussions in writing and documents decisions made and action items assigned. S/he communicates team decisions consistently and in a timely fashion. A team should designate a “recorder” for each meeting, and his/her responsibilities include electronically publishing and distributing the conclusions reached and action items assigned within 24 hours of the meeting.

### **Facilitator**

A facilitator is responsible for ensuring that all team members’ opinions are expressed and evaluated. Also, the facilitator keeps time during team meetings and assumes the lead responsibility for furthering team cohesion and camaraderie. As with the team leader and recorder/scribe roles, the team designates a “facilitator” for each meeting. In addition to the above duties, the facilitator is responsible for moving the meeting along according to the established schedule.

### **Liaison**

A liaison communicates with organizations outside of the team. S/he takes a lead role in establishing contact, following up on commitments, obtaining information, etc.

## TEAM CONTRACT

Establishing a team contract at the beginning of the project, and reviewing it at least monthly, promotes commitment to the goals of the team. Prior to committing to a contract, the team should discuss *and document* the following for each team member and the team as a whole:

1. In what role(s) is each person most comfortable?
2. What role is the greatest “stretch” for each?
3. The greatest trepidation each has about the development team is:
4. The 6-8 most important characteristics of working effectively as a team are:
5. List 6-8 reasons why teams frequently fail:

See the appendix at the end of this chapter for a general format to create a team contract.

## TEAM MEETINGS

Effective communication and strong leadership are at the heart of well-functioning teams. While each member of a team must fulfill his/her individual responsibilities and obligations to the objectives of the team, open and constructive communication between all members of the team is essential. Weekly meetings within the design teams and meetings between the team and the instructor promote common understanding of team objectives and progress.

Weekly team meetings provide an opportunity for team members to share their progress, challenges and concerns about the project. They also provide an opportunity for redirecting project tasks and reassigning work if necessary. In addition to the issue of task reassignments, team meetings create a scheduled format for creative brainstorming and problem solving.

“Productivity through people.”  
- Singapore Management Philosophy

Team effectiveness is dependent upon many things, including a shared vision of the team’s goals and objectives, and a sense of belonging. Team meetings serve to keep all members engaged, thus avoiding unintentional alienation of any person.

While team meetings are essential for team effectiveness, meetings that lack focus, that drag on and are unproductive can be a source of frustration.

### Elements for Effective Team Meetings

Effective team meetings do not just “happen”; they require leadership and an agenda that has been agreed upon and published in advance. Suggestions for effective meetings include:

- ◆ Designate team roles (leader, recorder/scribe, facilitator and liaison), rotating roles at each meeting to give all team members an opportunity to practice their teaming skills.
- ◆ Solicit meeting agenda items in advance and prepare a specific agenda for each meeting. Include time estimates for each agenda item.
- ◆ Choose a meeting place with few distractions and a consistent meeting time that is convenient for all team members.

- ◆ Agree on meeting rules of conduct (see below).
- ◆ Rotate providing refreshments for team meetings; eating together promotes camaraderie.
- ◆ Develop a specific list of action items from each meeting with commitment from the team member who will be responsible for completion of each task. Tasks might include exploring all patents related to the product, calling potential vendors to locate a component, etc. Publish a task list with a completion date for each action item in the meeting minutes.
- ◆ Commit to commitment. Remember, “a meeting is a process that begins when you decide to have one, and it doesn’t end until all the action items are completed” [9].

### **Rules of Conduct for Team Meetings**

In order for team meetings to further the objectives of the team, they must be productive. Attendance at team meetings should be mandatory. On the rare occasions when one must miss a regularly scheduled team meeting, that person should notify all team members *in advance*, apprising others of their progress and pending action items.

Agreeing *in advance* on acceptable rules of conduct for team meetings promotes meeting that maintain focus, promote respect and order during team meetings, and establish processes for resolving conflict. Suggestions include, but are not limited to:

- ◆ Mandatory attendance at scheduled team meetings.
- ◆ Stick to the agenda. When the items on the agenda are dealt with, other non-agenda items may be added if time allows and the team agrees to discuss additional topics.
- ◆ Remain focused on the task at hand.
- ◆ Begin and end the meeting on time.
- ◆ Come prepared.
- ◆ Use an analytic, facts-based approach to problem solving whenever possible [4].
- ◆ Manage meeting time wisely.
- ◆ Brainstorm when fresh ideas are in short supply or complex problems present challenges.
- ◆ Allow for the expression of every person’s ideas, and give all ideas a serious hearing.
- ◆ Listen carefully to each other, and be courteous.
- ◆ Accommodate disagreements and criticisms without hostility.
- ◆ Refrain from all personal attacks.
- ◆ Demonstrate flexibility.
- ◆ Make meetings enjoyable; employ humor and respect.
- ◆ Resolve conflict through compromise and consensus whenever possible.

### **Team Meeting Agenda**

Establishing a meeting agenda creates an atmosphere for team meetings that are orderly, focused and productive. Agendas should include:

1. Date, time and place for the meeting.
2. Designated meeting leader, facilitator and recorder.
3. Designated person(s) to bring refreshments.
4. Brief overview and agreement on the meeting agenda, with a statement of the primary objective of the meeting.
5. Short (5 minutes maximum) individual updates on progress made since last meeting, including a synopsis of any major obstacles encountered.
6. Group assessment of overall team progress, with a review of the project schedule.
7. Brief discussion/reflection of how the team is functioning as a unit.
8. Assignment of action items to be accomplished by the next meeting, with a responsible person assigned and a completion date established.
9. Meeting adjournment.

### **Team Meeting Complaints**

Not all team meetings are effective. Inevitably, there are complaints about the productivity of team meetings. For example, the purpose of the meeting may seem unclear or team members may come to the meeting unprepared. Another frustration occurs when the meeting focus veers off track. If the meeting has deteriorated, participants may end up not discussing the issues at hand; they may dominate the conversation, start arguments or fail to actively engage in the discussion. This type of disruption can be extremely frustrating and obviously lead to a number of complaints from other team members. Lastly, complaints also arise when there is no follow-up to decisions made during prior meetings. It is the responsibility of *all* team members to respectfully keep meetings on track and focused. Every team member is responsible for the outcome of the meeting.

### **Instructor Meetings**

Periodic meetings between all members of the team and the instructor contribute to a common understanding of the successes and challenges experienced by the project team. A key objective of the instructor is to help the team succeed. This is best accomplished if open communication and a spirit of collaboration is established and maintained throughout the project between all members of the team and the instructor and teaching assistants. A sample agenda for instructor meetings may include:

1. Date, time and place for meeting.
2. Review of progress since and action items from last meeting.
3. Discussion of major challenges faced.
4. Tasks to be completed by the next meeting and assignment of specific action items with deadlines.
5. Brief reflection by all on team performance.



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## **CONFLICT RESOLUTION**

The diversity of knowledge, skills and experience brought by people from different disciplines to the team is a source of strength and also one of challenge as individuals struggle to communicate with people outside of their own discipline. The needs and strongly held personal beliefs of individuals within a team often result in nonproductive conflict. Regardless of how well most team members work together, one person can sometimes slow group progress based on strongly-held personal principles. Controversy can be a positive contributor to the creative process; however, keeping controversy funneled so that it does not break down into interpersonal conflict is a challenge for teams. The team must judge when it is appropriate to let the controversy naturally dissipate, or if it is interfering with team cohesion and productivity, when it must be dealt with in a proactive manner.

One thing is clear, however, controversy that results in lowered team performance or diminished satisfaction of team members should be dealt with as soon as possible. It takes energy to cooperate with others. Conflict that arises within the team due to personality conflicts consumes energy that would be much better spent on achieving team goals.

Adapted from Johnson and Johnson [4], the following steps guide a team through a negotiating process to resolve a problem that arises from conflict between team members.

### **Step 1: Describe Your Interests and What You Want**

Tactfully describe your perception of the problem and what you want as a desired outcome. Define the conflict as small and specific, not general and global. Take ownership of your interests and make personal statements about your wants and goals as the first step in the negotiation process. Remember that because you want something does not mean that the other person is obliged to give it to you. You should be *negotiating for common interest*, not for what you *want*. Approaching the conflict as a *mutual problem* to be solved, not as a win-lose struggle, creates opportunity for a successful outcome. Suggestions that may aid the negotiation at this stage include:

- ◆ Set aside a specific time and place where the interested parties can sit down to meet.
- ◆ Do not monopolize the conversation; take turns speaking with two-minute time limits for each speaker.
- ◆ Avoid being aggressive or intentionally hurting the other person.
- ◆ *Do* be assertive about your interests, goals and needs.
- ◆ Take ownership for your interests by using personal statements such as “I,” “me” or “my.”
- ◆ Define your views in as short and specific a manner as possible.
- ◆ Acknowledge the legitimate goals of the other person as part of the challenge to be addressed.
- ◆ Focus on a long-term cooperative relationship with statements such as, “I think it’s in the best interests of the team for us to talk about our argument.”
- ◆ Listen to the *wants* and *needs* of the other person.
  - Strive to understand the other person’s interests and feelings.

- Be a good listener; face the other person and be quiet while they take their turn.
- Show that you understand by paraphrasing what s/he said. This may feel strange at first. Try this approach: “You said...; I say...” For example: “You said that I’m always late for team meetings; I admit that I’ve been unreliable the last two weeks.”
- ◆ Describe your perspective of the other person’s actions towards you.
  - Focus on their behavior, not on them as a person.
  - Describe *behaviors* you have observed (e.g., rolling of eyes, interrupting when you’re trying to speak, not attending scheduled work sessions, etc.) without applying value judgments as to her/his motives.
  - Avoid personalized attacks.
  - Define the conflict as a specific set of actions, not the person’s general state of being.
  - Describe your personal reaction and feelings about the others’ actions.

### Step 2: Describe Your Feelings

Feelings must be openly expressed in order to be resolved. If feelings are not dealt with in an open manner, “stuffed” emotions may later resurface as the root of additional conflict. Acknowledging that every person’s feelings are valid is essential for furthering the negotiation. To effectively negotiate, you must take responsibility for your feelings and constructively express them. Do not assume that the other person knows what you are feeling—tell them!

### Step 3: Exchange Underlying Reasons for Your Opinions and Positions Relative to the Problem at Hand

By this stage, you should each have an understanding of the others’ interests, wants and feelings, as well as a clear mutual understanding of the specific, confined conflict. It is now appropriate to better understand the *underlying reasons* each of you have for your position.

- ◆ Set the stage for this step by *expressing your cooperative intentions* through statements such as “If we work together on this, we get through it easier” or “Let’s try to find a solution that works for all of us on the team.”
  - Be genuine; look for a win-win strategy.
  - Avoid subtly suggesting that one of you is right and the other is wrong.
- ◆ Present your reasons and listen to the reasons of the other person. Give the underlying *reason(s)* for what you want and work to understand her/his reasons. Only through this empathetic understanding can you search for creative, win-win solutions.
- ◆ Focus on the broad *interest* you and your team are trying to serve, not the *position* you have taken on a specific issue.
  - Approach the other person from the perspective of his/her *underlying* wants and goals.
  - Work to create new positions that let all parties reach some of their goals.
  - *Clarify the differences* between each of your wants and needs before trying to find mutually satisfying solutions.

- ◆ Empower the other person by being flexible and providing a choice of options. Feeling powerless leads to anger and frustration that can readily be avoided through alternative solutions. Allow yourself the flexibility to change your opinion as the negotiation proceeds.
- ◆ Timing can be everything; ensure that both parties are *currently* motivated to find a solution.

#### **Step 4: Understand the Other's Perspective**

This is a challenging part of the negotiation process. Do not assume that all parties to the conflict see the problem(s) from the same perspective. Both parties must work to see all sides of the issue, viewing the conflict from the other person's perspective while simultaneously keeping one's own perspective in mind. Clarifying the intentions of your teammate may help you realize that his/her intentions are not the same as your fears. Be sure that you understand both perspectives, and openly discuss opposing perceptions. Frequently confirm your understanding by restating what you think you have heard others say.

#### **Step 5: Invent Options for Mutual Gain**

Use each other's perspective to promote the generation of new, creative solutions. Generating multiple solutions is not easy! Be creative; think of as many potential solutions as possible. An approach to make this easier is to search for mutual gain, keep all perspectives in mind, and avoid judging the options until later. Generate at least three workable alternative agreements before selecting the one solution that you will jointly employ. Write down all suggested alternative solutions to ensure that potentially workable ideas are not lost.

While brainstorming alternative solutions, one can ease tension through incorporating the goals and values of your teammate(s) in *your* proposals. Evaluate and discuss each other's propositions before making a decision, remembering *to clarify differences* and *seek similarities*.

#### **Step 6: Reach a Wise Agreement**

A wise agreement is one that meets the needs and wants of both parties, promotes the long-term relationship of the parties and is perceived as fair by all. To test whether the solution is wise and should be adopted, evaluate if it can be judged against objective criteria such as:

- ◆ Does everyone have an equal chance of benefiting?
- ◆ Does the agreement meet the legitimate needs of everyone in the team (or those directly impacted by the conflict)?
- ◆ Do all parties to the conflict have a stake in the outcome?
- ◆ Are the gains and losses of all parties roughly in balance?
- ◆ Are team values honored?

Lastly, ensure that the agreement is fully implemented by defining measurable objectives and setting specific milestones. This can be readily accomplished by working together to answer the question: "How will we know if we have succeeded in implementing our solution?" A key to success

is to define *in writing* intermediate objectives that will lead to the successful outcome. Examples might include:

- ◆ All team members attend each Tuesday design session, beginning August 31.
- ◆ Individual ideas for conceptual design of the rotating arm will be presented at the September 7 team meeting.
- ◆ Janet and Larry will meet briefly every Wednesday morning for the next four weeks to review progress regarding their working relationship.
- ◆ Project concerns will be openly discussed at every weekly team meeting.

Peter Senge [10] discusses the power of “team learning” to mitigate controversy associated with differences of opinion. Senge’s concept of team learning requires mastering the practices of both *dialogue* and *discussion*. Dialogue is akin to brainstorming; it involves the free and creative exploration of issues without the interjection of judgmental views. During discussion, one’s views are debated and defended as the team together searches for sound arguments to support pending team decisions. During the discussion, controversy will inevitably emerge.

Creating an environment where respectful and constructive controversy is healthy and stimulates the expression of different points of view is exactly the goal of a well-functioning team! The key to success in constructive controversy is understanding how to respectfully and productively *manage* the controversy to promote both creativity and productivity.

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## REFERENCES

1. Galvin, Christopher, Chief Executive and Chairman, Motorola, Inc., 1996. Presentation at the ASEE International Conference on Engineering Education. Washington, DC, June 1996.
2. Scholtes, Peter, 1988. *The Team Handbook: How to Use Teams to Improve Quality*. Madison, WI, Joiner Associates, pp. 2-7.
3. Katzenbach, J., and Smith, D., 1993. *The Wisdom of Teams: Creating the High-Performance Organization*. Cambridge, MA. Harvard Business School Press, p.45.
4. Johnson, David D. and Frank P. Johnson, 1997. *Joining Together: Group Theory and Group Skills*. Boston, MA. Allyn and Bacon.
5. Tuckman, B., 1965. Developmental Sequence in Small Groups, *Psychological Bulletin*, 63, pp. 384-389.
6. Hanwit, Jesse. Four Stages of Teambuilding. <http://www.ttacev.org/articles/team.html>.
7. Cog’s Ladder of Group Development. <http://www.teleport.com/~oro/ndindex/Cogs.html>.
8. Lewis, Philip, Aldridge, Dayne and Swamidall, Paul M., 1998. Assessing Teaming Skills Acquisition on Undergraduate Project Teams, *Journal of Engineering Education*, 87, pp. 149-155.
9. Lippincott, Sharon M., 1994. *Meetings Do’s, Don’ts and Donuts: The Complete Handbook for Successful Meetings*. Lighthouse Point Press, Pittsburgh, PA, ISBN 0963796631.
10. Senge, Peter M., 1994. *The Fifth Discipline: The Art and Practice of the Learning Organization*. Currency/Doubleday.



**APPENDIX: TEAM CONTRACT**

We, the undersigned members of Team \_\_\_\_\_, have fully discussed and reached consensus on the following items:

- 1. Methods of Communication: List all the methods of communication that will be used by our team, including individual's commitments to those methods.
  
- 2. Team Meetings: List the time, location and goals of regularly scheduled team meetings.

Does each team member **commit** to contribute to all team meetings? (circle and initial)

_____	yes	no	_____	yes	no
_____	yes	no	_____	yes	no
_____	yes	no	_____	yes	no

What action is required *in advance* if a team member must miss a meeting?

How will the non-attending team member's contribution be captured in advance of the meeting?

- 3. Conflict Resolution: The conflict resolution process(es) our team will employ include (describe ways to reach consensus on items of disagreement):

I fully commit to the items above and understand that contributing to the effectiveness of my team is required in this class.

Signed: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Date: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_



# Design Process

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## INTRODUCTION

One definition of engineering is “design under constraint.” For private enterprise to be successful, a product line must be competitive in many ways. Products must be attractive, functional, efficient, durable, reliable, affordable and most importantly, they must satisfy the needs of the customer. Also, products must reach the marketplace quickly. A structured design process helps the design engineer achieve these goals.

One view of the design process is shown in Figure 7.1. Most products begin “in the clouds,” as an expression of a specific need, but with no clear vision of how to fill that need. Eventually, a shiny new product will emerge. In between, however, the design engineer will generate many alternative concepts and will decide among those concepts. Sometimes, one concept will conflict with the project constraints, shown in Figure 7.1 as the hard boundaries that cannot be crossed. Constraints can range from the laws of physics to economic or even political constraints. Another feature of the design process is that it is *iterative*—it may be necessary to back up and start over. Also, successful products usually evolve over time. Today’s automobile, for example, is the result of many years’ evolution, with improvements being added continuously.

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## DESIGN PROCESS TOOLS

There are many tools and concepts that are useful in the design process. A few of the more useful tools are design journals and the design concepts of K.I.S.S., conservation of ambiguity, E.T.C. and rapid prototyping.

### Design Journals

Good documentation is essential. Keeping a design journal is a good idea practiced by most successful designers. In addition to serving as a useful reference, a written design journal can provide critical evidence of when an idea was conceived, which may be important in getting a patent.



Some suggestions for keeping a journal include:

- ◆ Use a bound notebook, as opposed to loose leaf.
- ◆ Do not be timid—write in ink!
- ◆ Carry the journal everywhere (good ideas pop up at all times).
- ◆ Paste in business cards, computer printouts, short articles, etc.
- ◆ Date all journal entries.
- ◆ Have two witnesses sign and date the page of a critical new idea.
- ◆ Write in the journal daily.

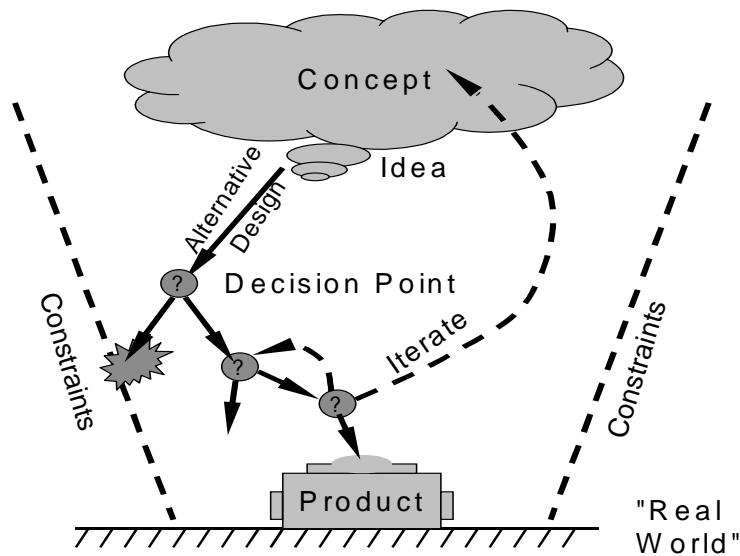


Figure 7.1. Schematic of the design process.

### **Some Design Concepts**

The following are basic concepts that can apply to any design project.

#### ***K.I.S.S.***

This stands for “keep it simple, stupid!” In general, the simplest design is usually the best; it tends to be the easiest to make, requires the fewest parts and is the most reliable. Even in a complex system, the simpler the individual components are, the better.

#### ***Conservation of Ambiguity***

Coined by Stanford University’s Design Division in Mechanical Engineering, “conservation of ambiguity” means that in the early stages of design, the designer should keep as many options open as possible. At this stage, it is important to focus on “what,” as opposed to “how.” Do not become too committed to the first idea that comes up, but instead keep searching for better (i.e., cheaper, faster, easier, etc.) ways to solve the same problem.

**E.T.C.**

Another Stanford concept, E.T.C. stands for “experiment-test-cycle.” As shown in Figure 7.2, E.T.C. suggests the iterative nature of design. Once a designer has a concept that s/he thinks will work, an experiment is designed to test the concept, and this process keeps cycling until it works well.

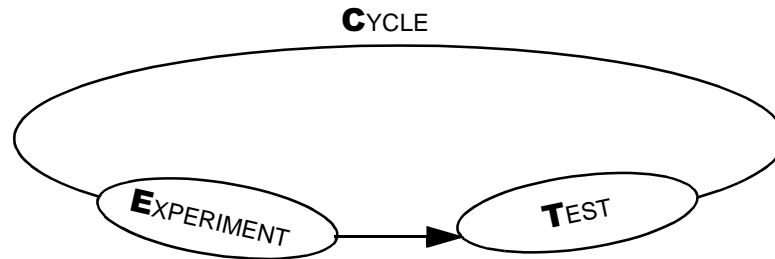


Figure 7.2. E.T.C. — The iterative nature of design.

**Rapid Prototyping**

It always works on paper! Only when new ideas are physically tried out does the designer get a real feel for the advantages—and disadvantages—of a new idea. Details on the use of modeling in the design process will be discussed in a later section.

**STEPS IN THE DESIGN PROCESS**

One framework for the design process is described below [1]:

1. Recognize the need.
2. Define the problem.
3. Plan and manage the project.
4. Gather information.
5. Generate alternative concepts to satisfy the design requirements.
6. Evaluate the alternatives.
7. Select the most promising concept.
8. Communicate the design.
9. Implement the design.

Although this listing is sequential, many of these phases should be done concurrently. “Concurrent engineering,” a process that conducts these phases in parallel—not in series, is widely practiced in industry today. This chapter provides more detailed information on the various steps in the design process, which may be useful on many open-ended design projects.

### **Step 1: Recognize the Need — The Customer**

Designers develop a product to sell at a profit, which implies that someone will like it enough to purchase it. Therefore, it is essential to determine in advance what the customer wants. One approach is to interview customers directly about their needs. For example, Storage Technology Corporation (STC) in Louisville, CO, produces high-capacity data storage systems. At the earliest stages of designing a new product line, STC flew in (at their expense) customer representatives from around the country and listened to their needs. An even better approach, though, would be to have a company go directly to the customer and listen to their needs, rather than have the customer come to them. Another method is to observe and video tape a customer actually using an existing product to explore potential improvements to that product.

But *who* is the customer? Clearly, the person buying a product is a customer. The outside client who sponsors a university design project is a customer. But usually, there are others who are customers as well: the factory worker who builds the product; the person who repairs the product if it fails; and perhaps even the store manager, who decides which products to purchase and stock. Ultimately, a successful product should satisfy the needs of as many customers as possible.

### **Step 2: Define the Problem**

There are two distinct phases to problem definition: articulating a *problem statement* and determining *design requirements*.

#### ***Problem Statement***

Expressing the design challenge in a succinct, carefully thought-out statement can help focus the issues. Suggestions for creating effective problem statements include:

- ◆ Generalize the statement to stimulate creative solutions (conservation of ambiguity).
- ◆ Do not include a preconceived solution to the problem.
- ◆ Express the problem in *functional* terms (i.e., a verb and a noun).

The intent is to focus on solving the correct problem. One of the most common mistakes that designers make is to create an elegant solution to the wrong problem. Following are some examples of problem statements:

#### **Acceptable**

Make a better can opener.  
Build a better mousetrap.  
Design a better lawnmower.



#### **Better**

Extract the contents from a can.  
Keep mice outside.  
Shorten grass, or keep grass short.

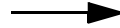
#### ***Design Requirements***

It is important to articulate the exact specifications for the product. If possible, have the customer review the specifications. Wherever possible, design requirements should be expressed in quantitative terms.

Following are some examples of design requirements:

**Acceptable**

Light weight  
Inexpensive  
Fast  
Compact



**Better**

Weigh less than 10 lbs  
Manufacturing cost less than \$50  
Accelerate from 0 to 60 mph in 6 secs  
Fit inside a 2-ft cube

Not all design requirements can be expressed quantitatively, but it is important to list them anyway. For example, *all* products should be safe to use. When designing a product for safety, try to envision all the possible ways it could be misused and then design a way to prevent that misuse. Do not assume that the user of your product will read the instruction manual or warning labels!

### Step 3: Plan and Manage the Project

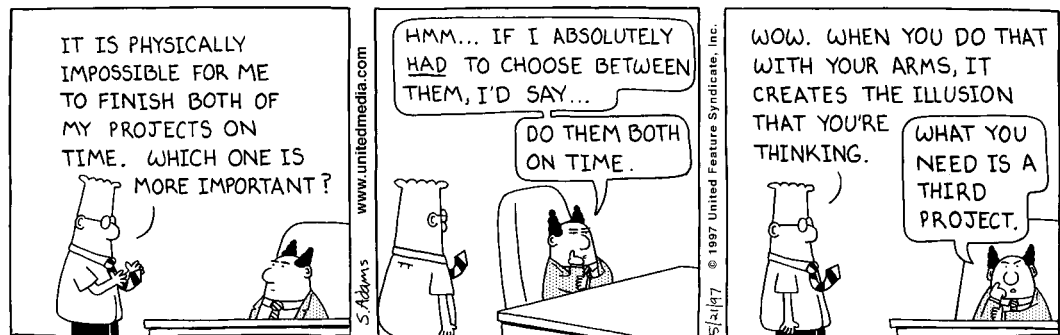


Figure 7.3. Keeping engineers busy with multiple projects. (DILBERT reprinted by permission of United Feature Syndicate, Inc.)

Most people perform better once they understand what they are doing. This means that you must *observe* and *manage* your actions. Even during the early stages of design, a little bit of planning and process management can work wonders. Continuous assessment of the design process allows the opportunity to improve the process both in terms of effectiveness and efficiency.

Although management of real-world engineering design can be a complex task, the application of a simple management approach can improve the design process immensely. The most basic sequence of project management activities is the *Plan - Assess - Adjust* sequence.

#### **Plan**

Design work planning involves thinking about the tasks to be accomplished, the resources that are available and the deadlines for products—or parts thereof—to be ready. Next, distribute the resources over the tasks and over time. The result is a “schedule,” which shows *who* will work on *what* issues *when* and *which* materials will be applied to *what* task.

The combined scheduling of tasks and people can be handled in various ways. When tasks are driven by predetermined deadlines, a backward approach is especially useful. For instance, if the

preliminary design review is on April 8th, plan on finalizing the design presentation a few days before that.

Note that a workplan generally evolves from a raw sketch with rather abstract tasks into a detailed plan in which each of the major tasks is subdivided into smaller tasks, requiring more detailed scheduling. Good plans take into consideration the dependencies between tasks. For instance, the drywalling of a house comes after the framing but before the painting. It would be ineffective to schedule the drywalling before the completion of the framing, but it would also be inefficient for the drywall to arrive before it is ready to be hung. It could sit outside becoming ruined by the weather (and the distributor would be paid earlier than necessary), or the additional cost of temporary storage might be realized. The latter is one of the reasons that in manufacturing the “just-in-time” concept is so popular.

Uncertainty also plays an important role. For example, if the completion date of a certain task is uncertain, then the start date of the next task becomes uncertain as well. To reduce the risk of wasting valuable resources, plan for alternative tasks (contingency plans) that other people can pursue in case the first task takes longer than expected.

### Use Scheduling Tools

A useful tool for specifying and tracking task scheduling is a Gantt<sup>1</sup> chart (Figure 7.4), a table in which each task is allocated in time. The chart indicates the progression of work over time and provides an easy way of seeing which activities are planned at any given time.

Task	January	February	March	April
Requirement Meetings with Customers	■ ■ ■ ■ ■	■ ■ ■ ■		
Initial Conceptual Design		■ ■ ■ ■ ■		
Initial Development Plan		■ ■ ■ ■	■ ■ ■ ■	
Final Conceptual Design			■ ■ ■ ■	
Initial Materials Design			■ ■ ■	■
Customer’s Approval of Conceptual Design				■ ■ ■ ■ ■

Figure 7.4. Gantt chart.

Like a Gantt chart, a PERT<sup>2</sup> chart (Figure 7.5) indicates the timing of activities, but it also contains their dependency relationships. In Figure 7.5, for instance, the “Testing Task” depends on completion of both the first and second programming task.

1. H.L. Gantt was an industrial engineer who pioneered this technique during World War I.  
 2. PERT stands for Program Evaluation and Review Technique.

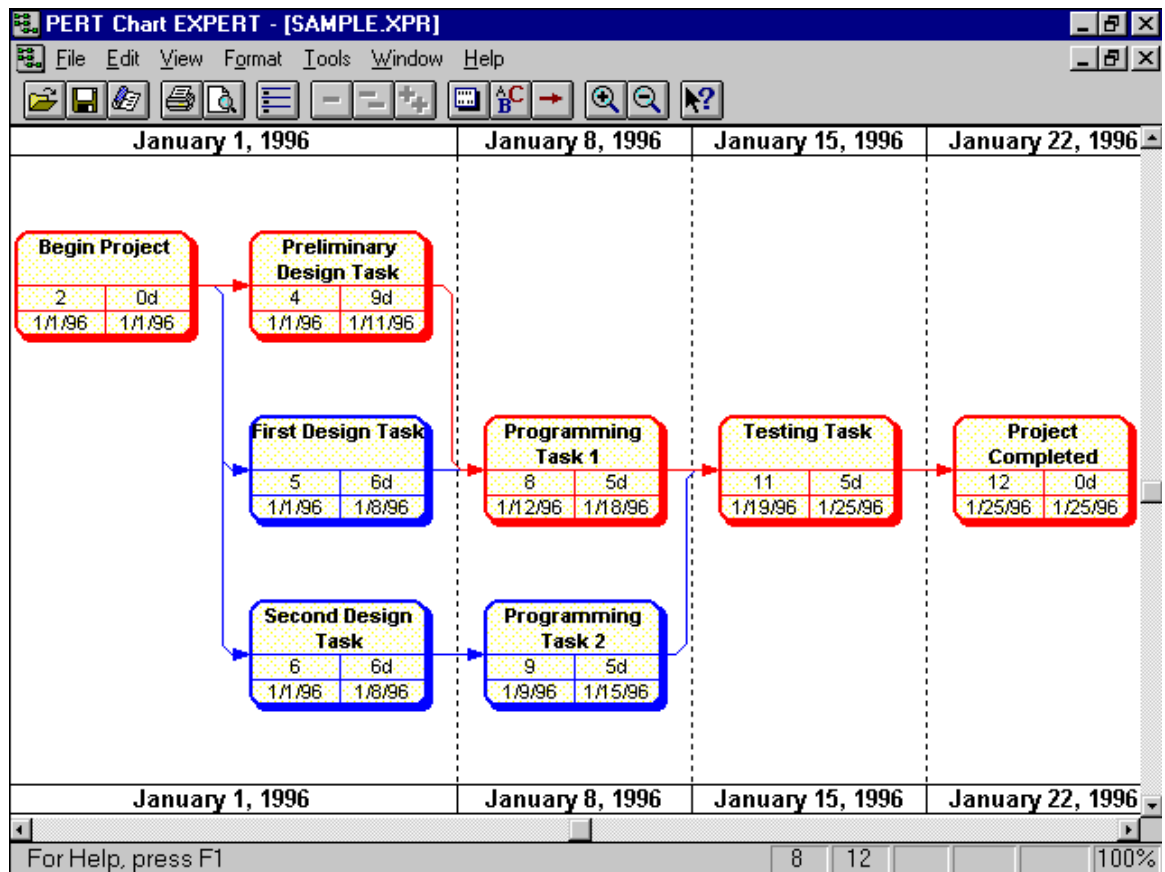


Figure 7.5. PERT chart.

Although these tools are often handy and easy to use, they are only as good as the estimates of how long a task will actually take. Experience reduces the uncertainty of the estimates, but even the most experienced task estimators often increase their estimates to allow for future unknowns.

When scheduling tasks, it is wise to document different types of information associated with each task:

- ◆ A short description of the task.
- ◆ The task's staffing.
- ◆ The task's planned start and completion dates.
- ◆ An overview of task dependencies.
- ◆ The task's estimated cost.
- ◆ An estimate of the consequences of missing a planned date.

A plan must be communicated to all members of the design team. This can be done through a team leader who presents and monitors the plan. Another method is to post the plan in an accessible location where team members can periodically verify their perception of the plan, annotate the plan or even indicate that certain tasks are finished.

### **Assess**

Plans are only plans, and schedules and deadlines seem to be made to be violated. Therefore, it is wise to periodically assess how the project is actually matching with the plan: scheduled start and completion dates are compared with actual start and completion dates, and estimated costs are compared with actual costs. When plan and process are no longer in sync with each other, the uncertainties for the rest of the process increase. To bring this uncertainty back within manageable limits, the plan must be modified.

Periodic assessment of how well the process is following the plan is critical to any type of engineering process. Not only does it provide an opportunity to review current practice and improve the process, but it is also the means to curtail any future damage and cost. Although no team leader likes to hear that a task is behind schedule, effective team leaders prefer learning such news a month—rather than a day—before the deadline. The key, naturally, is that the earlier the problem is noticed, the greater the likelihood it can be fixed or mitigated.

Periodic progress reports keep a team, and its customers, informed about the state of the project. At regular intervals, report on the state of the tasks and the overall state of the plan maintained in the Gantt or PERT charts. Attach to each task some new information:

- ◆ Actual vs. planned start and end dates for a task.
- ◆ A brief explanation for the difference between planned and actual dates.
- ◆ A brief summary of the incurred cost or gains as a consequence of missing or beating the planned dates.
- ◆ A set of brief statements about *who* needs *what* from *whom*. If a customer does not provide the required feedback on a design plan, clearly state so in the progress report.

### **Adjust the Plan**

Although assessment is useful in itself, its primary utility lies in the changes it brings about. Small deviations from the planned vs. actual start and end dates of a task, for instance, may not require a modification to the plan. However, when the discrepancy between plan and process becomes too large, the plan must be adjusted.

At this point, it should be clear that periodic assessment is vital for project management. Indeed, it is from the information collected during assessment that we learn not only *that* we have to modify the plan, but also *how* to modify the plan for the future. For instance, the average difference between previously estimated task durations and their actual duration contains information about our general capability to estimate a task's time requirements. Also, data about how resources are being used tell us whether we over- or under-utilize certain people in our group. This, in turn, should provide information as to how to staff future tasks in a more balanced way.

### **Manage as a Team**

"Leadership" and "management" are not the same thing. Good management implies good leadership, but it also needs structured and predictable processes, careful measurement and critical

analysis. Charging ahead with great enthusiasm can easily degrade into frustration and non-productivity when the current course of action is not periodically subjected to critical analysis. The late Karl Popper, famous theorist of science, maintained that the mistakes we make are our *only* source of learning [2] [3]. From this perspective, it is crucial that an engineering team remains open to critique and recognizes that in good management, there are roles and tasks for most styles and approaches to managing a process.

#### Step 4: Gather Information

The more information, the better. Complete and thorough information can prevent a product from being designed that already exists in the marketplace or that violates federal standards. One source of information is to purchase and test competing products. Referred to as *benchmarking*, this industry practice establishes market norms for the product. A new product must improve on those norms if it is to be successful.

A *patent search* is another source of useful information that can help prevent designing a product that infringes on someone else's legal protection. A full patent search can be expensive and time-consuming, but information is available on the Internet:

IBM Patent Information	<a href="http://www.patents.ibm.com">http://www.patents.ibm.com</a>
US Patent and Trademark Office	<a href="http://www.uspto.gov">http://www.uspto.gov</a>
Do It Yourself Patenting/Inventors FAQ	<a href="http://doityourself.com/finance/invent.htm">http://doityourself.com/finance/invent.htm</a>
Interviews with Inventors	<a href="http://www.thetech.org/revolutionaries">http://www.thetech.org/revolutionaries</a>
Inventor's Digest Magazine	<a href="http://www.inventorsdigest.com/">http://www.inventorsdigest.com/</a>

Extensive codes and standards established by federal, state or local governments, or even by industry itself, bind many products. Standards are useful because they allow for easy interchangeability of parts. For example, a ¼"-20 nut purchased at any hardware store in the country will fit a ¼"-20 bolt purchased elsewhere, thanks to precise industry standards for threaded fasteners.

#### Step 5: Generating Alternative Design Concepts — Invention

Invention can be the most creative and stimulating phase of the design process. It can also be the most frustrating! The challenge is to come up with as many alternative design concepts as possible from which to choose. For example, in designing a power sander, there must be a method of fastening the sandpaper to a sanding pad. Possible solutions to this problem include a clamp, glue, vacuum, magnets, snaps, a zipper or Velcro®. Some of these seven design concepts are well known, but others may be novel. Hopefully, the use of one of these concepts will be both new and feasible. The goal of this section is to present some useful techniques to stimulate the generation of creative ideas. Most of them are especially useful in a team situation and can be applied to overall design concepts or to focused components or subsystems.



### ***Brainstorming***

Although a commonly used term today, *brainstorming* was originally coined by Osborn in 1948 [4]. Brainstorming is an effective group problem-solving process, especially if a few simple rules are followed:

1. All ideas are written down.
2. Criticism is forbidden during the brainstorming session (critique comes later).
3. Combinations and improvements to ideas are sought.
4. The more ideas, the better.
5. Wild and crazy ideas are especially encouraged; they stimulate new, feasible solutions that may not have been considered otherwise.

As an example of the last point, a group of engineers at General Electric, including Osborn, were trying to come up with an easy way to connect a wire to a circuit in order to measure voltage. Existing methods at the time included screwing a wire to a post or soldering, both of which were time-consuming and too permanent. Someone suggested having a mouse bite two wires. This obviously "crazy" idea led to a very practical device in widespread use today, the alligator clip (Figure 7.6).



Figure 7.6. The alligator clip was the result of a "crazy" idea in a brainstorming session.

Choose a facilitator to moderate the brainstorming session. Pose the problem to the team (refer to the *Problem Statement* section), and have each team member think about the problem silently and write ideas on an index card. After a few minutes of individual thinking, the facilitator solicits an idea from each team member and writes it on a board or flip chart. Writing all ideas where everyone can see them is important because it can trigger new creative solutions or improvements to existing ideas. When the prepared solutions are exhausted, the facilitator solicits spontaneous ideas from the group in random order. A brainstorming session should be freewheeling and fun, lasting about 20-30 minutes.

### ***Inversion***

*Inversion* means turning something upside down or inside out. The basic idea of inversion is to imagine what would happen if the order in which various pieces of a system interact were changed. If Part A were fixed and Part B moves, what would happen if you fixed Part B and moved Part A? For example, in 1826, Oersted figured out that if a current is passed through a wire in a magnetic field, a lateral force is produced, the basic operating principle of an electric motor. In 1831, Faraday discovered an inversion to this concept: if a wire is forced through a magnetic field, it generates an electric current, which gives rise to a generator. And, in fact, an electric motor will generate electric current if it is forced to turn.

Another example is the contact lens cleaner case shown in Figure 7.7. In order to minimize irritation to the eyes after contact lenses are disinfected, a catalytic insert is placed in the cleaning solution at the bottom of the lens case. In an early design, the insert was wedged into the bottom of the case, which made it difficult to replace. A clever designer, perhaps stimulated by customer reaction to this design, came up with an inversion: fasten the catalytic insert to the lid instead of the case. Each time the contact lens wearer unscrews the lid to remove the lenses, the insert comes with it.

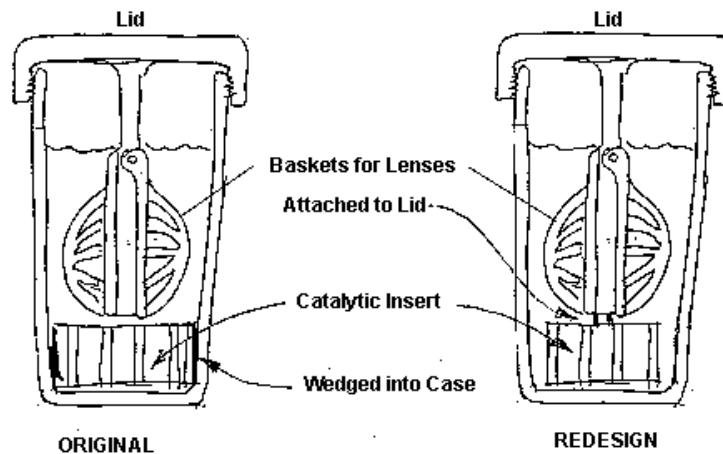


Figure 7.7. Two designs for a contact lens cleaning case.

### ***Analogy***

Many good design ideas are borrowed from other areas. Being aware of the surrounding world can stimulate creative solutions. For example, a toy store can be a rewarding source of new ideas. Examples of inventions and their source include:

**Inspiration**

Bat navigation  
Pistol grip  
Burrs  
Rattlesnake fangs  
Fireflies

**Invention**

Sonar  
Hand power tool handles  
Velcro  
Hypodermic needles  
Cold chemical light

***Empathy***

Imagine being an intimate part of the problem at hand. For example, if the challenge is to find a new way to clean CDs, imagine being about one inch tall standing on the CD. How could it be cleaned? A broom? A hose? These “crazy” ideas may lead to a cleaning brush or nozzle that is in fact very feasible, even though shrinking people is not! Or, if the problem is to design a new urban transportation system, imagine a giant straddling the entire city. How would that giant move people and goods across town?

***Explain the Problem***

People often get so entrenched in a problem they are attempting to solve that it is difficult to see it from a different perspective. Try explaining the problem to a friend or colleague who comes from a different viewpoint. Expressing the problem clearly to someone else can often help the designer see it in a new light.

***SCAMPER***

SCAMPER is a mnemonic device attributed to Bob Eberle [5], based on the ideas of Alex Osborn, the father of brainstorming. It was referenced in an excellent creativity book by Ed Sobey [6], who provided the example below. The word suggests different changes that could be made to an existing design to make the ideas start flowing. Each letter represents one or more ways to change the design:

- S**ubstitute
- C**ombine
- A**dapt
- M**odify, **M**agnify, or **M**inify
- P**ut to other uses
- E**liminate
- R**everse or **R**earrange

Example: suppose that your problem is how to keep your lunch cold until you eat it at noon. Running down the letters in SCAMPER, you might ask:

- ♦ Can I **substitute** the materials from which the lunch bag is made? Are there better insulating materials?
- ♦ Can I **combine** insulators? Is there something I could wrap around the lunch bag to keep it colder?
- ♦ Can I **adapt** an idea from somewhere else? What other products use insulation?
- ♦ Could I **modify** the lunch bag; for example, into a mini-cooler?
- ♦ What **other uses** could I make of a colder lunch bag? How about keeping freshly-caught fish cool on the way back to camp? Does that suggest any new ideas?
- ♦ Is there anything I can **eliminate** that might be transferring heat to the inside of the box?
- ♦ Could I **rearrange** anything? For example, could I make different arrangements for how or when my lunch gets made and gets to me at school?

### Step 6: Evaluate the Alternatives — Engineering Analysis

One of the differences between engineering design and design in general lies in the use of *engineering analysis* to help make decisions and to guide the design process. For example, any good designer might choose steel as a material for an automobile drive shaft, but engineering analysis is used to size the shaft to transmit the torque from the engine and last the life of the vehicle.

Because many of the analytical tools necessary to perform appropriate engineering analysis are learned in the later stages of an engineering curriculum, it is often difficult for beginning engineering students to perform adequate analysis. Nevertheless, good analysis is essential for good design. Students should bear in mind that even in the “real world,” engineers are called upon to learn and apply new material constantly, often in a “just in time” manner. Given the estimate that knowledge doubles every seven years, engineers must cultivate a habit of lifelong learning.

Several chapters at the end of this book provide fundamental electrical and mechanical concepts that can aid beginning students in analysis. Other sources for guidance with analysis are engineering instructors with appropriate expertise, teaching assistants and upper division or graduate students.

### Step 7: Select the Best Alternative

Engineering design always requires making decisions, since the design process generates alternative concepts from which to choose. While some decisions are easy to make, it is more typical to have a complex array of attributes that makes choosing the best alternative difficult. It may be useful to use a methodology to help with this process.

Like other design methodologies, this one is a process and forces decisions to be made based

on rational evaluation of alternatives [7]. And, like other techniques, the result is only as good as what is put into it! The fundamental law of computer programming applies here as well:

*Garbage In*       $\longrightarrow$       *Garbage Out*

### **List Criteria**

The design engineer should make a list of all the criteria s/he can think of to compare design solutions. Start with the original design requirements and add others that help compare competing design concepts. Some possibilities (not exclusive) are:

- ◆ Weight
- ◆ Appearance
- ◆ Ease of assembly
- ◆ Number of parts
- ◆ Time to produce
- ◆ Safety
- ◆ Estimated life before failure
- ◆ Size
- ◆ Ease of use
- ◆ Ease of repair
- ◆ Corrosion resistance
- ◆ Cost to produce
- ◆ Shelf life
- ◆ Environmental impact

### **Assign Priority Values to Criteria**

There are two ways to set priorities. One way is to use a 1 (least important) to 10 (most important) scale, but any type of scale can be used. For example, if appearance is rated 10 and cost 8, that implies that appearance is 25% more important than cost. To reduce bias, have each group member assign priority values independently and average the results.

If there are a large number of people in the group, or if there are a large number of criteria to evaluate, an *interaction matrix* is an effective (and fast!) way to assess the relative importance of each criterion relative to all the other criteria. As shown in Table 7.1, make a matrix chart listing all the criteria both in rows down the left and in columns across the top. (A spreadsheet is an excellent, and easy, way to simplify this process.) Choose a facilitator, and poll the entire group for their opinion of the relative importance of a given criterion vs. each other criterion, one pair at a time. For example, the first non-blank cell in row 1 tallies the number of people who feel that Criterion 1 is more important than Criterion 2 (the diagonal cells are blank, for obvious reasons). After each vote, fill in the two appropriate off-diagonal cells (note that if there are N people in a group, and X people vote for Criterion 1 over Criterion 2, then the number of people who must favor Criterion 2 over Criterion 1 is simply N-X).

Table 7.1. Interaction matrix to assign design requirement priorities.

	<b>Criterion 1</b>	<b>Criterion 2</b>	<b>Criterion 3</b>	<b>Criterion 4</b>	<b>Criterion 5</b>	<b>ROW TOTAL</b>	<b>NORMALIZED VALUE</b>
Criterion 1		1 vs. 2	1 vs. 3	1 vs. 4	1 vs. 5	$T_1$	$T_1/SUM$
Criterion 2	2 vs. 1		2 vs. 3	2 vs. 4	2 vs. 5	$T_2$	$T_2/SUM$
Criterion 3	3 vs. 1	3 vs. 2		3 vs. 4	3 vs. 5	$T_3$	$T_3/SUM$
Criterion 4	4 vs. 1	4 vs. 2	4 vs. 3		4 vs. 5	$T_4$	$T_4/SUM$
Criterion 5	5 vs. 1	5 vs. 2	5 vs. 3	5 vs. 4		$T_5$	$T_5/SUM$
<b>COLUMN TOTAL</b>						<b>SUM</b>	

### **Normalize the Priority Values**

In order to get a better “feel” for the relative priority values, it is a good idea to *normalize* the val-

Example: Table 7.2 shows what the results might look like for a hypothetical problem in which a playground structure, with the following design requirements, is to be designed: light weight, low cost, long lasting, corrosion resistant and attractive. The bar graph in Figure 7.8 clearly displays the relative priority values.

ues, which means to calculate each value as a proportion of a total that equals 1. Divide each value by the total sum of values. Each criterion will now have a priority value between 0 and 1, and the sum of all values will be 1 (i.e., 100%). A pie chart is a good way to visualize the overall results (Figure 7.8).

Table 7.2. Interaction matrix for playground structure example

	<b>Low Cost</b>	<b>Light Weight</b>	<b>Long Lasting</b>	<b>Attractive</b>	<b>Corrosion Resistant</b>	<b>Row Total</b>
Low Cost		7	6	5	5	23
Light Weight	0		1	2	1	4
Long Lasting	1	6		4	2	13
Attractive	2	5	3		4	14
Corrosion Resistant	2	6	5	3		16
<b>COLUMN TOTAL</b>						<b>70</b>

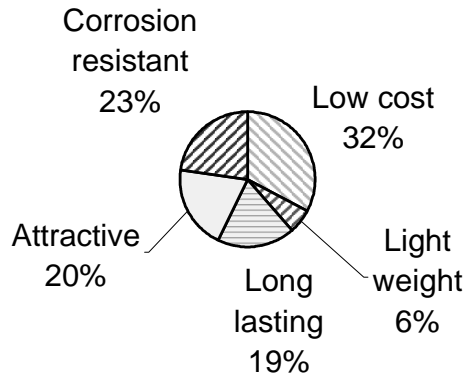


Figure 7.8. A pie chart clearly displays the relative priority values.

### **Analyze Alternative Designs**

Rank each alternative design concept according to how well the group feels that concept could satisfy each of the design criteria identified in steps 1-3. Use a consistent scale, e.g., 0-5 or 0-10. A ranking of 0 means the concept does not meet that criterion at all, and a maximum score implies that the concept meets that criterion perfectly.

### **Compare Alternative Designs**

Make a chart of the normalized criteria values, ordered from largest to smallest. This puts the most important criteria at the top of the list. Make a separate column for each idea being compared. Multiply each ranked value by the normalized criterion value factor, and sum them at the bottom (suggestion: use a spreadsheet).

### **Analyze Results**

The concept with the highest value is the "best" one; i.e., it best meets the criteria as selected. Some concepts may have significantly lower totals than others, which suggests that they can be discarded. The concept with the highest score may be selected, or the chart can be studied for the highest score within each category and the concept with the majority of high rankings selected. Also, this method allows time and energy to be focused on the lowest ranked criteria of the "best" concept to see if improvements can be made. Yet another technique is to take the highest ranked concept from each criterion and generate a new idea that incorporates the better features of all concepts.

One caution: since the values are subjective, do not ascribe too much precision to the results. A score of 4.96 is not appreciably different from a score of 5.04.

Example (continued). Assume that a design group has identified four possible materials from which to construct the playground structure: wood, steel, aluminum and PVC (polyvinyl chloride, a type of plastic). Assuming that the structure will be outside, Table 7.3 shows what the results might be. Based on the priority values given the design criteria, wood is the clear choice. On the other hand, if the structure were going to be indoors, the relative priority values might change, giving the results shown in Table 7.4. Either aluminum or PVC now emerges as a possible candidate.

Table 7.3. Decision matrix for playground structure example—outdoor use.

Criteria	Priority value	Normalized Priority Value	Wood		Steel		Aluminum		PVC	
Low Cost	10	0.37	5	1.85	2	0.74	1	0.37	2	0.74
Corrosion Resistant	8	0.30	5	1.48	1	0.30	5	1.48	5	1.48
Long Lasting	5	0.19	3	0.56	3	0.56	5	0.93	5	0.93
Attractive	3	0.11	2	0.22	3	0.33	5	0.56	5	0.56
Light Weight	1	0.04	3	0.11	2	0.07	5	0.19	5	0.19
TOTALS	27	1.00		4.22		2.00		3.52		3.89

Table 7.4. Decision matrix for playground structure example—indoor use.

Criteria	Priority value	Normalized Priority Value	Wood		Steel		Aluminum		PVC	
Low Cost	10	0.34	3	1.03	2	0.69	5	1.72	5	1.72
Corrosion Resistant	8	0.28	2	0.55	3	0.83	5	1.38	5	1.38
Long Lasting	7	0.24	3	0.72	3	0.72	5	1.21	5	1.21
Attractive	3	0.10	5	0.52	1	0.10	5	0.52	5	0.52
Light Weight	1	0.03	5	0.17	2	0.07	1	0.03	2	0.07
TOTALS	29	1.00		3.00		2.41		4.86		4.90

### Step 8: Communicate the Design

In days gone by, products were designed and fabricated by one creative and hard-working individual. Today's society is much more complex, and any given engineer or worker is responsible for only a small piece of the larger puzzle. In order for a complex project to be accomplished smoothly and effectively, good communication is vital.

Communication methods include written reports and instruction manuals, oral presentations and poster sessions. Details regarding written reports can be found in *Chapter 11: Writing*. Details regarding oral presentations can be found in *Chapter 12: Oral Presentations*. Engineering graphics communicate design intent efficiently and unambiguously, either through hand-drawn sketches or computer-aided design (CAD) methods; more information can be found in *Chapter 10: Engineering Drawing*.



### **Step 9: Implement the Design**

It always works on paper! Only by creating a physical design can the unforeseen problems inherent in any design become apparent.

#### ***Models in Engineering Design***

Modeling is an effective way to quickly answer questions about a design as a step toward final prototype production. As listed below, models can take many forms. The ideal model should answer the question being asked, but no more. In other words, models should be no more complex than necessary. For example, a complex, fully-rendered CAD model is a waste of time if the conceptual design stage is still being explored, when in fact good hand-drawn sketches will suffice. Some basic types of models that can help the engineering design process include:

#### ***Physical Model***

Physical models can help answer questions of geometry, motion, interference, etc. Use any available material that is adequate for the task, such as cardboard, foam core, plastic, sheet metal, etc. One creative team of students answered many geometric questions about a complex 3D part by carving it from a block of soap. Heavy poster board and sewing eyelets can create complex movable mechanisms, but they will not transmit any significant forces.

#### ***Conceptual Model***

A good hand-drawn sketch is the starting point for most engineering designs. For additional information, see *Chapter 10: Engineering Drawing*.

#### ***CAD Model***

CAD models, especially fully-rendered solid models, are effective ways to depict issues of space, mobility, interference, etc., especially if they are parametrically based so that they can be easily changed. For more information, see *Chapter 10: Engineering Drawing*.

#### ***Free-Body Diagram***

A simple diagram that shows all the forces and moments acting on a part under load is the starting point for analyzing most structures. But, many students do not realize that a free-body diagram can be an effective modeling tool, even if it is not solved explicitly. Just knowing the directions and approximate magnitudes of all the forces acting on a part can often provide good insight into what its design must be to perform the function. For additional information, see *Chapter 14: The Basics of Engineering Mechanics*.

#### ***Mathematical Model***

The fundamental tool of engineering analysis is the mathematical model that represents the response of a component or system to external inputs such as force, voltage, temperature, etc. Care

should be taken in using mathematical models to know the assumptions and simplifications that are implicit in any model.

### **Spreadsheet**

A good spreadsheet is an excellent way to perform the mathematical computations quickly and efficiently. The user-friendly graphical capabilities of spreadsheets can help one visualize trends and correlations between variables. Also, spreadsheets are excellent at “what if” calculations that show the impact of changing one or more variables.

### **Computer Simulation**

A powerful tool, computer simulations can be used to simulate the behavior of complex systems or components. Typical examples include computing the stresses and strains in a structure, the temperature distribution in a part, the flow of a fluid in a complex chamber, or the behavior of an electrical circuit. Some computer simulation tools, such as finite element stress analysis, link directly to CAD models of part geometry. *Care must be taken in using computer simulation to validate the results by separate, perhaps simpler calculations.* The results from a complicated finite element stress analysis are worthless if the wrong forces are applied.

### **Prototype Fabrication**

The ultimate goal of the design process is to fabricate a prototype perfectly the first time. If done carefully, this can save tremendous amounts of time and energy. Perhaps the best example of this is the Boeing 777 aircraft, which underwent such sufficient modeling, simulation and analysis in the design phase that the very first airplane flown in 1995 was also the first one sold, saving millions of dollars and considerable time.

Final prototypes should be fabricated as professionally and carefully as possible, as they reflect all the previous work that has gone into them. Some prototypes can be fabricated with simple hand and power tools. More complex designs may require professional machine shop capabilities. Outside vendors can often do professional fabrication at a reasonable cost. For example, a piece of Plexiglas could be purchased from a vendor that is larger than what is actually needed. Then, the designer could cut it to specification him/herself. Alternatively, if the vendor is provided with the exact specifications, s/he can cut the piece to exact size, with a better quality. Using the best tool for the job generally produces the best results.

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## **DESIGN FOR ??? (DFX)**

The somewhat ambiguous title of this section refers to the fact that many aspects must be considered in any design. This includes Design for Manufacturability (DFM), Design for Assembly (DFA), Design for Serviceability (DFS) and universal design.

## **The Four Fs**

The four Fs [8] are: *form*, *fit*, *function* and *finish*; they refer to detailed design aspects of components of a larger system.

*Form* refers to shape. Is the part shaped correctly to perform its function? If it is too thin, it may fail by breaking or by deforming excessively. If it is too large or too thick, it will be heavy and expensive. If it has a sharp external corner, it represents a safety hazard because sharp corners are cutting edges. If it has a sharp internal corner, high stresses will develop (which may lead to premature failure), and it will be difficult to produce.

*Fit* is involved when assembling two or more pieces to form a subsystem. Will the pieces fit together without gaps or discontinuities? If holes are drilled in a given component for bolts, are they in alignment so that bolts fit without interference? Fit becomes critical when dealing with rotating shafts that require bearings. If the bearing is to fit properly, tolerances required for the housing containing the bearing are very tight and require precise machining of the component parts. If the fit is too tight, the bearing will overheat and seize. If the fit is too loose, vibration will occur which detracts from performance, and shortens the life of the bearing and other components.

*Function* is the ability of the system to perform satisfactorily with its components. If a part fails in service, then the system cannot function. Suppose a crankshaft for an automobile vibrates excessively at an engine speed of 3800 RPM. It has the right form, it fits properly and it has the correct surface finishes on the bearing journals. But the crankshaft vibrates at or near highway cruising speed. The design fails because the performance of the auto has been severely compromised by the vibrations induced in the engine by the crankshaft. The crankshaft has not functioned correctly.

*Finish* refers to the surface finish of the part. Is the surface rough, smooth or polished? Does it matter? Some surfaces are important because of appearance. The sheet metal on an automobile is very smooth so that the paint will have a high gloss finish. Other surfaces are not important. The aluminum block on an automobile engine is die cast, and its outside surface reflects the finish of the die. An engine is rarely looked at in terms of beauty, and so a relatively rough surface finish is acceptable. Some surfaces are polished or ground to enhance their performance in bearing applications. When a part is designed, it is important to know how it will be used in service and specify the appropriate surface finishes on the detail drawing for that part.

## **Design for Manufacturability (DFM)**

One of the intriguing aspects of engineering design is that alternative design concepts can be conceived which all perform the required function equally well, yet the cost to manufacture them can differ by a factor of ten or more. For example, one way to make a simple bracket is to machine it from a solid block of metal, a time-consuming and expensive process. Comparable function, *with no sacrifice in quality*, can be achieved by stamping and bending the bracket from a thin piece of sheet metal.

For parts that are produced in large quantities, the way in which each part will be manufactured is equally as important as function. The design engineer must carefully consider manufacturing methods such as die casting, injection molding, forging, casting, drawing, machining, stamping, etc.

in the detail design of mass-produced parts. Even one-of-a-kind prototypes can benefit from careful DFM consideration.

Bralla [9] has produced an excellent reference containing detailed DFM guidelines for a wide range of manufacturing processes, and Boothroyd et al. [10] have published general DFM guidelines to be followed in design. Storage Technology Corporation has outlined 12 fundamental concepts of DFM [11]:

1. *Reduce the Number of Parts.* Simplicity is the key. The ideal product has one part.
2. *Use Modular Design.* Use “building blocks.”
3. *Don't Fight Gravity.* Design so that a product can be assembled from the top down.
4. *Reduce Processing Surfaces.* Avoid expensive part reorientation. Finish processing on one surface before moving to the next surface.
5. *Process in the Open.* Minimize restricted access and vision problems.
6. *Eliminate Fasteners.* Fasteners are expensive, difficult to handle and vibrate loose. Use snap fits, adhesives, etc.
7. *Optimize Part Symmetry.* Either design parts so that they can function in any orientation (e.g., a washer), or make the parts obviously asymmetrical. Design so that a product *cannot* be assembled incorrectly.
8. *Optimize Part Handling.* Provide gripping surfaces; avoid flexible parts or parts that tangle.
9. *Design for Easy Part Mating.* Provide “guide surfaces,” such as chamfers.
10. *Provide Nesting.* Design features to locate parts during assembly.
11. *Reduce, Simplify and Group Processes.* Group “like” processes.
12. *Optimize Process Sequence.* During design, think about how a product will be made!

### **Design for Assembly (DFA)**

Most designs consist of assemblies of components. Once the components are individually manufactured, they must be assembled into the final system. Design engineers tend to focus on function while ignoring how components can be manufactured or how components can be assembled. While more extensive coverage of this topic can be found elsewhere [10], one of the fundamental DFA concepts is to minimize the number of parts. A part that is not there does not have to be manufactured, inspected, shipped, inventoried or assembled. It will not, therefore, ever vibrate loose or need to be replaced.

### **Design for Serviceability (DFS)**

The perfect design would *never* require maintenance. However, this is not always possible. For example, an automobile oil filter keeps the oil clean by trapping small particles, preventing them from damaging the engine. But eventually, both the oil and the oil filter must be changed on a regular basis in order to prolong the life of the engine.

Changing the oil filter varies tremendously from car to car. On some cars, the body of the car must be raised; someone would have to crawl under the car and reach up to unscrew a horizontally-

oriented filter. When the filter is loosened, it leaks, and oil runs down the side of the engine and onto the mechanic. Clearly, the design of this engine and the placement and orientation of the oil filter did not accommodate the need for periodic and scheduled maintenance. On other cars, the filter is replaced from the top without going under the car. The designers have also oriented the filter vertically so that the oil does not spill when the filter is loosened. This second filter is an example of design for serviceability. The designer recognized the need for periodic maintenance and developed the product to allow for easy access and rapid, inexpensive replacement of the required parts.

For a design project, design to minimize maintenance. However, if servicing is required, design the product so that it can be easily serviced, and provide clear, written instructions.

### **Universal Design**

The concept of *universal design* means that products should be usable by as many people as possible, including a range of ages, abilities and disabilities. Seven principles should be considered as a part of design decisions:

1. *Equitable Use*. The design is useful and marketable to people with diverse abilities.
2. *Flexibility in Use*. The design accommodates a wide range of individual preferences and abilities.
3. *Simple and Intuitive Use*. Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills or current concentration level.
4. *Perceptible Information*. The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities.
5. *Tolerance for Error*. The design minimizes hazards and the adverse consequences of accidental or unintended actions.
6. *Low Physical Effort*. The design can be used efficiently and comfortably with a minimum of fatigue.
7. *Size and Space for Approach and Use*. Appropriate size and space is provided for approach, reach, manipulation and use regardless of user's body size, posture or mobility.

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### **REFERENCES**

1. Hyman, B., *Fundamentals of Engineering Design*, Prentice-Hall, 1998, 499 pp.
2. Popper, K.R., *Logic of Scientific Discovery*, Harper & Row, New York, NY, 1965.
3. Popper, K.R., *Conjectures and Refutations: the Growth of Scientific Knowledge*, Harper & Row; New York, NY, 1968.
4. Osborn, A.F., *Your Creative Power*, Charles Scribner, New York, NY, 1948.
5. Eberle, B., *SCAMPER: Games for Imagination Development*, DOK Publishers, Buffalo, NY, 1971; adapted from A.F. Osborn, *Applied Imagination*, Charles Scribner, New York, NY, 1963.

6. Sobey, E., *Inventing Stuff*, Dale Seymour Publications, Alternative Publishing Group, Addison-Wesley Publishing Co., 1996.
7. Walton, J., *Engineering Design: From Art to Practice*, West Publishing Co., 1991.
8. Dally, J.W., *Introduction to Engineering Design*, Book 2, College House Enterprises, 1997.
9. Bralla, J.G. Ed., *Handbook of Product Design for Manufacturing*, McGraw-Hill, 1986, 1120 pp.
10. Boothroyd, G, Dewhurst, P. and Knight, W., *Product Design for Manufacture and Assembly*, Marcel Dekker, New York, NY, 1994.
11. Storage Technology Corporation, Louisville, CO, *Twelve Fundamentals for Design for Manufacturability*, Unpublished notes.



# Aesthetics in Engineering Design

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## INTRODUCTION

Many considerations go into *any* new design, including function, cost, material, how it will be fabricated, safety, environmental aspects, etc. The point of this chapter is that *how* a design looks is also an important consideration, one that can often mean the difference between a good design and a great one. From automobiles to airplanes to appliances, engineers create many of the physical forms that surround us. Therefore, it is their responsibility to make them as visually appealing as possible, so that these designs are pleasing now and in the future.

"When I am working on a problem, I never think about beauty. I only think about how to solve the problem. But when I have finished, if the solution is not beautiful, I know it is wrong."

- Buckminster Fuller<sup>1</sup>

This chapter provides a broad overview of aesthetics and how it applies to engineering design. Some basic aesthetic concepts are discussed, and some aesthetic elements that can be used in engineering designs are presented. Finally, a tour of the

University of Colorado at Boulder is presented to show how some of these aesthetic concepts are exemplified in campus architecture.

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## ASPECTS OF BEAUTY

One definition of *aesthetic* is; *sensitive to the beautiful; artistic*.<sup>2</sup> But, what is considered beautiful is dependent on individual tastes. However, beauty can be broadly interpreted to have two different aspects: emotional and intellectual. An emotional appreciation of beauty depends on the personality of the perceiver and is therefore variable. In addition, it varies with time. The fashions shown in Figure 8.1, for example, were considered very stylish at the time, but today they look "old fashioned."

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1. R. Buckminster Fuller (1895-1983) was one of the century's most original minds, holder of more than 2,000 patents. His foremost invention is the geodesic dome.

2. American Heritage Dictionary





Figure 8.1. Emotional beauty changes over time: on the left, 1500s, on the right, 1920s.

An engineering designer is more concerned with the intellectual aspect of beauty. From this aspect, the appearance of an object is strongly linked with its function, measuring the suitability of an object for its intended use.

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## AESTHETIC CONCEPTS

The following are broad overall concepts that may apply to any design.

### Less is More

Mies van der Rohe<sup>3</sup> was an architect who coined this apparent paradox. What he meant by this saying is that simple designs are the most pleasing and last longest over time. For example, the high-rise apartment buildings he designed for Lake Shore Drive in Chicago in 1952 still look modern and pleasing today (Figure 8.2).

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3. Ludwig Mies van der Rohe (1886-1969) was a German-born architect and designer. His buildings were characterized by accessible, simple designs devoid of applied ornament and were composed of spaces rather than masses.



Figure 8.2. These high-rise apartment buildings on Lake Shore Drive in Chicago are as pleasing today as they were when they were built in 1952.

### Form Follows Function

Louis Sullivan<sup>4</sup> was another architect who designed many buildings in Chicago. His dictum "form follows function" means that the first job of a designer is to make sure that the design functions

Mumford expanded Sullivan's concept<sup>5</sup>:

"Form follows function, underlying it, crystallizing it, clarifying it, making it real to the eye."

as it is intended. Its form will then imply its function, suggesting *what it is* and *how to use it*.

An example of how this concept applies to design is shown in Figure 8.3. While the primary function of a chair is for

sitting, the ability to stack chairs and move them around easily is another important function that is intimately linked with a chairs' form.

4. Louis Henri Sullivan (1856-1924) was perhaps the foremost exponent of the Chicago school of architecture, producing 120 buildings, many of them landmarks. Frank Lloyd Wright was his student.
5. Lewis Mumford (1895-1990) was a social thinker and writer who was the architectural critic for the *New Yorker*.



Figure 8.3. Form and function are closely linked in the design of these chairs.

If tools are designed well, it is obvious how to use them. No one is likely to need to read the owner's manual to be able to pick up the tools shown in Figure 8.4 and use them.



Figure 8.4. The form of these tools tells how to use them.

### Unity

The aesthetic concept of *unity* suggests that everything in a design looks like it belongs there. Nothing is missing, and nothing is extra. Manufacturers of a variety of different products use common colors, shapes, type fonts, etc., to create a "family" of products. For example, Figure 8.5 shows two different electronic instruments made by the same manufacturer. The basic shapes, color of the cases, etc. are similar between the two. The assumption is that if a user is familiar with one of these products, then they are more likely to purchase another product from the same vendor (assuming, of course, that the product works well).



Figure 8.5. Two different Hewlett-Packard instruments illustrate the concept of *unity*.

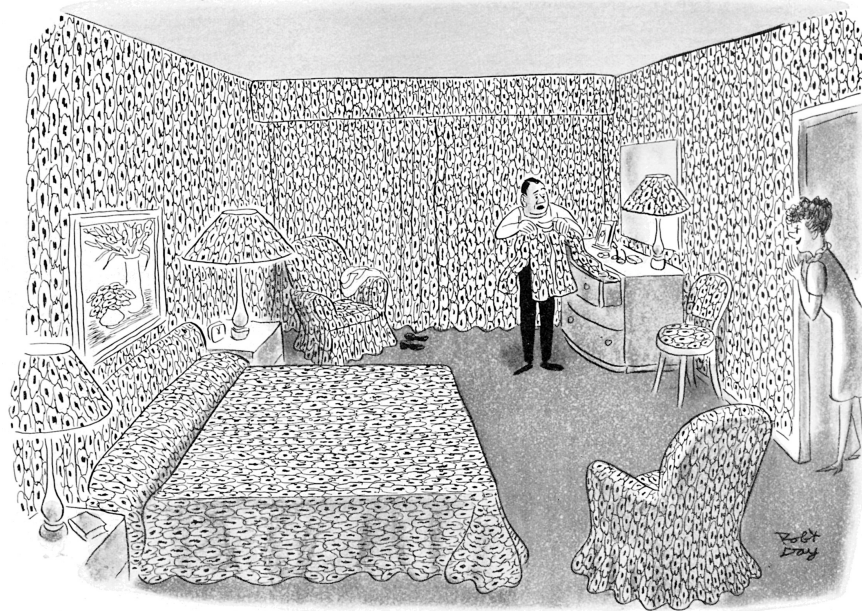
However, care must be exercised. There is no exact formula for beauty, and too much of anything soon becomes repetitive and boring. The amateur decorator in Figure 8.6 has clearly gone too far!

Alberti<sup>6</sup> put it this way:

"I shall define beauty to be harmony of all parts, fitted together with such proportions and connections that nothing could be added, diminished or altered but for the worst."

Roger Fry<sup>7</sup> observed:

"The first quality that we demand in our sensations will be order, without which our sensations will be troubled and perplexed. The other quality will be variety, without which they will not be fully stimulated."



"Good grief, Marge! Not my pajamas, too!"

Figure 8.6. Anything can be overdone (*The New Yorker*, reproduced by permission).

6. Leon Battista Alberti (1404-1472) was one of the most brilliant figures of the Renaissance. He was an architect, musician, painter, poet and philosopher.
7. Roger Fry (1866-1934) propounded an extreme formal theory of aesthetics in his role as an art critic, painter and aesthetic philosopher in England and New York City.

## Styling

While the first three aesthetic concepts described above are concepts to emulate, styling is an aesthetic concept that should be avoided. Styling refers to ornamentation that is added to a product for sales appeal, but has no function rationale. Styling is the opposite of *form follows function*; it appeals to the emotional aspect of beauty and usually tarnishes with time. Clothing styles illustrate this concept well. The Porsche 911 (Figure 8.7), first produced in 1963, looks much better today than the “styled” Lincoln of the same vintage (Figure 8.8), because the Porsche’s clean, flowing lines are simple and aerodynamically functional.



Figure 8.7. The Porsche 911 was first produced in 1963 and still looks good today.



Figure 8.8. This heavily styled Lincoln from the 60's looks very outdated.

Another good example is the bicycle. The touring bicycle has evolved out of function into an aesthetically simple and pleasing shape (Figure 8.9), in contrast to a much heavier, styled bicycle (Figure 8.10).



Figure 8.9. The modern touring bicycle exemplifies the concept of “form follows function.”



Figure 8.10. The bicycle with heavy styling is physically heavier and even looks like it might move slower.

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## AESTHETIC ELEMENTS

It is from basic aesthetic elements that one creates form. Some of these elements are listed below, although this chapter will not discuss color or contrast:

- ◆ Lines
- ◆ Space
- ◆ Proportion
- ◆ Contrast
- ◆ Mass
- ◆ Balance
- ◆ Color

### Lines

Both artists and engineers use lines as the basic building block to create shapes. However, there are many different styles of lines, and the style of line in a design can convey subtle messages about its function (Figure 8.11). For example, bold lines suggest strength and ruggedness and, therefore, would be good choices for depicting earthmoving equipment. Thin, fine lines, on the other hand, suggest precision and would be good to delineate parts of electronic instruments. Jagged lines convey danger and could be used in high voltage products.



Figure 8.11. Different line types suggest different emotional qualities.

One aspect of lines is that engineers have a tendency, acquired in engineering school, to think of the world in an X-Y-Z Cartesian<sup>8</sup> co-ordinate system. While this system has mathematical advantages, it is important to realize that not all angles need to be 90° and not all lines need to be straight. For example, consider the two light poles in Figure 8.12. The one on the left has parallel lines and right angles, whereas the one on the right uses tapered lines for the main column and radiused connections. In addition to being lighter, the pole on the right is also more aesthetically pleasing.

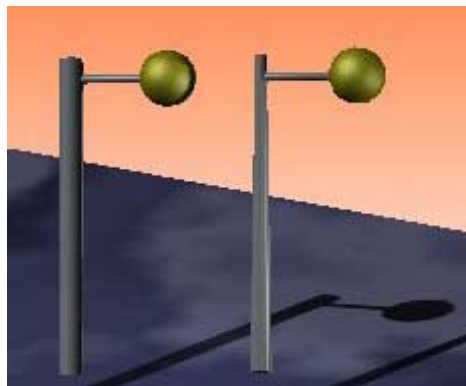


Figure 8.12. Two designs for a light pole: one using parallel lines and right angles, the other using a tapered form and radiused connections.

### Mass

In physics, *mass* is the property that creates weight in a gravitational field such as on earth. From an aesthetics viewpoint, however, mass is the visual suggestion of weight. For example, consider the fork-lift truck shown in Figure 8.13, which is used to move heavy pallets of cartons around a warehouse. Under the covers, which define the overall shape, is probably a collection of individual components like a battery, hydraulic pumps, electronic circuits, wires, etc. By hiding these components with a monolithic covering, a single, massive shape is created that gives the appearance that it is powerful and rugged enough to do the job. In addition, the covering protects the inner workings

8. René Descartes (1596-1650) was a French philosopher and mathematician. In addition to making major contributions to optics, he founded co-ordinate or analytic geometry.

from damage, dirt, moisture, etc. Of course, the truck must in fact be powerful enough to do the job, or it is of no use. This is a good example of *form follows function*.



figure 8.13. A fork-lift truck appears to be massive enough for its task.

## Space

When considering aesthetics, the opposite of mass is *space*, and designers can use space to their advantage to create light, airy designs that are visually interesting. One artist who understood the relationship between visual mass and space very well was Escher<sup>9</sup>, who created wonderful optical illusions that played with these two concepts. His etching “Day and Night,” for example, changes seamlessly between mass and space in two dimensions (Figure 8.14). The fields in the lower portion

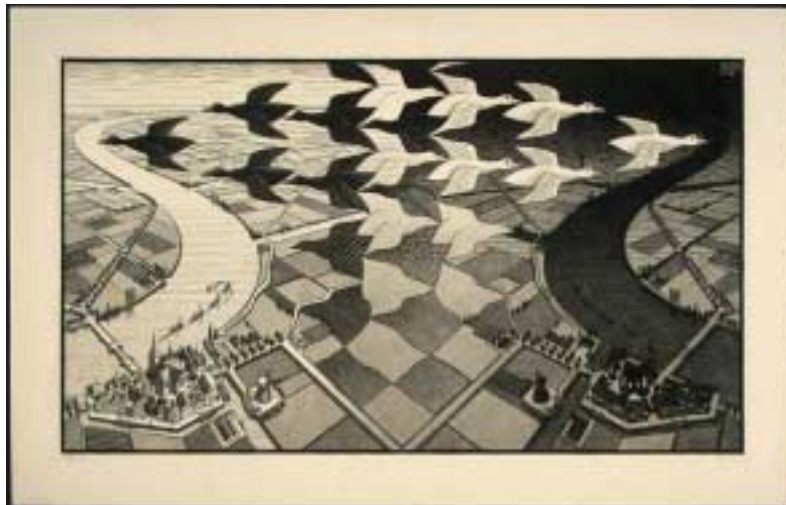


figure 8.14. “Day and Night” by M.C. Escher.

of the drawing become flying geese as the eye moves up. In the daytime scene on the left, the dark geese fly in the lighter colored air, while on the mirrored nighttime scene on the right, the geese are white and the night sky dark.

9. The works of the Dutch graphic artist, Maurits Cornelis Escher (1898-1972) have intrigued and delighted for generations. His distortions of space and time have created a dedicated following around the world.



## Balance

From the study of physics, we know that there are several ways to balance a weight on a lever. In the top of Figure 8.15, equal weights will be balanced if they are equal distance from a fulcrum. This may be termed “symmetric balance.” A lighter weight may also balance a heavy one, however, if the lighter one is further from the fulcrum, as seen in the bottom of Figure 8.15. This principle is equally well understood by children on a teeter-totter on a playground!

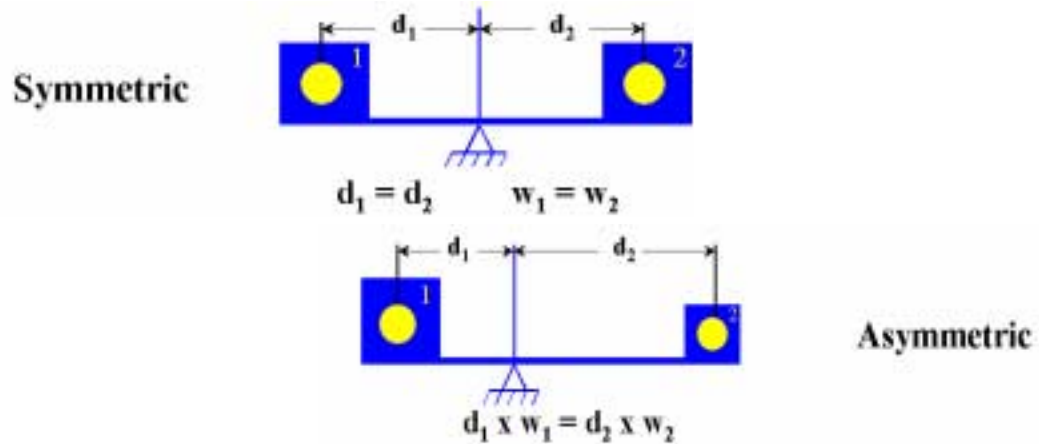


Figure 8.15. Symmetric and asymmetric balance.

From an aesthetics viewpoint, objects may also be either symmetrically or asymmetrically in balance (Figure 8.16). In general, designs that are symmetrically balanced suggest stability, precision, and simplicity; they can also be boring. Designs that exhibit asymmetric balance are more dynamic and interesting to the eye.

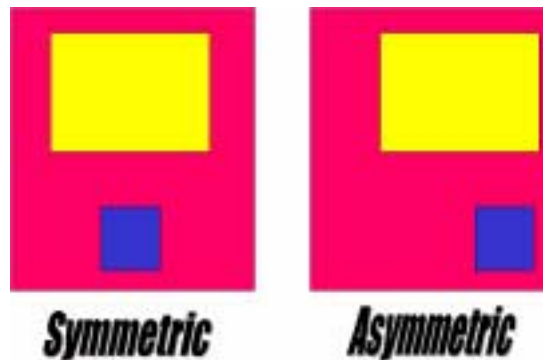


Figure 8.16. Three simple shapes can be symmetrically (L) or asymmetrically (R) balanced. Symmetric balance connotes stability, while asymmetric balance is more eye-catching.

Early space capsules were symmetric for aerodynamic reasons (Figure 8.17), while the Space Shuttle exhibits asymmetric balance (Figure 8.18). Its shape suggests that it really can fly, as opposed to the Apollo capsule, which is more of a ballistic particle.



Figure 8.17. The Apollo space capsule's symmetric aesthetic balance is driven by its aerodynamic function.



Figure 8.18. The Space Shuttle exhibits asymmetric balance and is more visually intriguing.

The symmetric balance of the calculators in Figure 8.19 suggests the precision they display. The oscilloscope in Figure 8.20 is also a precision instrument, but the asymmetric balance created by the extreme left screen placement makes it more visually interesting.



Figure 8.19. These calculators are symmetrically balanced.



Figure 8.20. This oscilloscope exhibits asymmetric balance due to the extreme screen placement.

### Proportion

Lines can be combined to create geometric shapes. *Proportion* refers to the relationship between the lengths of lines in a geometric shape. Using the same proportioned shapes throughout a design is one way to create aesthetic unity. While many systems of proportion are possible, we will consider a classic system of proportion for rectangles that was discovered and utilized by the ancient Greeks.

Consider the three rectangles in Figure 8.21. To most observers, the top rectangle is “too skinny,” the bottom one “too fat,” but the one in the middle appears “just right.” While the other two rectangles are arbitrary, the middle one is known as a *golden rectangle*, which has a unique proportion that is precisely defined and has interesting properties.

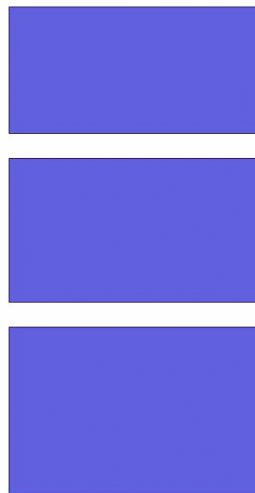


Figure 8.21. The middle rectangle, known as the golden rectangle, appears to be the most pleasing of these three shapes to most people.

One of a golden rectangle's properties is that if a square is subtracted from (or added to) a golden rectangle, the resulting shape will also be a golden rectangle (Figure 8.22). This allowed the ancient Greeks to scale this proportion up or down geometrically (without using calculators!) to relate different aspects of buildings to each other in a visually pleasing way (Figure 8.23).

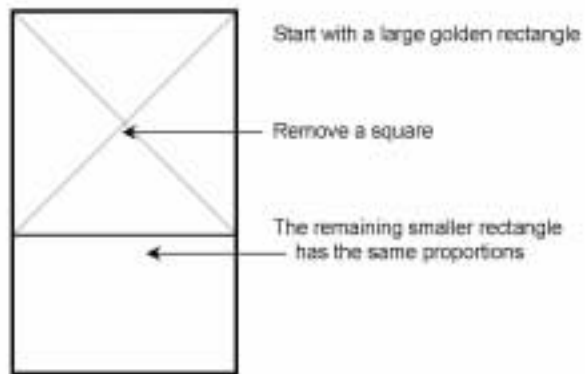


Figure 8.22. If a square is removed from (or added to) a golden rectangle, the resulting shape is also a golden rectangle.



Figure 8.23. The Parthenon in ancient Athens (started c. 447 BC) employs the proportions of the golden rectangle pervasively throughout its design.

A simple mathematical derivation shows that this “divine ratio,” as it is also called, is numerically equal to an irrational number:

$$\Phi = 1.618034\dots$$

The intriguing fact about this ratio is that it appears repeatedly throughout nature. For example, the ratios of the successive lengths of the finger bones in the human being follow this proportion. The ratio  $\Phi$  can also be found throughout the natural world of plants, fish, etc. (Figure 8.24).

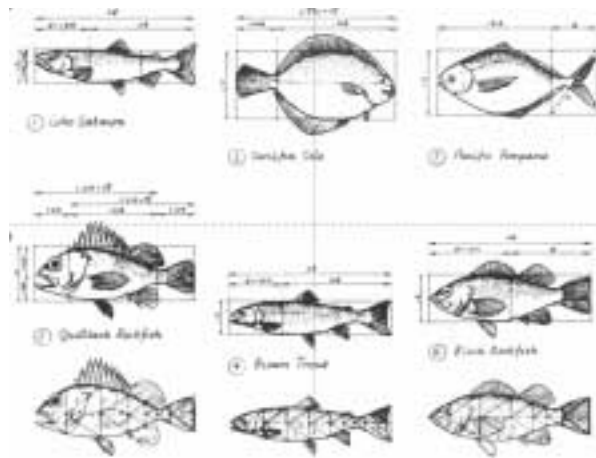


Figure 8.24. The “divine ratio” ( $\Phi = 1.618034\dots$ ) is found throughout the natural world.

One may speculate why this proportion appears so pleasing to the human eye. Perhaps its prevalence in nature is significant. Another possibility is that the field of vision of the human eye is elliptical and fits neatly into a golden rectangle. In any case, the use of a consistent proportion, such as the golden rectangle, throughout a design can contribute to a sense of aesthetic completeness, or unity. It should not be overdone, however. The world would be a boring place if every building and every human-made artifact were based on golden rectangles.

## A CAMPUS TOUR

The University of Colorado at Boulder campus is renowned for its aesthetic beauty. One architectural critic calls it the most beautiful public college campus in the US, and fourth<sup>10</sup> among all institutions [1]. Although the emphasis of this chapter is on aesthetics in engineering design, many of the concepts apply to the campus architecture as well

In 1876, what is now known as Old Main became the first building on a new campus, which was then a treeless bluff (Figure 8.25). Since then, a succession of campus architects, working in cooperation with a strong Design Review Board, have maintained a consistency of style to uphold the integrity and harmonious look of the campus.

10. Top-ranked campuses are Stanford and Princeton Universities, and Wellesley College.

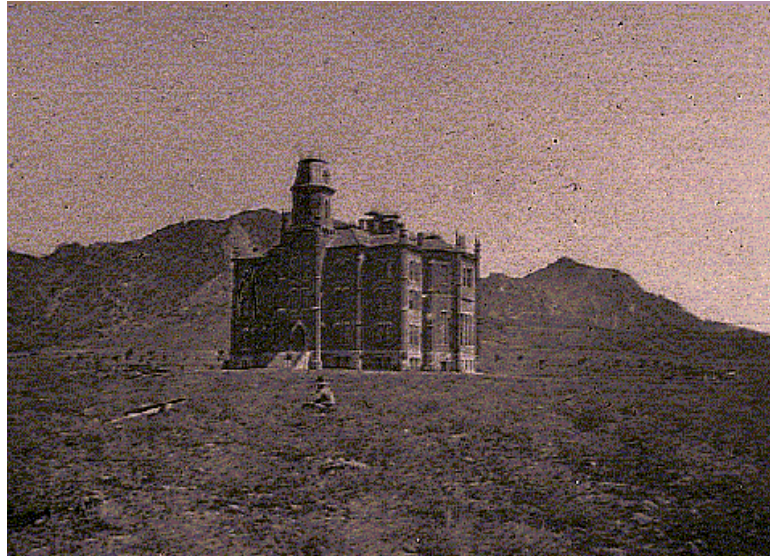


Figure 8.25. Old Main was the first building on the CU-Boulder campus, built in 1876.

The aesthetic concept of *unity* is evident, particularly in the native Colorado sandstone façades and red tile roofs that characterize almost all buildings on campus. For example, Ketchum Hall, which was the original engineering building, was built in 1937 (Figure 8.26).



Figure 8.26. Ketchum Hall (1937) was the original home for engineering studies.

Forty years later, an addition to Norlin Library (Figure 8.27) was built adjacent to Ketchum. Although building techniques changed much during forty years, the use of common architectural elements tie the two buildings together well (Figure 8.28). In addition, a large circular plaza unites these buildings.



Figure 8.27. This addition to Norlin Library was built in 1977.



Figure 8.28. The two buildings flank a large circular plaza that integrates them well.

Charles Klauder was undoubtedly the architect who most influenced the CU campus. His firm completed a campus master plan in 1919, and he designed 15 buildings during the next 20 years [2]. Sewall Hall, built in 1934, is considered the best of his buildings, exemplifying the *Tuscan Vernacular* style that characterizes the CU campus (Figure 8.29).



Figure 8.29. Sewall Hall (1834) was originally known as Women's Residence Hall.

The Student Recreation Center (1973) shows a strong influence of proportion (Figure 8.30). The prominent concrete columns on the façade define a series of rectangles (not Golden!) whose proportions are used throughout the facility to tie it together. Aesthetic beauty is not achieved by formula, and the human eye would quickly tire if all buildings used the same proportions.



Figure 8.30. The Student Recreation Center (1973) uses a rectangular form throughout, although it is *not* the Golden Rectangle.



Although the Engineering Center (1965) is certainly the most controversial building from an aesthetic standpoint, it has won awards for its bold, innovative architecture suggestive of the mining heritage of the state of Colorado (Figure 8.31). This 500,000-sq. ft. complex, while often confusing to navigate, has also proved to be very functional. Although it makes strong use of exposed concrete, the campus elements of Colorado sandstone and red tile roofs integrate it with the remainder of campus.



Figure 8.31. The Engineering Center (1965) is both controversial and functional.

When the Integrated Teaching and Learning Laboratory (ITLL) was designed 30 years later, the architects faced a daunting challenge: to respect the external architecture of the Engineering Center, while at the same time creating a more open, visible architecture that would stimulate creative learning within (Figure 8.32).



Figure 8.32. The Integrated Teaching and Learning Laboratory (1997) connects with the Engineering Center to the west. It was named the Grand Prize Winner for buildings built in Colorado by the Construction Management Report in 1997.

From the outside, large, sloping roof monitors that are identical in slope to those on the Engineering Center top the large, square building mass. However, whereas the roof monitors in the larger Engineering Center house mechanical equipment, those in the ITLL are open from below and contain large clerestory windows that bring in the wonderful indirect north light favored by artists. In both cases, these are good examples of *form follows function*. The ITLL architects chose the square as the geometric element to bring *unity* to the design. The goal is to create unity both within the laboratory, and to tie it to the Engineering Center. Close inspection finds this square shape prevalent in many places throughout the 35,000-sq. ft. building. For example, square acoustic panels are distributed throughout the large, open laboratory plazas to help control sound, another example of *form follows function* (Figure 8.33).

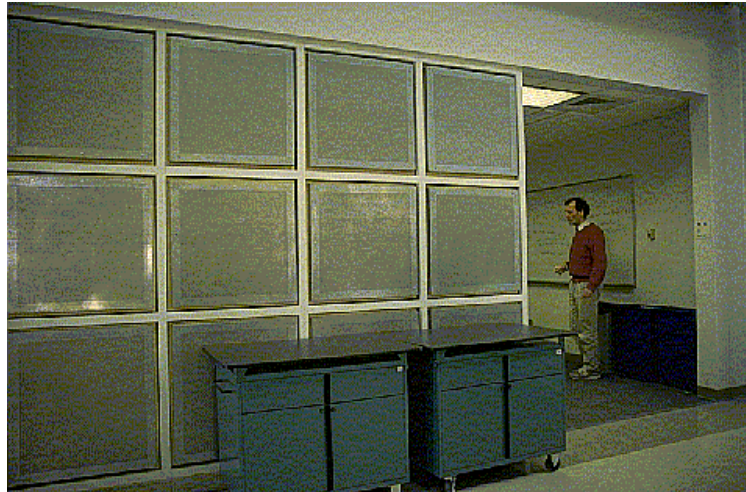


Figure 8.33. Square acoustic panels attenuate noise and also integrate well aesthetically.

The square wire mesh panels in the balcony and stair railings are both functional and aesthetic (Figure 8.34). However, the overall framework that contains them is rectangular to avoid overuse of the square element (recall the cartoon of Figure 8.6). When using any aesthetic element, like the square, it is important to use it in moderation.

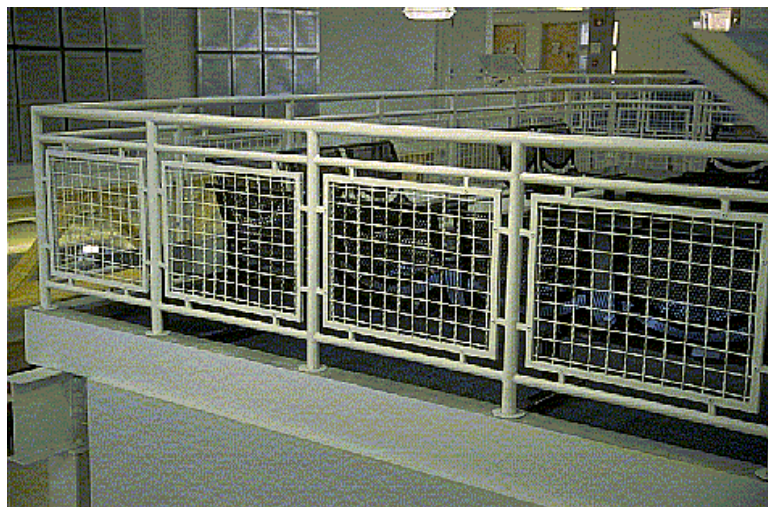


Figure 8.34. Square wire mesh panels are both functional and aesthetic.

Square glass blocks allow natural light to silhouette the stairway to the lower laboratory plaza (Figure 8.35). Their solid 3-in. thick construction provides both fire protection required by building codes and better light transmission than the more common hollow glass block form. This is another excellent example of *form follows function*.



Figure 8.35. Square glass blocks provide fire safety and allow natural light to illuminate a basement laboratory plaza in the ITLL.

The square cutouts in the steel stair risers (Figure 8.36) allow a small amount of light to pass through, but their function is primarily aesthetic.

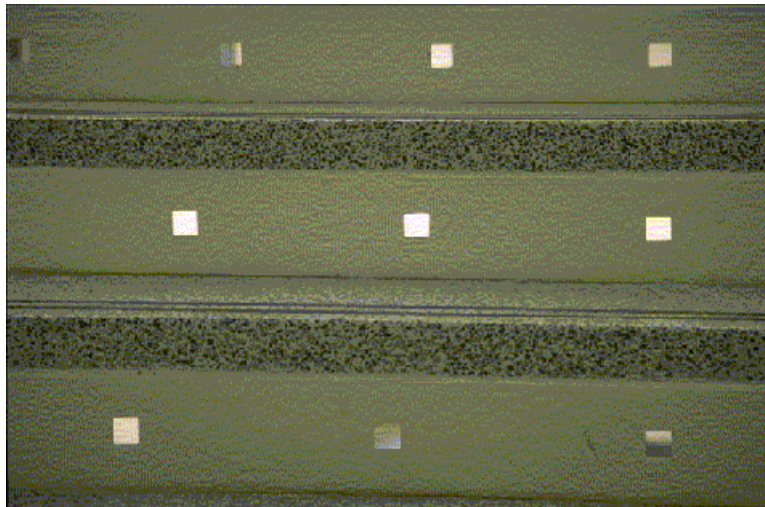


Figure 8.36. Square cutouts in the stair risers allow a small amount of light to pass, breaking up the solid feeling of the stairs.

The overall floor plan of the ITLL, like the Engineering Center it adjoins, is based on a 20ft x 20ft square modular dimension that is accentuated by the pattern of floor tiles in the laboratory plazas. This is particularly noticeable when viewed from the overlook (Figure 8.37).



Figure 8.37. Different colors of floor tiles are used in the laboratory plazas to highlight the 20ft x 20ft modular square pattern upon which the ITLL floor plan is based.

And, when outside looking up at the underside of the bridge that connects the ITLL with the Engineering Center, a square “waffle” pattern is evident (Figure 8.38). This pattern reduces weight in the structure and requires less concrete, saving cost. A square is the simplest pattern to implement, and this same feature is evident in the undersides of many exposed concrete structures in the Engineering Center. Using the same pattern in both locations makes them look like an integral structure, instead of structures that were built thirty years apart in time.



Figure 8.38. The square “waffle” pattern under the bridge saves weight.

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**CONCLUSION**

Engineers are responsible for most of the fabricated world around us and thus, have a responsibility to create products that are beautiful as well as functional. It should be the goal of any engineering designer to create designs that look as good twenty years from now as they do today. It is necessary to consider the aesthetics of a design during the design phase in order to create truly superb designs.

However, engineers must also exercise caution. Engineers love to use simple formulas to solve problems, but there is no simple formula that will guarantee aesthetic beauty. An awareness of some basic aesthetic concepts and recognition of them in the designs of others can help the designer create beautiful products.

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**REFERENCES**

1. Gaines, Thomas A., *The Campus as a Work of Art*, Praeger, New York, 1991.
2. Deno, William R., *Body and Soul – Architectural Style at the University of Colorado at Boulder*, University of Colorado Publications, Boulder, CO, 1994.

## INTRODUCTION

Probably the most critical stage in a project is when data are collected and are ready to organize and interpret. The final step—and the one that can have the most impact—is presentation of the data in a form that clearly shows functions, physical properties or dependencies. Often, scientists and engineers spend great amounts of time and energy designing and executing tests and experiments. They often fail, however, to apply the same spirit when tabulating the data into a form that can readily explore and effectively communicate inter-relationships and anomalies. Unexpected or “rogue” data points can signal an experimental or recording error, or they can herald an effect worthy of additional study. In addition, the data preparation and presentation stage often lacks sufficient exploration of the various possible displays that can make results clear to an audience.

Today, wonderful computer packages easily tabulate and display data. However, the great number of options and ease-of-use can create the illusion that great looking and meaningful tables and displays can be produced with little effort. Invariably, there remains a need to explore data and make wise, analytical choices concerning the types of presentations best suited to demonstrate important features.

A medical doctor performs tests on a patient, integrates the information and finally develops a diagnosis. Likewise, an engineer designs an experiment, records data, and finally tabulates and interprets the information before presenting it.

Therefore, just as a medical doctor works towards a diagnosis as a clear goal, an engineer must keep his/her goals in mind as s/he enters the data analysis and presentation phase of a project. In some ways, an engineer’s or scientist’s task can be made more difficult because the function or process represented by the data may not be understood. Papers are often published that clearly present data showing a complex, new relationship, but without an explanation. Such papers can be seminal in a field and lead to a major breakthrough. In other words, the creation and presentation of a data set can represent an important accomplishment in its own right.

In a series of books [1][2][3], E.R. Tufte addresses the visual display of quantitative information. His definition of the ideal data presentation is represented by the following quote [1]: “Excellence in statistical graphics consists of complex ideas communicated with clarity, precision and efficiency.” Tufte’s goals of graphic displays (slightly modified) are:

- ◆ Present the data.
- ◆ Get the viewer to think about substance rather than methods or graphic design.
- ◆ Do not distort the message of the data.
- ◆ Encourage the eye to compare different pieces of data.
- ◆ Reveal levels of detail from a broad overview to a fine structure.
- ◆ Have a clear purpose (e.g., description, comparison, exploration).
- ◆ Integrate with other descriptions of the data set.

The following sections present data in tabular form and explore methods of display, illustrating the strengths and weaknesses of different presentation formats.

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## **DATA SHOWING HOW A QUANTITY IS DISTRIBUTED**

To show how a resource is divided, a pie chart presentation is very effective. At a glance, the relative sizes of the segments provide the approximate distribution, and accompanying legends or tables provide precise numerical data, if required. For instance, a series of pie charts showing consecutive yearly distributions may indicate trend information. As an example, assume that a design class has time allotted to various subjects, as shown in Table 9.1.

Table 9.1. Distribution of course time by topic.

<b>Topic</b>	<b>Time Allotted (in minutes)</b>	<b>Percentage</b>
Mystery Artifact Challenge	330	8.4%
Design Loop	330	8.4%
Major Design Project	1760	44.6%
Social Styles & Team Dynamics	220	5.6%
Guest Lectures	250	6.3%
Design Lectures	150	3.8%
Other (e.g., Technical Writing)	310	7.8%
Reverse Engineering	600	15.2%
<b>Total</b>	<b>3950</b>	<b>100%</b>

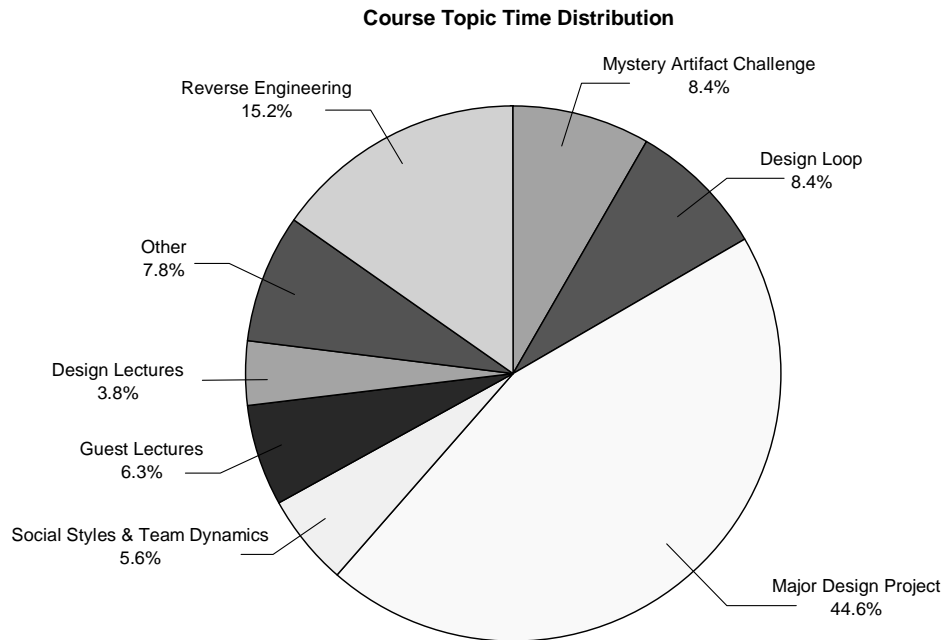


Figure 9.1. Pie chart of course topic distribution.

In Figure 9.1, the distribution by percent of time is clearly shown in a pie chart plot. At a glance, a plot like this provides guidance on how to apportion time among course topics.

## COMPARISONS OF VALUES FOR DIFFERENT CATEGORIES

An article in the *NY Times* [4] compares pairs of companies that had the same ratings from a financial viewpoint, but were rated differently on a scale of environmental performance. Table 9.2, adapted from the *NY Times* article and covering five industries, summarizes the performance of “green” and “not green” companies. It is evident from the table that the green companies showed a better return. Perhaps this is because engineers who are challenged to design products that are environmentally friendly are also challenged to think in a global way about safety, manufacturing, cost and other issues that impact efficiency and profitability.



Table 9.2. Green Begets Green: percent earnings 1994–97.

Industry	Company	Green	Not Green
Communications (COM)	NT	53.3%	
	AC		19.5%
Drugs (DRGS)	RER	59.2%	
	AL		33.7%
Utilities (UTIL)	EI	30.5%	
	DR		10.4%
Forest Products (FOR)	WAY	18%	
	LP		6.5%
Oil (OIL)	MOB	26%	
	UNC		17%

A bar chart display effectively presents these data. Although color can be expensive to print—relative to black and white—it can be worthwhile because of its impact on a presentation. (In this case, using green would be helpful.) Figure 9.2 and Figure 9.3 display the table information using vertically-oriented bars. There are two difficulties with the presentation of these data. The first is that two different plots are used, making a direct comparison difficult. The second is that two different vertical scales are used, creating the false impression that the “not green” companies provide greater or similar earnings.

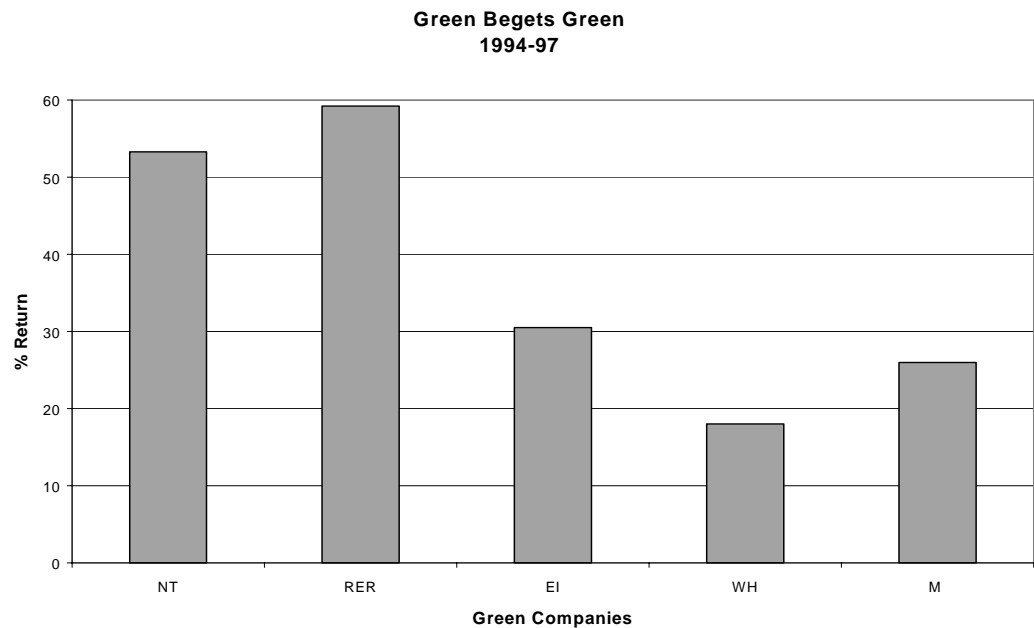


Figure 9.2. Vertical bar chart of “green” companies’ financial performance.

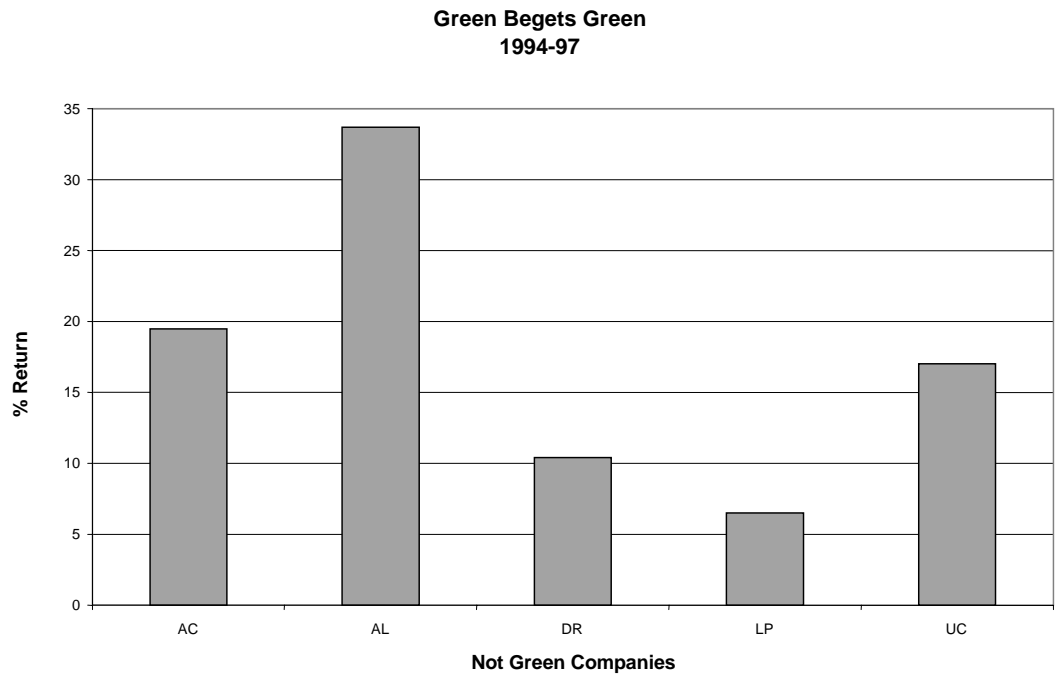


Figure 9.3. Vertical bar chart of “not green” companies’ financial performance.

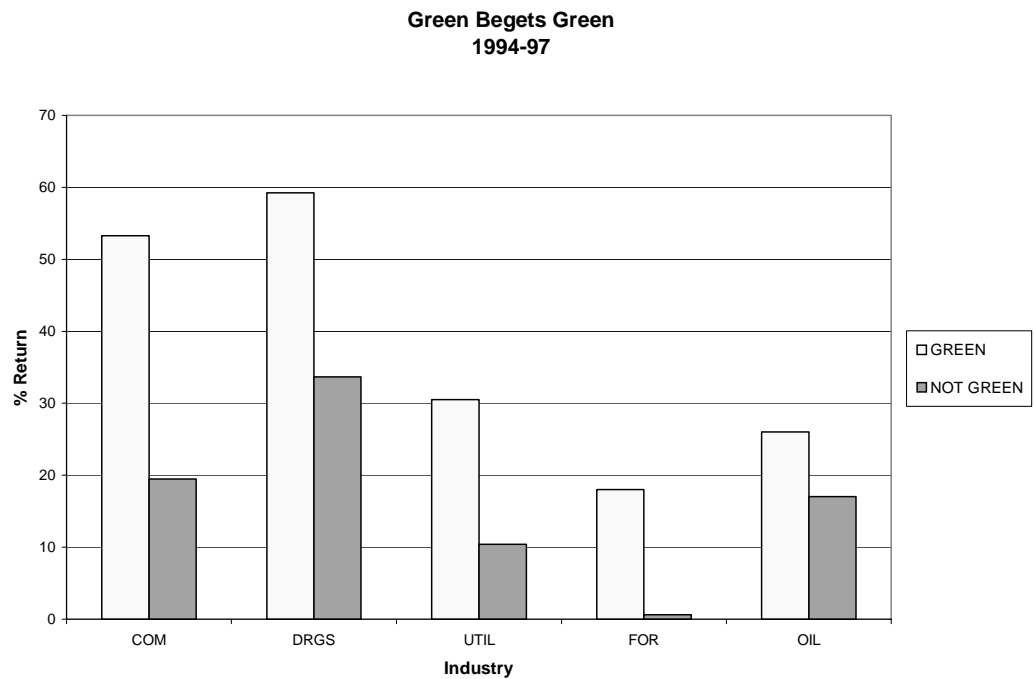


Figure 9.4. Vertical bar chart of “green” and “not green” companies’ financial performance.

In Figure 9.4, a combined plot directly compares the two classes of companies. This display has far more impact: the point that it pays to be environmentally friendly is made clear.

## TWO PARAMETER DATASETS SPANNING LARGE RANGES

Table 9.3 lists data for heartbeat frequency (beats per minute) and mammal mass (in kilograms). The series of plots that follow explore these data in a number of ways.

Table 9.3. Heartbeat frequency for mammals.

<b>Mammal</b>	<b>Heartbeats per minute</b>	<b>Mass (kilograms)</b>
Bat	750	0.0009
Least shrew	700	0.002
Door mouse	635	0.014
Mouse	650	0.025
Hedgehog	300	0.25
Guinea pig	210	0.4
Rabbit	140	2.5
House cat	120	2.27
Dog	150	12.5
Man	72	68
Hog	75	100
Donkey	47.5	400
Horse	35	400
Elephant	37	3,636
Whale	17.5	26,636

Note that the data ranges are quite large. There is nearly a factor of 50 in the range of heartbeat frequencies and over  $10^8$  in mass. The first plot shown in Figure 9.5 is a scatter plot (XY plot) with linear scales. Both data points and straight lines connecting the points are shown. This allows the reader to evaluate the data visually, while pointing out the relationship between data points. To present both measured data and model predictions, engineers commonly use this type of plot. Typically, when one variable is dependent on the other, such as  $y = f(x)$ , the independent variable is plotted on the horizontal axis, and the dependent variable is plotted on the vertical.

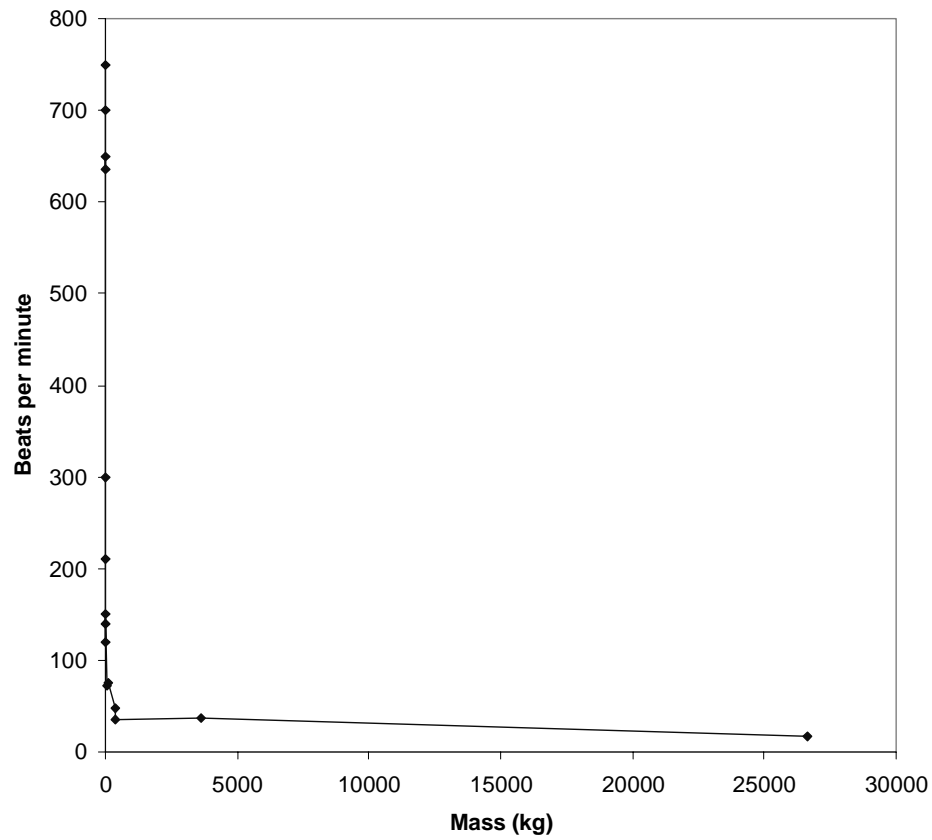


Figure 9.5. Scatter plot (using linear scales) of the heartbeat frequency of mammals.

Note that most data points in Figure 9.5 cannot be resolved visually, and only four points show their mass values clearly. This plot is certainly not a good choice for presentation or exploration of this data set. In Figure 9.6, a display using log axes is far more effective at presenting the data points so that all of the details are evident.

Further, a “best fit” model is presented in Figure 9.6, in the form of a plotted equation that approximates the data. “Best fit” means that the constants of the equation have been calculated to minimize the differences between the data and the best fit line. Such an equation is also known as a “linear regression” (whether or not it is a straight line), “least-squares fit” or “trendline.” The form of the equation must be selected first; i.e., a straight line ( $y = ax + b$ ), an exponential ( $y = ae^{bx}$ ), a polynomial ( $y = ax^2 + bx + c$ ), etc. Most data analysis and spreadsheet programs can then calculate the constants. Either the form of the equation can be suggested by a mathematical model of the physics represented by the data, or the form of the data can be used to suggest a mathematical model. If there is no model, it is *not* appropriate to present a best fit line just to make the plot look nicer. In the case of the data shown in Figure 9.6, a number of researchers have noticed the power law relationship ( $y = ax^b$ ) as a first step towards a mathematical model.

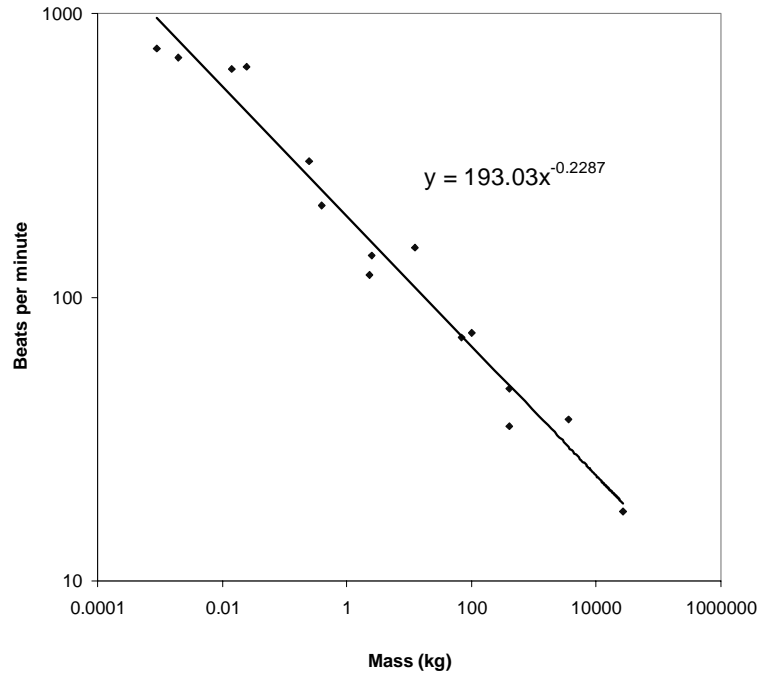


Figure 9.6. Scatter plot (using log-log axes) of the heartbeat frequency of mammals.

It may be of interest to try a semi-log plot, in which one axis uses a log scale and one axis uses a linear scale. The result is shown in Figure 9.7. This semi-log plot shows a best fit to the data for the frequency proportional to mass to the 1/4<sup>th</sup> power, which is consistent with the results from the earlier two figures. However, because of limitations in the way the best fit line is plotted by the program used to make the plot, the model appears to be a poor fit. Thus, a semi-log plot is not a good choice to best illustrate these data.

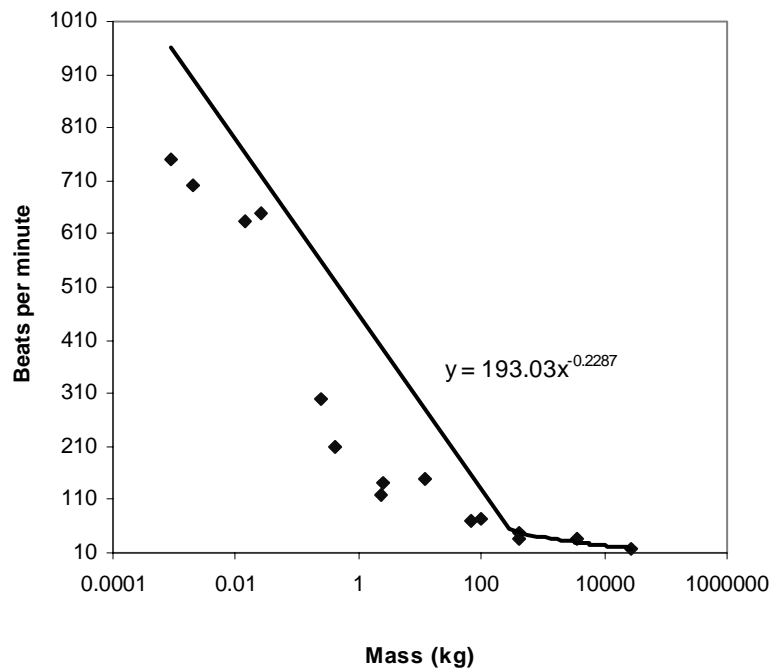


Figure 9.7. Scatter plot (using semi-log axes) of the heartbeat frequency of mammals.

## COMPARE AN ANALYTICAL EXPRESSION WITH EXPERIMENTAL DATA

Often a theory exists for predicting how a process changes with time, distance or some other variable. A frequent goal is to explore the limits of a theory or determine how accurately it applies over some range. In this example, there is an accepted expression for relating the dynamic pressure produced by a flow impacting a flat surface:

$$p = \frac{1}{2} \rho V^2$$

where  $p$  is the pressure,  $\rho$  is the density and  $V$  is the velocity.

This expression is Bernoulli's equation and has been derived from fluid physics, in contrast to the previous section where the equation was dependent on the experimental data. Measurements of pressure and velocity have been made using a highly accurate thermistor probe that can measure the flow speed to better than a centimeter per second. The pressure was measured using a transducer that has some noise estimated to account for an error of plus or minus a few microbars. A wind tunnel experiment provided data over a range of wind speeds up to four meters per second. A comparison of the measured pressure/ velocity relationship with what is expected from Bernoulli's equation will be used to validate the use of Bernoulli's equation for this flow configuration. Then, Bernoulli's equation can be used to guide the design of a simple mechanical indicator of wind speed. Table 9.4 contains computed and experimental values of pressure as a function of wind speed. Incidentally, tables represent the most accurate way of presenting data.

Table 9.4. Theoretical and experimental data on pressure as a function of wind speed.

Wind Speed (cm/sec)	Experimental Dynamic Pressure (microbars)	Theoretical Dynamic Pressure (microbars)
10	0.55	0.06
25	0.04	0.0375
50	1.45	1.5
100	5.8	6
150	13.3	13.5
200	25.5	24
250	40	37.5
300	70	54
350	72.5	73.5
400	98	96

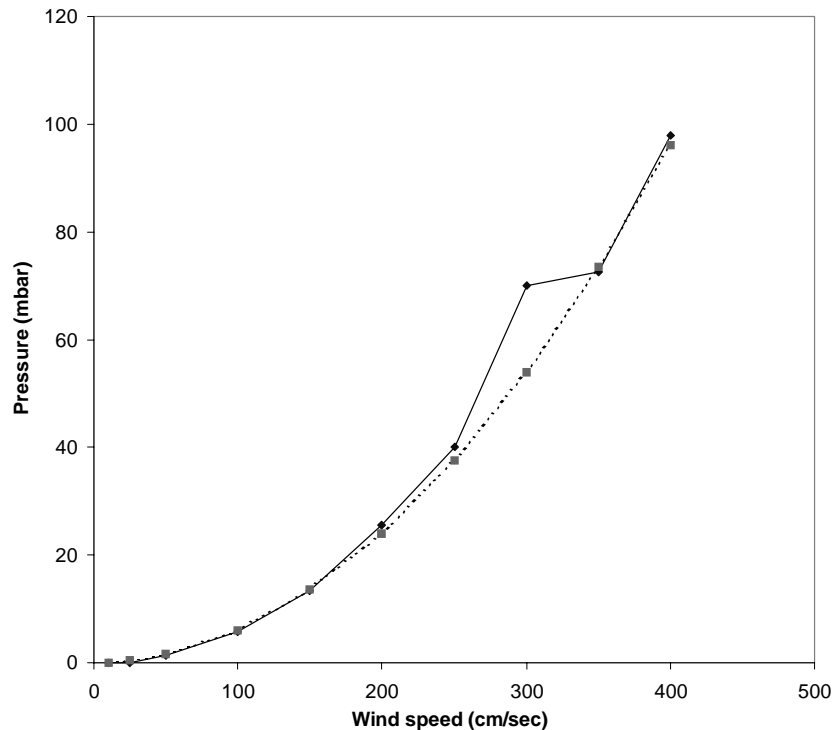


Figure 9.8. Scatter plot of predicted (dashed line) and experimental values (  $\blacklozenge$  ) of pressure vs. speed.

In Figure 9.8, the dashed line is the result of theory and the experimental data points are shown with error bars of plus or minus four microbars. The data point near 300-cm/sec-wind speed seems anomalous: the difference between the data and the prediction is larger than the uncertainty for which the measurements can account. In this case, the data should be checked. The deviation of this data point was not as evident from the tabular presentation. Even though the experimental data at very low wind speeds were not very reliable, the results can be used to defend extrapolating the theoretical curve with confidence. The conclusion that the equation is a good representation of the physics seems reasonable from this plot.

## REFERENCES

1. Tufte, E.R., *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, Connecticut, 1983, 197 pp.
2. Tufte, E.R., *Envisioning Information*, Graphics Press, Cheshire, Connecticut, 1990, 126 pp.
3. Tufte, E.R., *Visual Explanations*, Graphics Press, Cheshire, Connecticut, 1997, 156 pp.
4. Deutsch, C.H., "For Wall Street, Increasing Evidence that Green Begets Green," *NY Sunday Times*, Financial Section, July 19, 1998, p 7.

# Engineering Drawing

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## INTRODUCTION

Engineering drawing is a means of communication. “Communication” usually connotes writing and speaking, because they are more commonly employed in the course of everyday life. Writing and speaking, however, are insufficient to communicate design ideas. For one thing, the many languages around the world tend to inhibit written and verbal communication. It is more effective to transmit and receive design intent through drawings, sketches, pictures, graphs, etc. Graphic communication is clear, precise and unambiguous, conveying the same meaning anywhere in the world. This is increasingly important as the world develops into a global economy.

Both hand sketching and computer-aided design (CAD) are the two main tools to formulate and convey design intent. While CAD is an important tool for the engineering designer, hand sketching is still extremely important. The ability to clearly communicate design ideas on a blackboard or a piece of paper is an essential skill for an engineer. In the early conceptual stages of the design process, CAD can actually interfere with the creative flow of ideas.

Four aspects of engineering graphics are discussed in this chapter. First, the creation of pictorial drawings to show the three-dimensional (3D) form of objects is presented. The multi-view convention of engineering drawing is discussed next, followed by a discussion of the necessary dimensions and specifications that engineering drawings need to contain in order to portray clear communication of design intent. Finally, a broad overview of CAD, including an introduction to SolidWorks 98<sup>®</sup> software, is presented. For more in-depth coverage of engineering drawing, consult a comprehensive textbook [1].



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**PICTORIAL DRAWINGS**

A pictorial drawing is a 2D illustration of a 3D object. Many people have a difficult time mentally assembling the three standard engineering views (front, top and side) to “see” an object; pictorial drawings effectively convey its form, bringing objects to life. Because pictorials are so easy to visualize, they are often used for catalogs, maintenance manuals and assembly instructions.

Three different types of pictorials are commonly used:

- ◆ Isometric
- ◆ Oblique
- ◆ Perspective

A simple cube drawn in the three different types of pictorials is illustrated in Figure 10.1. The *isometric* pictorial is drawn with its three axes spaced  $120^\circ$  apart. The term isometric means “equal measurement,” indicating that the sides are all scaled by the same factor relative to their true length. Parallel lines defining edges on the object are also parallel on the isometric drawing. Drawing paper with isometric axes—available in good office and drafting supply stores—greatly facilitates drawing an isometric pictorial. Also, most 3D CAD programs generate isometric views automatically.

*Oblique* pictorials are drawn with the front view shown to true scale in the x-y plane. Oblique lines, which represent the z-axis, are projected at some angle, usually  $30^\circ$ -  $45^\circ$ . Parallel lines defining edges on the object are also parallel on the oblique drawing.

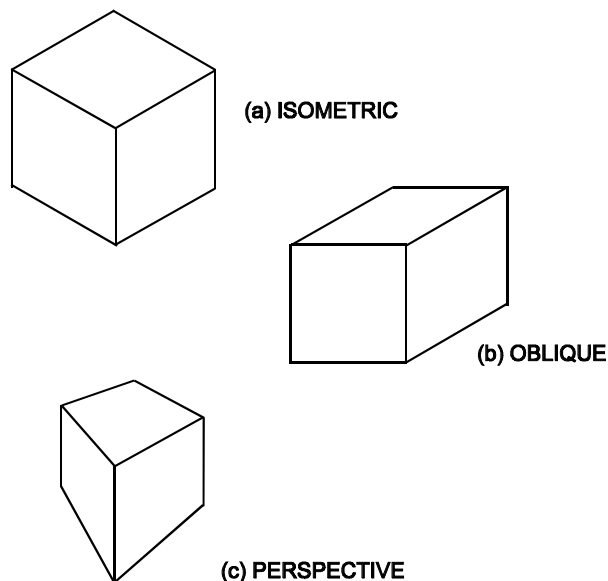


Figure 10.1. A cube represented by isometric, oblique and perspective pictorials.

A *perspective* drawing represents most realistically what is actually seen. Artists draw or paint using perspective style. While engineers sometimes represent their designs in this style, it is the most difficult of the three types of pictorials to master. In perspective drawing, there is no well-

defined coordinate system. Parallel lines converge to a vanishing point as they recede from the observer. The use of converging lines instead of parallel lines and the foreshortening of dimensions gives the drawing perspective, but makes it difficult to scale accurately.

### Isometric Drawings

In an isometric pictorial, the three axes are equally spaced  $120^\circ$  from each other, as shown in Figure 10.2. The axes divide the paper into three zones that represent three views of the object. If the axes make a Y, as in Figure 10.2, the view is downward toward the object. The top view is drawn in between the top branches of the Y. The left-side view appears to the left of vertical axis, and the front view is displayed to the right of this axis.

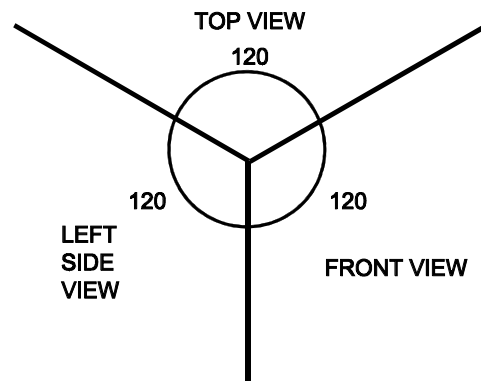


Figure 10.2. Isometric axes equally spaced at  $120^\circ$  angles divide the drawing into three regions: front, top and left-side views.

The isometric pictorial in Figure 10.3 was drawn on isometric paper, which provides evenly spaced lines parallel to the isometric axes to facilitate hand sketching, either freehand or guided by a straight edge. Also, Figure 10.3 depicts the three orthogonal views of the same object, with corresponding planes numbered in circles. A good exercise is to re-create the isometric view from the three views given.

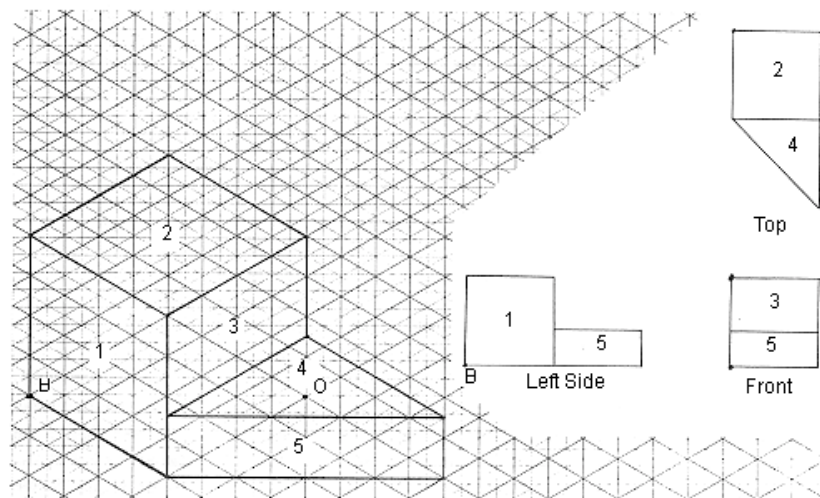


Figure 10.3. Isometric pictorial of a block with a step and tapered side.

Circular features appear as ellipses in isometric drawings. Figure 10.4 illustrates the isometric pictorial of a right-circular cylinder of diameter  $D$  and height  $H$ . Note that the circular-top view appears as an ellipse that is tangent to the isometric axes at four points. The major axis of the ellipse is horizontal, and the minor axis is vertical. Figure 10.5 shows how circles in the top, left and front views appear as ellipses on an isometric pictorial.

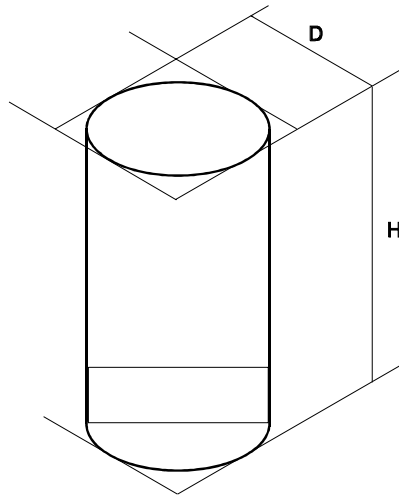


Figure 10.4. Isometric pictorial of a right-circular cylinder of diameter  $D$  and height  $H$ .



Figure 10.5. Circles appear as ellipses in an isometric drawing.

### **Oblique Drawings**

Oblique drawings are the easiest type of pictorial to draw by hand, but they are also the least realistic. Oblique and isometric pictorials are similar because both use parallel lines in constructing the three views. The difference between oblique and isometric pictorials lies in the definition of the axes. Oblique drawings use an  $x$ -,  $y$ - and  $z$ -coordinate system as shown in Figure 10.6. The three coordinate axes divide the sheet into three regions for drawing the front-, top- and right-side views. With the axes defined as shown in Figure 10.6, the object is viewed from above, looking from right to left. The  $z$ -axis, which is the receding axis in Figure 10.6, is drawn at a  $45^\circ$  angle relative to the  $x$ -axis; however, other angles such as  $30^\circ$  or  $60^\circ$  are often employed.

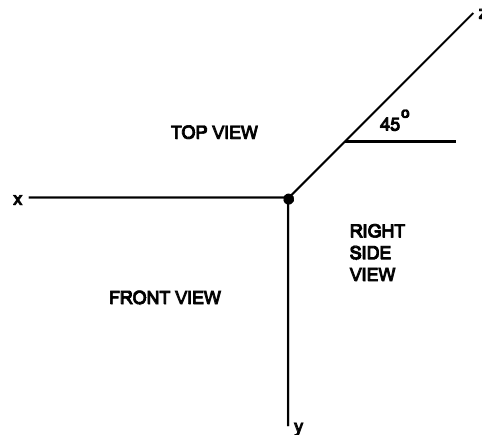


Figure 10.6. Coordinate system for oblique pictorials.

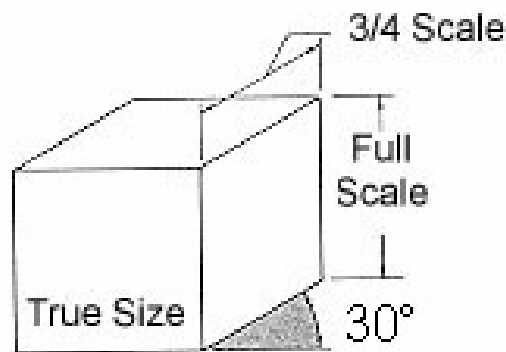


Figure 10.7. Oblique pictorial view of a cube.

Figure 10.7 shows a simple oblique pictorial of a cube. The front view is drawn full size, which means that horizontal and vertical dimensions may be accurately scaled. The z-axis depth, however, is usually drawn at a lesser scale because drawing its true size creates an illusion of exaggerated depth. In this case, the receding z-axis is drawn at  $30^\circ$  to the horizontal. Figure 10.8 is a more complex oblique drawing of two connected blocks, along with the three orthogonal views of the same object, with corresponding planes numbered in circles. A scaling factor of  $\frac{3}{4}$  is used for the depth for better realism.

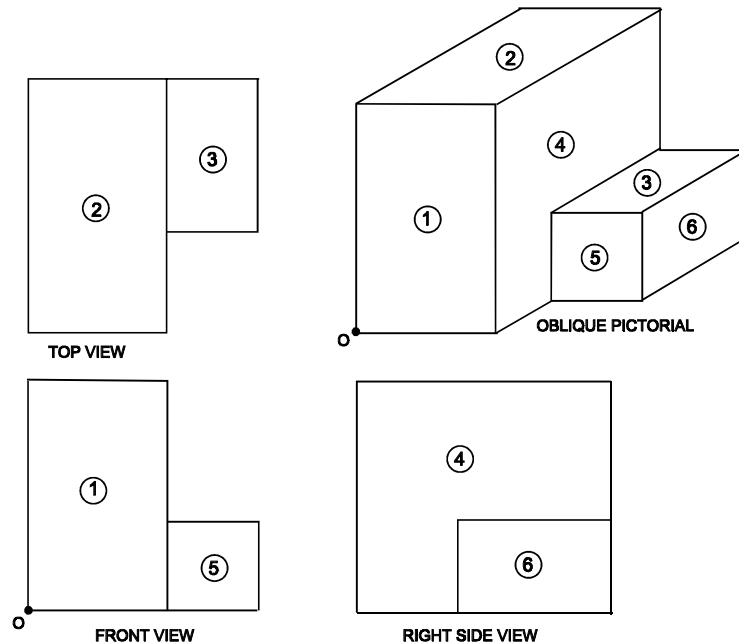


Figure 10.8. Three-view drawing of a pair of connected blocks and an oblique pictorial of the same object.

Figure 10.9 illustrates how circles appear in oblique pictorials. Circular features in the front view appear as true circles, which facilitates hand drawing. A compass or circle template can be used to accurately depict the circular feature. However, circular features on the top or side planes would appear to be elliptical. Notice that only a portion of the circle formed where the hole intersects the back plane of the object is visible in Figure 10.9(b).

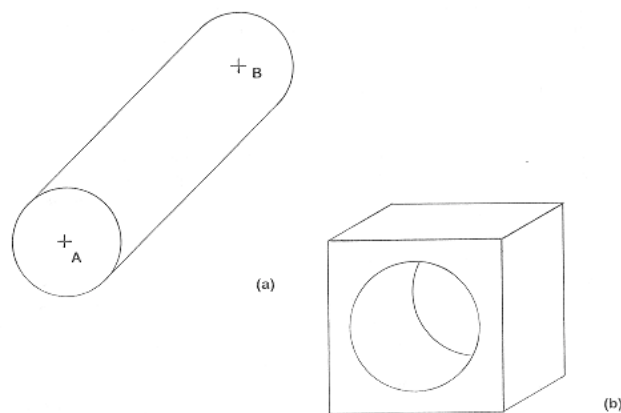


Figure 10.9. Oblique pictorials. (a) Right-circular cylinder (b) Rectangular block with circular hole.

## Perspective Drawing

Prior to the Renaissance in the 15<sup>th</sup> Century, paintings looked flat and unrealistic. Then, artists discovered how to create drawings that represent on a 2D medium what the human eye (or a camera) sees. The role for perspective drawing in engineering is primarily to communicate to others how objects appear.

The major difference distinguishing perspective drawings from oblique and isometric pictorials is that in the latter, the lines defining edges (e.g., top and bottom) are parallel to the axes, whereas parallel lines converge in perspective drawing. In Figure 10.10, for example, the railroad tracks converge to a single point and the ties appear to get shorter, even though in reality the tracks are parallel and the ties are all the same lengths.



Figure 10.10. Parallel tracks converge and the ties appear to shorten as they recede in this photograph of railroad tracks.

Four terms are useful in describing perspective drawing:

1. *Picture plane*: the surface (i.e., the sheet of paper) of the pictorial. The edges of the paper represent the window through which you “see” the 3D object.
2. *Horizon line*: divides the sky and the land or the sea if outdoors. The horizon line is at the eye level and changes with elevation. In a room where the true horizon cannot be located because the walls block the view, assume a horizon line at about eye level.
3. *Viewing point* and *direction of view*: the location of eyes relative to the object. Objects can be viewed from left to right, right to left, downward, upward, etc. How an object appears in a drawing changes markedly depending on these parameters.
4. *Vanishing point*: the point at which parallel lines converge as they recede into the distance. The vanishing point is where the tracks appear to meet in Figure 10.10.

### One-Point Perspective

An object can be represented using one-, two- or three-point perspective. In one-point perspective, the true width and height of an object in the front view are placed in the picture plane as illustrated in Figure 10.11. A horizontal construction line represents the horizon. The location of this line depends on the viewing point and the viewing direction. In Figure 10.11, the block is viewed straight on and from above. The elevation is taken into account by raising the horizon line. The vanishing point is centered on the horizon line because the view of the block is straight on. Construction lines are drawn from the vanishing point to the top corners of the block in the front view. The back edge on

the top view is drawn parallel to the front top edge to establish the depth of the block. Note that the back edge is much shorter in length than the front edge. The shortening of the lines on the recessed planes and the converging edges give the illusion of the third dimension.

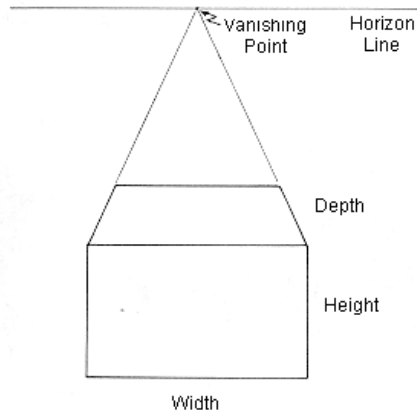


Figure 10.11. Simple box drawn in one-point perspective.

Another example of one-point perspective is the drawing of a coffee table, as shown in Figure 10.12. The front of the table is drawn to scale in the picture plane. Coffee tables are low, so the viewpoint is chosen looking downward, but straight on toward the top surface of the table. The horizon line is drawn at eye level aligning the vanishing point with the center of the table. Light construction lines connect the corners of the table to the vanishing point. These construction lines define several triangles. The larger outer triangle is used to define the top surface, while the smaller triangles are used to draw the bottom edges of the legs visible under the table.

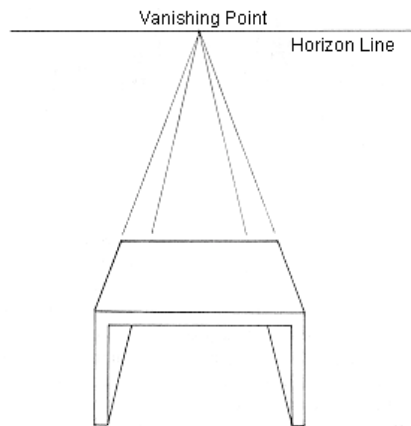


Figure 10.12. One-point perspective of a coffee table.

### **Two-Point Perspective**

One-point perspective is useful when an object is viewed straight on so that its front view lies in the picture plane. However, if the object is rotated so that neither the front or side view is in the picture plane, as illustrated in Figure 10.13, a two-point perspective is required.

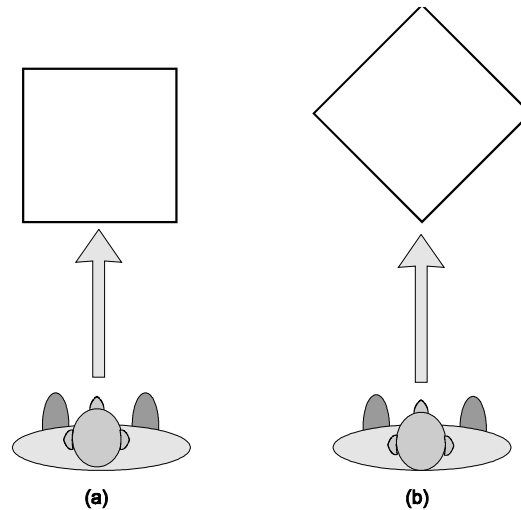


Figure 10.13. The direction from which an object is viewed controls the degree of perspective: (a) Straight on—use one-point perspective (b) Angle view—use two-point perspective.

Consider a rectangular block that is viewed diagonally, so that only one vertical edge lies in the picture plane. Figure 10.14 shows the two-point perspective and its construction. First, an elevated horizon line is drawn because the viewpoint is above the block. Two vanishing points (VP-R and VP-L) are drawn; spacing these points at different distances reflects viewing the block from a slight angle. Then, a true-length vertical line is drawn (1), and its endpoints are connected to both VP-R and VP-L with construction lines. The two vertical surfaces can then be drawn (ABCD and ABEF). Finally, points D and F are connected to the appropriate vanishing points to define the top surface. Notice that in one-point perspective, two edges of the top cube face are parallel and two are not (Figure 10.11), while in two-point perspective, none of the top edges are parallel (Figure 10.14).

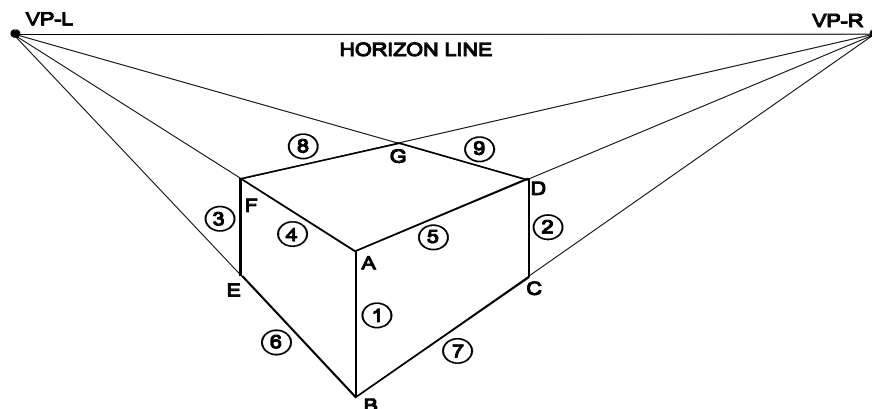


Figure 10.14. Rectangular block shown in two-point perspective.

Figure 10.15 shows a two-point perspective drawing and the construction of the coffee table previously shown in one-point perspective. The front-most vertical edge is drawn true length, but the vertical lines which define the width and depth of the table are drawn “by eye” to obtain correct proportions for the table.



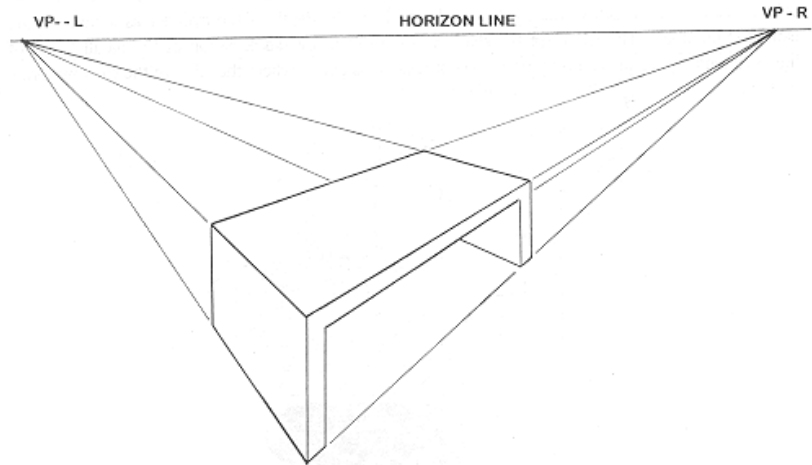


Figure 10.15. Two-point perspective drawing of a coffee table.

Three-point perspective is used when an object is very tall. Architects drawing a city view with skyscrapers use three-point perspective and taper the building as it extends into the sky. Engineers usually deal with smaller objects that can be represented in pictorials with either one- or two-point perspective. Therefore, three-point perspective is not described in this chapter, but Powell [2] provides an excellent in-depth description of perspective drawing.

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## **MULTI-VIEW DRAWING**

Multi-view engineering drawings are the standard format for communicating design details from the designer to the manufacturer. A multi-view drawing consists of as many 2D views of a part as are necessary to define it completely and unambiguously. A multi-view drawing is universal shorthand that contains all the information necessary to allow a part to be accurately and repeatedly fabricated. The ability to create and read engineering drawings is an important skill for design engineers. Even if the same person is designing and fabricating the part, which is often the case for student projects, an accurate engineering drawing is an invaluable tool for both design and manufacturing.

Consider a rectangular block with a slot, shown in an isometric pictorial in Figure 10.16. The arrows represent different directions of viewing the block, which isolate the front, side and top views. A three-view drawing of the block is shown in Figure 10.17. The single pictorial drawing of the block is now represented by three different 2D drawings representing the front, top and side views. These three drawings completely define the proportions of the block, its size and the location and size of the principle feature (the slot). Each view is accurately scaled.

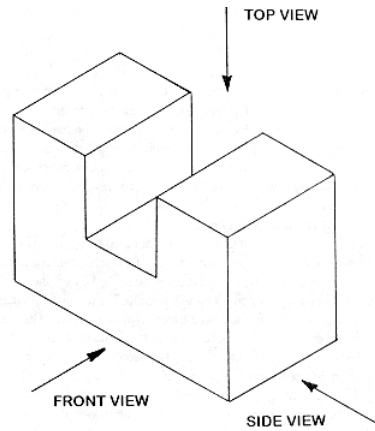


Figure 10.16. Isometric pictorial drawing of a block with a slot.

The arrangement of the views is important because anyone reading the drawing will assume that this convention is being followed. A drawing that does not follow convention may be confusing. The front view is placed in the lower left-hand corner of the paper, the top view is directly above it, and the side view is directly to the right of the front view. This arrangement is called “orthographic projection,” allowing dimensions to be projected from one view to another. The width of the object is shared in both the top and front views, and the front and side views share the height dimensions of the block.

Figure 10.17 also illustrates another convention in engineering drawings; namely, solid lines are used to show lines that are visible in a view, and dashed lines represent edges that are hidden in that view. For example, all of the edges formed by intersections of planes are visible in the front and top views, so all the object lines are solid. However, in the side view, the line formed by the inside corner of the slot is hidden from view. Adding the dashed line to the side view clarifies the drawing.

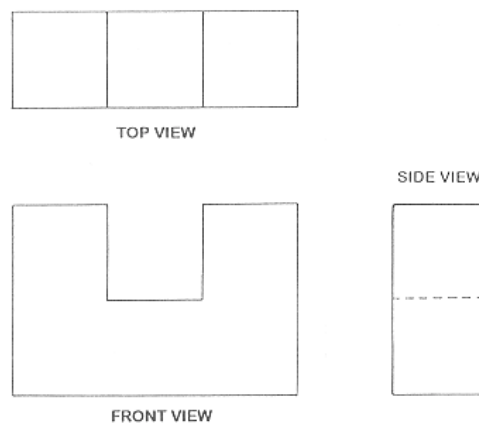


Figure 10.17. Three-view drawing of the block in Figure 10.16.

Drawings differ from photographs by the use of dashed lines to indicate hidden features. Figure 10.18 shows the conventional meanings of different types of lines.

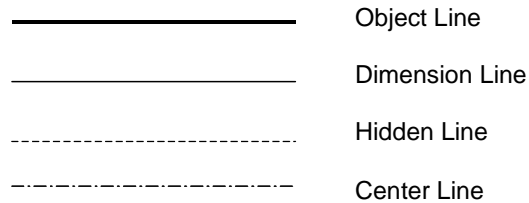


Figure 10.18. Conventions for line styles in engineering drawings.

Next, consider a block with both a slot and a step, as shown in Figure 10.19. Figure 10.20 shows the three-view drawing for that part. The front view is drawn first, in the lower left-hand corner of the paper. Even with the step and slot, the outline of the block is shown as a rectangle in the front view. The lines defining the slot and step are added next, completing the front view. The top view is constructed next, based on the thin construction lines projecting upward, as well as the known dimensions of the depths of the block, slot and step. Finally, the side view is drawn, based on the information contained in the front and top views. In this case, projecting the top view to the right to intersect the 45° construction line, and then projecting downward helps to define the geometry of the side view. Notice the hidden line, which again shows the depth of the slot.

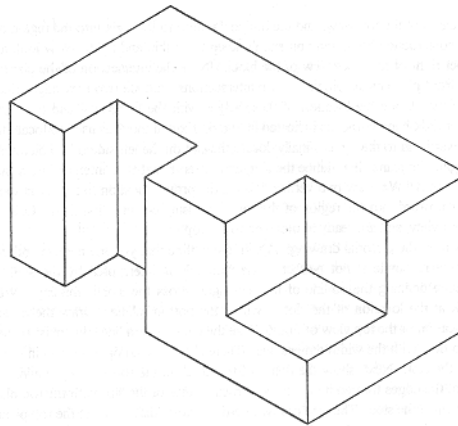


Figure 10.19. Isometric drawing of a block with a slot and step.

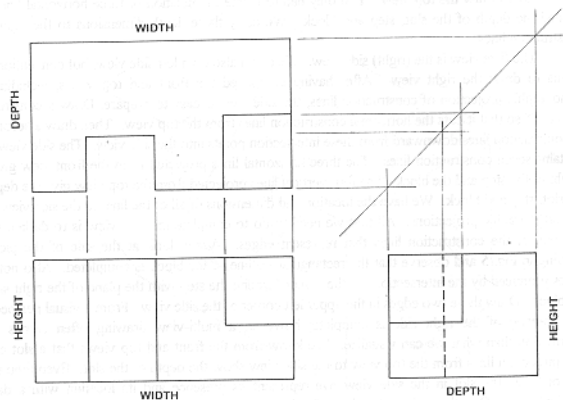


Figure 10.20. Three-view drawing of the block shown in Figure 10.19.

As a final example, consider the rectangular block with a step and a hole, shown in Figure 10.21. The corresponding three-view drawing is shown in Figure 10.22. The circular boundary outlining the step is evident only in the top view. Instead, the rightmost projection of the step shows in the front view as a single vertical line. Note the use of centerlines (long and short dashes) to define the location of the center of the hole in the top view. Centerlines are a form of shorthand which tell readers that the feature defined by the vertical hidden lines in the front and side views is a circular hole, as opposed to a square hole.

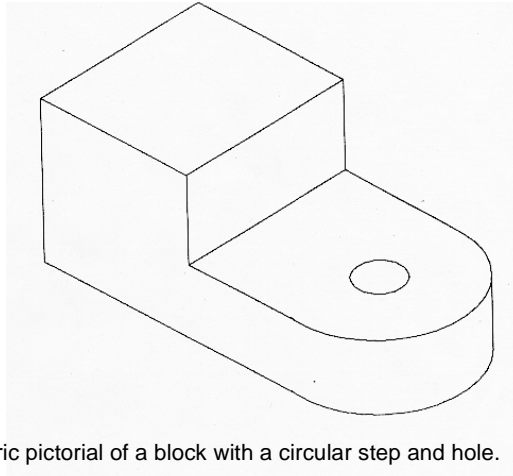


Figure 10.21. Isometric pictorial of a block with a circular step and hole.

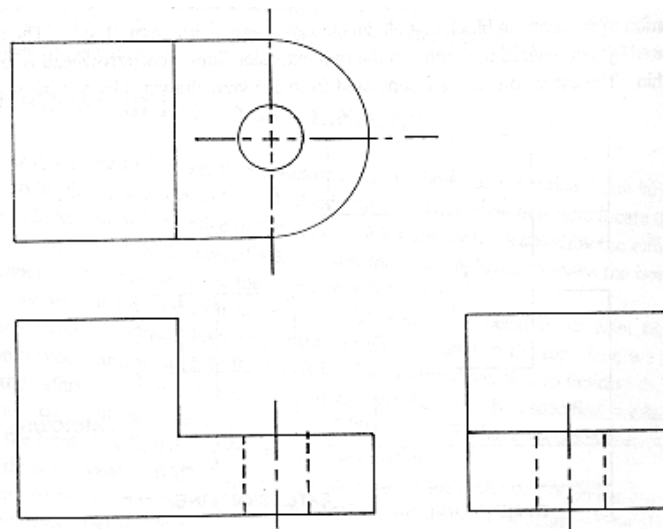


Figure 10.22. Three-view drawing of the block in Figure 10.21.

## DIMENSIONING

Multi-view drawings are drawn to a precise scale, so theoretically they contain adequate information about the size of parts. However, for a variety of reasons, an engineering drawing must also contain explicit numerical dimensions that precisely define its geometry.

## Tolerances

No part can be manufactured *exactly* to specification, so designers dimension components so that they will function correctly when assembled into a system. Associated with dimensions are *tolerances*, the allowable variation in dimensions that still creates a functioning product. Tolerances can be stated explicitly; e.g., a dimension of  $X = 2.500 \pm .001$  in. says that the part is acceptable as long as dimension  $X$  lies between 2.499 and 2.501 in. It is important to realize that the tolerances are implicit, even if they are not explicitly stated. Table 10.1 gives commonly agreed-upon values for implicit tolerances based on the number of significant figures in the dimension value. CAD systems have the capability to change the decimal precision of dimensions to imply the correct tolerance.

As tolerances become tighter, the manufacturing cost increases significantly. Therefore, designers use tolerances that are as loose as possible, providing the product will still function correctly.

Table 10.1. Tolerances implied by dimensional precision.

Dimension Precision	Implied Tolerance
Fractional	$\pm 1/64$ in.
X.X	$\pm .05$ in.
X.XX	$\pm .01$ in.
X.XXX	$\pm .005$ in.

## Dimensions

Dimensions are important from two points of view. The designer of a new component starts with a blank sheet of paper and assigns dimensions that optimize the design of the component. In redesigning an existing component, the designer begins with the drawing (or CAD model) of the part and modifies existing dimensions as appropriate to refine the design. Dimensions are also critical for a

person using the drawing, as s/he may manufacture the part, assemble the product that incorporates the part or repair the product. Many people not involved in the design may use the single engineering drawing that defines the part; therefore, precise definition of the part is critical.

Dimensions have been added to the part shown in Figure 10.23 to illustrate several conventions about dimensioning. Note that units are not specified on each dimension value. Rather, they are specified in the drawing block, described in detail in Figure 10.24. Dimension

lines and extension lines (the lines to which the arrowheads point) are usually fine lines, as opposed to the heavier lines that define the object. In a CAD drawing, line weights can be set to follow this convention.

Holes and other circular features are located from an edge of the part to the centerline of the hole, because the drill that is used to make the hole enters the part at the intersection of centerlines.

### Rationally-Based Dimensions

Whenever possible, dimensions should be rationally based on engineering analysis. For example, the size of a round steel rod to support a load is based on the size of the load, the strength of the steel and an appropriate factor of safety.

The designer should be aware, however, that many engineering materials come already formed in standard sizes.

In the example above, if the engineering analysis indicates that the diameter of the rod should be 0.237 in., then the designer should specify 1/4 in. rod (0.250 in.), rather than going to the trouble (and expense) of machining down a 1/4 in. rod to the exact size.

But note that the center of a hole, after it has been drilled, is an imaginary point in space. The symbol R denotes the radius of an arc. Complete circular features (e.g., holes or cylinders) are specified by their diameters and indicated by the symbol  $\phi$ . Circular features are typically dimensioned in the view in which they appear circular (e.g., the top view on Figure 10.23).

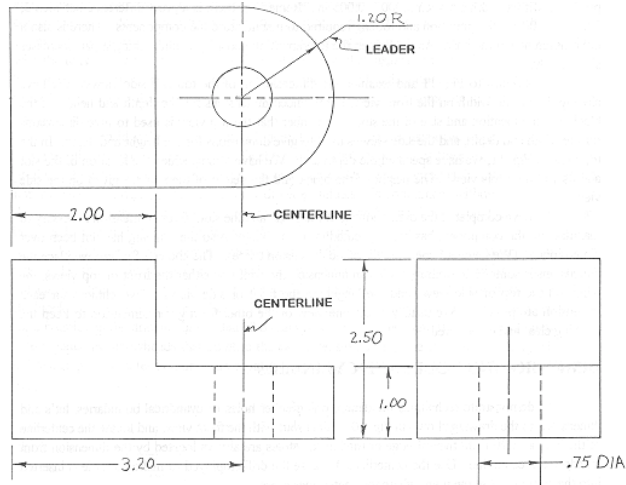


Figure 10.23. Dimensioning example showing centerlines, leaders, and radius and diameter specifications.

While it is important to completely dimension a part, over-dimensioning (specifying the same dimension twice) should also be avoided. Because of the tolerances associated with actually producing any dimension, having multiple dimensions can lead to a confusing situation in which one dimension is satisfied but the other is not. However, it is good practice to give the overall dimensions of a part (length, width and depth), because it clearly tells the fabricator the size of material with which to begin. For example, the depth of the block shown in Figure 10.23 can be computed by multiplying the radius by two ( $1.20 \times 2 = 2.40$ ). But to avoid confusion, this information has been added to the side view. Redundant dimensioning is avoided by adding the symbol REF, which indicates to the fabricator that this is a dimension to be used only for reference purposes. The specified radius of 1.20 in. is the critical dimension in this case. If not otherwise specified, Table 10.1 indicates that the tolerance for this dimension should be held to  $\pm .01$  in. A parametrically-based CAD program, like SolidWorks, automatically tells the designer if a part is under-defined, fully-defined or over-defined.

Dimensions can be placed arbitrarily on a drawing, and most dimensions could appear in at least two different views. The general rule is to locate dimensions so as to keep the drawing clear and uncluttered; dimensions should not be located on the part itself. CAD packages, like SolidWorks, that support dimensioning also allow them to be easily moved and/or modified (e.g., typeface style or size, dimensional precision, explicit tolerances, etc.) after they have been added to a drawing.

### Drawing Blocks

The drawing block serves an important function on an engineering drawing by specifying many details that are necessary to define the part. As illustrated in Figure 10.24, the drawing block is

located in the lower right-hand corner of the drawing, just inside the border. Some of the information conveyed in a typical drawing block is common to all of the drawings produced by a specific company, and some is unique to the individual drawing.

Information commonly shown in the drawing block includes:

1. Name of the company issuing the drawing.
2. Name of the part that the drawing defines.
3. Scale used in preparing the drawing.
4. Tolerances to be employed in manufacturing the part.
5. Date of the completion or the release of the drawing.
6. Material to be used in manufacturing the part.
7. Heat treatment of the part after manufacturing.
8. Units of measurement to be used in manufacturing the part.
9. Initials of the individual preparing the drawing.
10. Initials of the individual checking the drawing.
11. A drawing number that uniquely identifies the drawing.

<b>COLLEGE OF ENGINEERING</b>			
<b>PART NAME</b>			
<b>SCALE</b> FULL	<b>TOLERANCES</b> FRACTIONS $\pm 1/64$ DECIMALS $\pm 0.005$		
<b>DATE</b> 9/9/98	<b>MATERIAL</b> CRS	<b>HEAT TREAT</b> NONE	<b>UNITS</b> IN.
<b>DR</b> JWD	<b>CK</b> GZ	<b>DRAWING NO.</b>	

Figure 10.24. The Drawing block summarizes essential information about the part.

CAD programs usually have pre-defined drawing blocks in which the designer can store information common to most drawings and easily add the information specific to each individual drawing. The specific format is not as important as the information the drawing block conveys.

## COMPUTER-AIDED DESIGN (CAD)

Historically, engineering drawings were done by hand and in pencil so that they could be changed. Because of the requirements for precision, this usually involved many hours of laborious work with drawing instruments (e.g., T-square, compass, triangles, etc.) on a specially designed drafting table. Drawings were difficult to alter, which discouraged iteration to optimize a design concept. Most drawings were 2D multi-view drawings; realistic images of the 3D part were usually left to photographs or technical illustrators.

One of the first uses of computers as an engineering tool was to simply automate the drafting process. Early CAD software programs (e.g., AutoCAD) had the capability to precisely create and connect drafting entities like lines, circles and arcs, first in a 2D space, and then later in a full 3D space. The 3D models of parts that could be created were restricted to these basic elements which defined the edges and intersections of planes and were referred to as *wire frame models*.

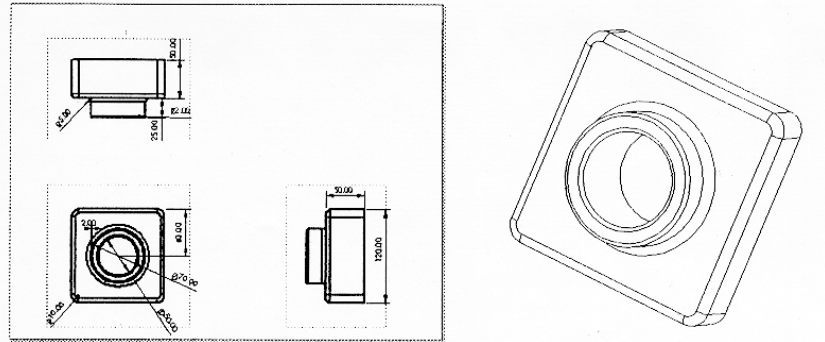


Figure 10.25. 2D multi-view drawing and wire frame model.

Recent advances in computer hardware and software allow a part to be represented as a full 3D *solid model*, which is a 3D digital representation of the part, instead of just its edges (Figure 10.26). This offers tremendous advantages to the designer, including the capability of performing complex *finite element analysis* to predict the stress and strain inside the part or the flow of heat through it. Another advantage that solid models offer is the capability to be automatically produced by computer-controlled machine tools, known as *computer-aided manufacturing (CAM)*.

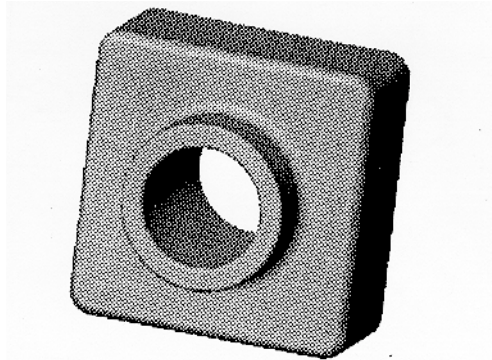


Figure 10.26. 3D solid model of the part shown in Figure 10.25.

Solid modeling changes the way designers work. The designer starts with a *sketch*, manipulates the sketch to form *features*, then builds *parts* from those features. The 2D multi-view drawings, which still play a role, are created last to document the end result of the design process.

### **SolidWorks 98<sup>®</sup>**

Created by engineers from Parametric Technology Corporation (producers of ProEngineer<sup>®</sup>) and Autodesk<sup>®</sup> (producers of AutoCAD<sup>®</sup>), SolidWorks is mechanical design-automation software



that operates under the Microsoft Windows<sup>®</sup> graphical user interface. It is extremely powerful, yet relatively simple to learn if the designer has a working familiarity with Windows. This section presents a broad overview of the SolidWorks software package. To learn to use the software, consult the Tutorial [3] or User's Guide [4]. A novice user can create the part shown in Figure 10.26 in less than 40 minutes by following the Tutorial.

A SolidWorks 3D model consists of *parts*, *assemblies* and *drawings* (Figure 10.27). Any changes made to one view are automatically updated in the other views.

- ◆ A *part* is a completely defined single component, made from a single material. The creation of parts is the first step in the design process.
- ◆ An *assembly* is a combination of parts that are connected together as they would be in the physical system. Parts are mated together in an assembly according to kinematic constraints that define how parts can move relative to each other. This allows fully mobile 3D mechanisms to be simulated, as well as checking for how individual parts will fit together in the actual assembly.
- ◆ A *drawing* is a conventional 2D multi-view representation of a part or assembly. It typically contains the dimensions and other information (material, heat treatment, etc.) necessary to actually fabricate the part.

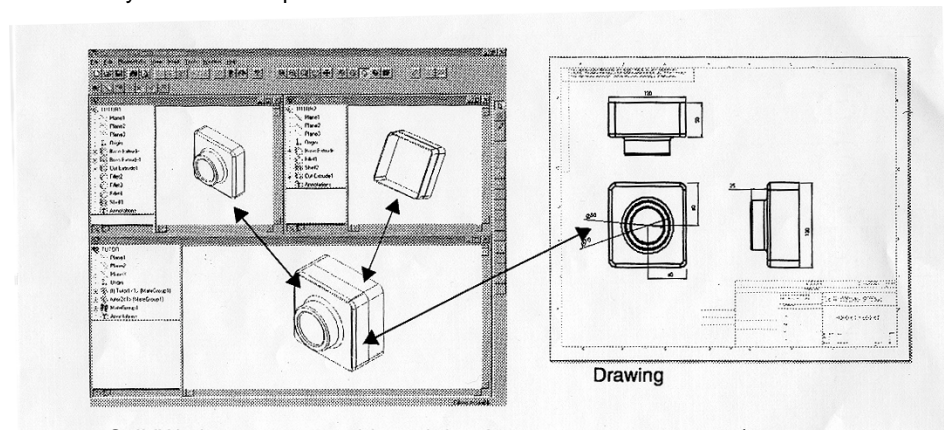


Figure 10.27. SolidWorks parts, assembly and drawings.

Other useful capabilities supported by SolidWorks include:

- ◆ Creating parts by stamping and then bending *sheet metal* (Figure 10.28).
- ◆ Creating *molds* from solid models that could be used, for example, to mass-produce plastic parts by injection molding.
- ◆ Creating photo-realistic *renderings* of models.
- ◆ Using a design table, which allows an easy way to design *families of parts* with similar features, but different dimensions (Figure 10.29).
- ◆ Modeling assemblies that are fabricated by *welding* individual parts together.

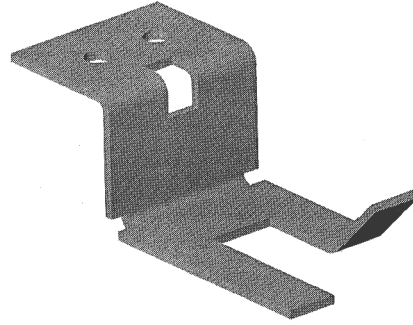


Figure 10.28. Sheet metal part modeled in SolidWorks.

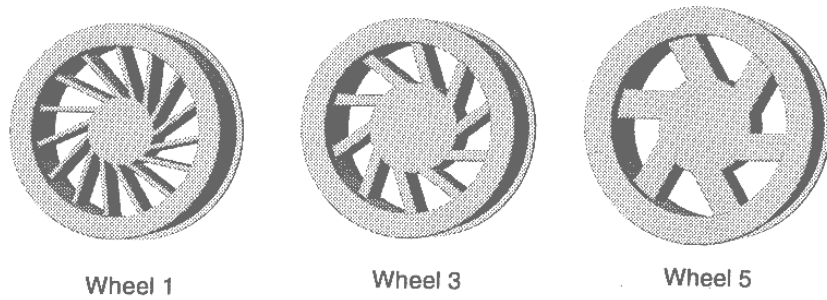


Figure 10.29. Family of parts modeled using a design table.

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## REFERENCES

1. Earle, J. H., *Engineering Design Graphics*, Addison Wesley, Reading, MA, 1983.
2. Powell, W. F., *Perspective*, Walter Foster Publishing, Laguna Hills, CA, 1989.
3. *Learning to Use SolidWorks 98*, SolidWorks Corporation, Concord, MA.
4. *SolidWorks 98 User's Guide*, SolidWorks Corporation, Concord, MA.



## **INTRODUCTION**

Writing well, a basic requirement for most engineering jobs, is an important component of communicating well. Most students are surprised by the amount of writing that is required in an introductory engineering projects course as it is certainly beyond the demands of typical engineering courses. Surprise is realized again when new engineers find themselves assiduously writing at their jobs. Most engineers leave the university prepared to perform tests, simulations, analyses and calculations; they do not expect to write reports, documentation, memorandums and executive summaries. Thus, the heavy emphasis placed on writing in this course reflects the requirements of real-world engineering jobs.

Students also find that the style of writing in introductory engineering projects courses is quite different from that of other, non-technical classes. *Concise*, *factual* and *complete* are the desirable attributes of good technical writing for introductory engineering projects courses. To write clearly and factually requires practice and iteration. Implicit in this statement is that a great deal of effort is needed to produce useful engineering documentation. For most engineers, this effort is equivalent to time: time spent on gathering information or data, on writing, and on editing and re-editing the technical document.

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## **WHO READS A TECHNICAL REPORT?**

A technical document is a vehicle to convey facts to the reader. Thus, the engineer aims to share information, give knowledge, and tell others about things they need or want to know. In a typical engineering position, managers read written documents to learn the results of a study, the engineer's recommendations for work, or the cost of a proposed design or project. If the job is related to research, journal articles are published to document the findings and are read by technical peers. Similarly, the best target audience in an introductory engineering projects course is *not* the instructor, but other students who have a rudimentary knowledge of the topic or the course. Writing for a

peer audience means the writer must include all the important details of the topic. In contrast, when the writing assignments are targeted for the instructor, students often exclude important details because it is assumed that the instructor already “knows” specific facts. For course sections that are client-based, reports are written for the clients. Consequently, it is important to write effectively to communicate ideas to a specific audience.

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## **THE WRITING PROCESS**

Writing follows a specific, iterative process to organize, compose and edit written reports. These steps are shown in the following diagram.

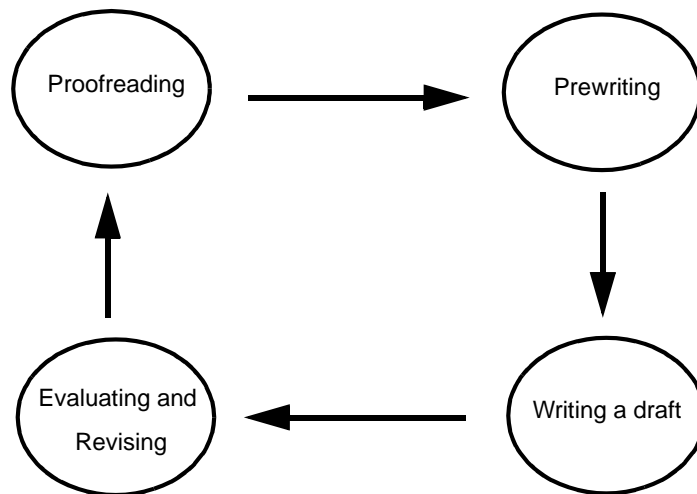


Figure 11.1. A schematic depiction of the iterative steps used in the writing process.

While not required, the writer follows these steps to review and edit each version of the document more than once. In developing the final version, the writer has the primary goal of producing a polished, comprehensive document that has no spelling or grammatical errors. In other words, the report is one in which pride and accomplishment are evident in the words, format and figures.

### **Prewriting**

The goal of prewriting, or developing the initial versions of the document, is to make sure that all ideas, drawings, tables, references and results pertaining to the subject are brought forth for consideration. Several techniques may be used to elicit ideas and develop the main themes. The writer uses a notebook or computer software to collect the prewriting ideas.

#### ***Brainstorming, Free-Writing and Clustering***

In the prewriting stage, all ideas are documented in an informal, unstructured manner. By *brainstorming*, the writer uses words or phrases to capture potential ideas. Nothing is eliminated at this time from consideration for inclusion in the document. When *free-writing*, the writer states or develops ideas further with full sentences. At this time, the writer notes if information or answers to ques-

tions require additional investigation. Sometimes *clustering* shows the development of ideas more efficiently than either brainstorming or free-writing. Less formalized than an outline, clustering is a technique that encourages the formulation of a logical sequence of ideas. For example, in Figure 11.2, clustering is used to collect the main topic ideas for a document discussing the development of a new heater. The writer notes the ideas associated with the purpose, the choice of material or shape, and the cost considerations. Some ideas are more fully developed in this example. The writer has extended the pathway of ideas for the shape of the heater to include the more detailed concepts of manufacturing and size. It is important to remember that ideas can be added to the clustering diagram whenever the writer needs to include additional details.

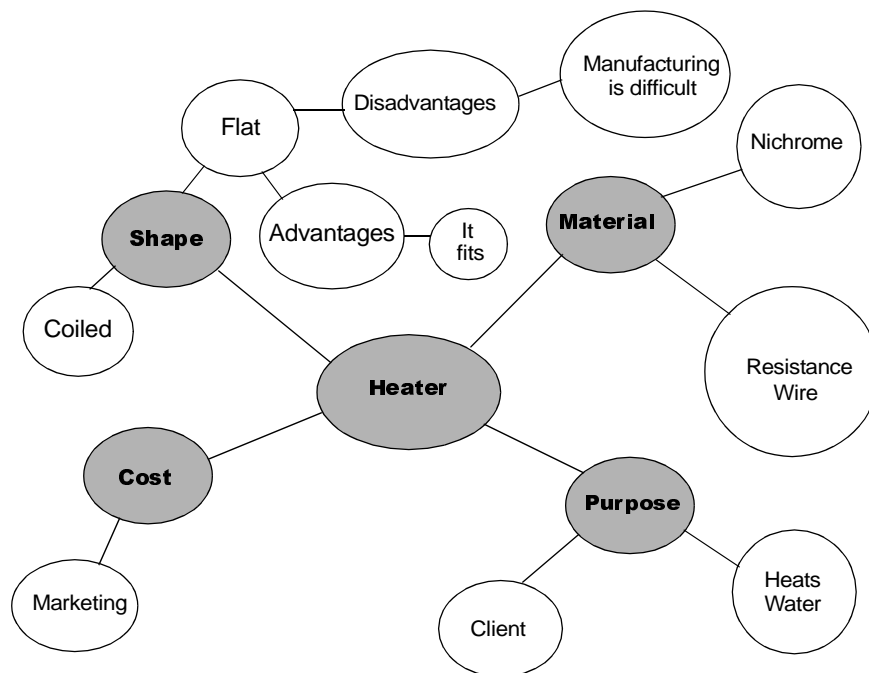


Figure 11.2. This diagram illustrates the “clustering” approach to prewriting. It shows the development of ideas considered for inclusion in a document describing the development of a heater.

### **Who — What....?**

Almost all engineering projects are undertaken for a set of specific reasons. Use the answers to the common questions—who, what, where, when and how—to inform the readers of these basic ideas. The technical document addresses the client or target audience for the completed work. The document states what was accomplished (a product, a study, an analysis, a measurement, etc.). Include the purpose for the document and/or project. Describe how the work was completed, by using entries from design journals, data and results, and other documentation developed in the work. In the prewriting step, these ideas may be briefly noted instead of being fully developed into sentence or paragraph formats

### ***Reading / Listening***

Writing engineering documents requires an evaluation of previously developed information for the support of ideas or as reference information for the reader. Consequently, a significant amount of time is spent searching for and reading literature that may be pertinent to the engineering document being developed. Sufficient time should be allocated in the writing process to find information in journal articles, textbooks, the Internet, various library references, the new media and other sources. Team members or peers can listen as the writer reads important passages from these reference documents. By reading, listening, and discussing the ideas from outside sources with others, the writer develops important ideas more efficiently.

### ***Arranging Ideas***

In the prewriting step, ideas are noted and developed with little formalized structure. However, the writer can organize or arrange ideas in several additional ways. Chronological order is often used when writing documents that give instructions—a “how-to” manual, for instance. Spatial order is used to describe the relationship of objects to other things. A writer may wish to organize ideas in their order of importance. Here, the intent may be to develop an argument to persuade or justify. Logical order is used to define an idea, often when comparing and contrasting relevant topics.

### ***Writing a Draft***

After the ideas are assembled in the prewriting step, the writer is ready to write an outline that leads to writing a draft. A detailed outline often serves as the starting point for composing an engineering document. It is appropriate to use word processing software to create the detailed outline. The outline contains the major topics for discussion, useful notes and any outside references to support the writing. Begin by setting up the major writing topics. Expand the outline by selecting the appropriate subtopics based on the technical highlights of the work.

At this point, as much detail as possible should be filled in for each subtopic using the information developed in the prewriting step. Note whether any items require more thorough examination. At any time, it is appropriate to add subtopics that were previously forgotten.

It is not necessary to use correct grammar in creating the outline, as short phrases, notes and headings are usually sufficient to remind the writer what is meant. The resulting outline should be a brief, yet useful, document from which the written report is developed.

The first writing is a rough draft. If a word processor is used, the writer can expand the detailed outline into the first draft. For these initial writing sessions, the emphasis is placed on building sentences and paragraphs around the major subtopics from the outline. Include sufficient detail to fully describe each topic. Use a sufficient number of paragraphs and sub-sections to delineate all ideas effectively. It is not expected that the final form of the written report be completed in the first draft. It is important to note that several drafts of the document are expected to be developed in the writing process to obtain a polished final version.

## Evaluating and Revising

Editing is critical to good writing. This step includes evaluating and revising the document for content, for grammar and for style. Editing for content requires a careful and thoughtful evaluation of what was said and what should be said. Determine if anything has been forgotten or whether new information is required. Assess whether new interpretations of the results or the research are required. Analyze areas that do not make sense and correct these sections. Also, determine if the document is comprehensive and discusses all the points as desired by all contributors.

### ***Evaluating the Document***

Once a written draft is completed, the writer should set aside the document for a brief period of time. This important step enables the writer to regain a fresh perspective of the written work. Often a few minutes is sufficient, but sometimes it helps to let several hours or days pass. The writer then reads and rereads the document, marking the paragraphs or sentences that require revising. Reading aloud also helps the writer evaluate and modify the draft.

A useful way to obtain a critical examination of the document is to use a peer evaluation. A peer evaluation directly benefits the writer, since the written document is aimed for that target audience. An informal evaluation is often sufficient to gain constructive comments. However, a more formal evaluation method can produce detailed, useful comments and ideas. The writer first prepares a list of questions about uncertain parts of the document. The peer evaluator reads the document with the objectives of stating what is effective and good, providing polite and constructive suggestions and criticisms, and providing specific suggestions for improvement. It is important for the writer to not feel personally criticized. Instead, the focal point of an effective peer evaluation is to highlight those sections of the document that require additional work.

### ***Revising the Document***

The writer revises the document based on the comments obtained from all the evaluations. Several revision techniques are suggested in Table 11.1 to help the writer develop effective ways to improve the content, format and objectives of the engineering document.

Table 11.1. Revision Techniques to Improve Content.

<b>Writing Objective</b>	<b>Revision Technique</b>
Make the writing more interesting.	Add examples or details.
Eliminate vagueness.	Expand on the facts or details. Use examples.
Focus all sentences on the topic.	Remove those sentences that are unrelated.
Clarify the presentation of ideas in each section, paragraph or sentence.	Reorder as needed.
Display a clear connection between ideas and sentences.	Add transition words such as “because” or “for example.”
Use language that is appropriate for the reader and technical forum.	Replace slang words and contractions with more formal word choices



## Proofreading

It is important to use correct grammar in any writing. If a report contains numerous misspelled words, incomplete or run-on sentences, or other grammatical errors, the reader will be distracted from the focus of the report. Furthermore, a poor grasp of writing fundamentals could be a detriment to advancement in *any* career. Take advantage of the spell-checking and grammar-checking features available in word processing software. Be aware, however, that these spell-checkers cannot distinguish between homonyms, synonyms or other inappropriate word choices. A word-by-word reading of the text is required to ensure that proper word choices are used. Table 11.2 provides examples of some common grammatical errors seen in technical writing, with a suggestion on how to correct each error.

Table 11.2. Suggestions to Improve Grammar.

Type of Error	Instead Of	Use
Plural-singular verb mismatch	"The data <i>supports</i> our hypothesis."	"The data <i>support</i> our hypothesis"
Incorrect word choice	" <i>It's</i> color is red." " <i>Their</i> going to meet at noon."	" <i>Its</i> color is red." " <i>They're</i> going to meet at noon."
Vagueness	"This means that the code is satisfactory."	"This <i>result</i> means that the code is satisfactory."
Incomplete sentence	"Which is the intent of the project."	"To enable movement is the intent of the project."

Use a technical style reference [1] to help develop proficient writing mechanics and style. Table 11.3 provides examples and suggestions to convey meanings clearly and completely and to improve technical style.

Table 11.3. Suggestions to Improve Technical Style.

Objective	Instead Of	Use
Use simple, clear language	"consider using" "due to the fact that" "in order to" "at the level of your eyes"	"use" or "employ" "because" "to" "at eye level"
Be concise and avoid wordiness	"The longer section was used in the second joint. This configuration is used because the shorter piece restricted the angle of the second joint so in order to obtain a larger angle a longer piece was required."  "The need for testing will confront teams with the challenge of inventing new methods."	"To compensate for the smaller angle in the second joint, a longer section is used."  "The need for testing will challenge teams to invent new methods."

Table 11.3. Suggestions to Improve Technical Style.

Objective	Instead Of	Use
Focus on the concept	“We decided that option A was better than option B. We found information that supported our findings.”	“The literature supports the use of option A over option B.”
Use active voice	“to be,” “can be” or “may be” “There has been an effort made to make the code more efficient.”	“is” “The code was made more efficient.”
Omit unnecessary phrases	“The main reason for these opposing results from the theory is due to the lack of accuracy in the experimental data.” “One final thing that should be noted is that...”	“Inaccuracy in the experimental data led to these opposing results from the theory.” “Finally, note that...”

Most writers find that a fresh outlook is required for efficient editing to occur. Enlist another team member or an outside editor to critique the document. Also, discussing the work or contents of the report with someone other than team members may result in new insight that can enhance the final document.

### Iterating the Writing Process

The writing process is an iterative cycle, as shown in Figure 11.1. Occasionally, one pass through all steps in the writing process results in a polished final document. Usually, the writer uses several complete iterations to ensure that the document is complete. One proofreading pass primarily addresses content. Another pass ensures that all figures and tables are complete and included. Another proofread makes sure that grammatical errors are eliminated. The final pass through the process verifies that the document is polished, error-free and ready for its official submission.

---

## REFERENCES

Following are a few of the many grammar and writing style guides available at most bookstores:

1. Hacker, Diana, *A Writer's Reference*, 3<sup>rd</sup> edition, 1998.
2. Shelton, James H., *Handbook for Technical Writing*, NTC Publishing Group, Lincolnwood, IL, 1996.
3. Steinmann, Martin and Michael Keller, *NTC's Handbook for Writers*, NTC Publishing Group, Lincolnwood, IL, 1995.



## INTRODUCTION

Engineers use oral presentations to efficiently and effectively transfer information to a wide range of audiences. Usually, the setting and circumstances allow for direct interaction between the speaker and the audience. Oral presentations are a common method of evaluating the progress of a project *and* the progress of the individual. The ability to present oneself and one's project in a competent and succinct manner enhances one's college and career development.

Multiple components make up an oral presentation: 1) the audience, 2) the content and organization, 3) visual aids, and 4) the speaker. Student design teams have control over the last three items, but little control over the audience. Thus, a presentation goal is to prepare effective visual aids and a presentation method to capture and maintain the attention of the audience. As with writing, styles of oral presentation are numerous. All good presentations rely on clarity of expression, an easily followed train of thought and well thought-out visual aids that illustrate key points in the talk. High-quality visual aids can make or break a presentation as can poor organization and a sloppy presentation style (e.g., mumbling, talking to one's feet or failing to make eye contact with the audience).

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## THE AUDIENCE

Since presentations are always prepared for an audience, the presenter must evaluate the audience and determine the best way to pique its interest. Determine *who* will attend the presentation. Gather information on the technical awareness of the audience as a whole and the degree of familiarity that the audience has in the subject. For instance, a presentation on modeling weather patterns in the Pacific Ocean would be different for an audience of middle school students versus one prepared for an audience of applied mathematicians. By assessing the audience correctly, the speaker determines the best way to interest the audience. Explain *why* the presenter(s) finds the subject interesting. Convey enthusiasm when explaining *how* it was determined *what* the best

course of action was that led to the solution. The interested audience then responds with questions and comments that show an appreciation for the content and the style of the talk.

Audiences rarely have a uniform composition. Those attending may include, for instance, peers, managers, contractors, vendors and clients. Before discussing any specific details, present background information for those who have a limited level of expertise in the subject matter. This information helps bring the audience up to a common knowledge level.

Often, the audience includes those who are assessing the work itself and the capabilities of the presentation team. These individuals probably understand the topic well. For instance, an instructor evaluates a design team as a requirement for an introductory engineering projects course. In a professional setting, managers listen to presentations to evaluate alternative courses of action. In these situations, convey the technical information in a comprehensive, interesting and competent manner.

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## **THE CONTENT AND ORGANIZATION**

Preparing an effective presentation takes thought and effort. Use an organized method to develop the talk. First, express all thoughts on paper and organize the ideas. Consider the best way to present the material. Note which ideas are best presented in either text, graphical or illustrated formats. Next, develop interesting visuals that clearly display the content. The first slide (or overhead transparency) provides the **Title** of the talk. Give the title of the project, the reason for the talk (e.g., Preliminary Design Review, Final Report, etc.), the team members' names, course number and date.

Divide the rest of the talk into three main sections: the **Introduction**, the **Body** and the **Closing**. Use the simple rule-of-thumb, "*Tell them **three times**,*" according to the following general format for an oral presentation:

<b>The Introduction</b>	→	Tell them what you're <i>going</i> tell them.
<b>The Body</b>	→	Tell them.
<b>The Closing</b>	→	Tell them what you told them.

### **The Introduction**

The second slide (or overhead transparency) presents a brief outline of the information to be discussed. The presenter briefly (10-15 seconds) overviews what is going to be discussed. Usually, the title of the slide for this section is "Overview," "Outline" or "Introduction." This becomes the first time the speaker "Tells them," providing the audience with a map of the signposts of the presentation. It is helpful to the audience if the speaker occasionally reviews the progress of the presentation; for instance, a speaker might say, "That completes the Design Objectives. Now, I'll talk about the manufacturing process before finishing with a discussion of the tests that were performed."

## The Body

The slides between the second and last form the body of the presentation and contain the important details of the presentation content. They represent the second time the speaker “Tells them.” These important slides require the majority of the preparation time. Include some or all of the following types of information, as required to convey the message:

- ◆ *Present the background or theory.* Give a broader perspective of the motivation behind the work and any pertinent applications or existing equipment. Typical titles are “Background,” “Previous Devices” or “Theory.” Use two to four lines of text to supplement what is said.
- ◆ *Discuss the design or research methods.* Show illustrations and technical drawings that highlight any important features. Use titles such as “Design Objectives,” “Research Methods” or “Critical Design Component.” If more than one or two sentences are spent explaining an item, then include a few lines of text addressing that point for the audience to read during the talk.
- ◆ *Discuss the results.* Interpret and compare expectations with the real outcomes. Address how the results affect the final design or decisions. Use slides that have sketches to illustrate points and titles such as “Metal vs. Plastic,” “Evaluation of Operational Speed” or “Considerations for Final Design.” Include three or four lines of text that can be used as discussion points for each of these slides.
- ◆ *Tell the interesting parts of the story.* Describe any mistakes and lessons learned. Use titles such as “Pitfalls of Method 1,” “Reasons to Use Plastic Instead of Cardboard” or “Computational Problems.” Again, list the items that will be discussed.

## The Closing

The last one or two slides present a summary of the key points of the talk, and represent the third time the speaker “Tells them.” No new information should be introduced at this time. Each point that is mentioned must have been previously addressed in the main body of the talk.

For example, the talk might end with something like, “Now you’ve heard about how our design of a toy manipulative takes the abilities of 2-5 year olds into account, which led to our choice of polyethylene for the construction of the prototype. Our tests went well, but showed that the base needs to be reinforced. Currently, our revised design is in fabrication and will be ready in time for the Design Expo.”

Use a final slide to summarize the points that have been discussed, such as the example in Figure 12.1

## **Findings for Final Design of New Toy Manipulative**

- ◆ Dexterity of 2-5 year olds appears sufficient to manipulate toy
- ◆ Polyethylene is smooth and safe
- ◆ Prototype shows that base needs reinforcement
- ◆ Completion planned for Design Expo

Figure 12.1. Example summary slide (or overhead transparency).

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### **VISUAL AIDS**

All presentations should use visual aids, and some engineers regard them as their most important product. Visual aids, the objective of which is to convey enough information for the audience, should be carefully developed to transmit only pertinent information. The most common form of visual aid in professional settings is the overhead transparency, variously called overheads, slides or viewgraphs. Thus, it is beneficial to become familiar with the operation of an overhead projector.

Presentation software packages (i.e., PowerPoint®) are commonly used to prepare visual aids. Such packages provide a selection of templates, borders, backgrounds, typefaces and color options that give the visual aids a professional appearance. Selected colors can have remarkable impact; however, extraneous graphics and colors can be distracting.

In addition, electronic presentations are possible, wherein the slides are stored in—and projected—directly from a computer.

Following are some answers to commonly asked questions about how to prepare visual aids:

#### **How Many Slides Should Be Prepared?**

- ◆ Plan on one slide per minute of talk, which ensures the right amount of information on each slide.
- ◆ If a slide takes more than two minutes to discuss, then there is too much information; the audience may become confused. Conversely, if it takes only ten seconds to cover the information, it may be better to include that information on the previous or next slide.
- ◆ Never talk without having a slide that emphasizes important points. If it is not worth putting on a slide, it is not worth discussing at all.

## **What Is the Format of Each Slide?**

### ***Keep Slides Simple and Uncluttered***

Carefully choose the templates (optional borders or backgrounds included with many presentation software packages) to avoid adding distracting graphics to the slides. Choose colors that add impact and enhance the legibility of any text. Use care in adding clip art images that do not contribute to the technical message. Fancy images do not make up for poor content or organization.

### ***Title Each Slide***

Use a title to emphasize the most important point being made. Avoid using “horse charts”; e.g., a picture of a horse with the title of “Horse.” Obviously, the title does not reveal much. The goal is to communicate all points visually and not raise questions that can be answered only by talking.

### ***Use Large-Sized Typefaces***

A font of 20 pt or more should always be used. To determine if the size is big enough, use the “drop on the floor” technique. If the overhead transparency can be read when it is on the floor and the speaker is standing up, then the size is large enough.

### ***Use Horizontal Orientation***

Most overhead projectors allow for both horizontal (landscape) and vertical projections. Horizontal allows the slide to be moved to the top of the screen, making it visible to those at the back of the room. Also, horizontal orientation provides for longer text lines that are generally easier to read.

### ***Cover Four Points (Approximately) Per Overhead***

A graphic should present a distilled form of the speaker’s comments, so words should be chosen carefully. Use the overheads to reinforce spoken words, not to repeat them.

### ***Present Results Graphically***

Show illustrations or photos of the prototype or device. Resist the temptation to show tables of values, as the audience cannot possibly read and understand what the data mean. For plotted results, use titles such as “Result of Torsion Tests” or “Experimental Results for Spring Made of Thin Plastic.” It is helpful to add a few lines of text to tell the audience why the results are being shown.

### ***Have Duplicates Ready***

Sometimes only a portion of a slide needs to be discussed and returned to later. If it is put aside, chances are the slide will get lost in the pile. In the time it takes to locate the slide, the audience’s attention will be lost. It is worth the extra expense to have another slide already prepared and in order.

### ***Avoid Overlays***

People try to take advantage of transparencies by having some information on multiple slides, stacking or removing the slides one at a time. This technique often leads to the presenter trying to



line up two or more transparencies while the audience waits impatiently. It is better to have one slide with the first part of the information and a second slide with the remaining information.

### ***Avoid Using Physical Objects as Visual Aids***

Unless they are large enough to be seen by the entire audience, avoid using physical objects. If an object will be passed around, be aware that it will distract each person who examines it. Several objects may be needed to make sure that everyone gets the chance to see one.

### ***Make Clear Photocopies***

Graphics and other material photocopied from textbooks or journals should be of good quality. Illegibility gives the impression that the presentation was hastily thrown together.

### ***Use Numbers Sparingly***

The audience will only remember a few key numbers, so do not bore them with too many. Whenever possible, use graphical—instead of tabular—displays of results. If equations are included, explain their relevance and results, and discuss the important variables.

### ***Plan Graphics Harmoniously***

Design or choose a format that presents the information attractively, and stick to that format for all graphics.

### ***Create Smooth Transitions Between Overheads***

Plan (and practice) smooth and clear transitions between overheads. Include text or graphics on one slide that smoothly leads the viewer to the next slide.

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## **THE SPEAKER**

Some engineers dislike giving oral presentations. However, such a negative approach can inhibit the development of an effective presentation style. Keep two things in mind when preparing a presentation: (1) *the speaker* (and the student team) have more knowledge about the topic compared to that of the audience, and (2) the audience *has an interest* in what is being said. In other words, *the speaker* and *the material* are informative and interesting. With this in mind, approach the presentation with a positive, productive attitude and develop an individual, yet professional style.

Speakers have four main objectives. First, gain the *attention of the audience* quickly. The first few minutes of the talk should intrigue the audience with the discussion to come. Next, convince the audience of the *value of the ideas*. The object is to give the audience meaningful information and guide them to the conclusion in a well-paced, interesting manner. Third, make the presentation memorable by using *effective visual aids and an engaging presentation style*. Finally, *stimulate (activate) the audience* with movement, voice and the appropriate use of visual aids. An easy way to remember these criteria is with the phrase, "I **AMMA** good presenter," with the acronym defined as:

**A**ttention-getting

**M**eaningful

**M**emororable

**A**ctivating

Effective presenters almost never refer to notes when they speak; they take their cues from the text and graphical images on their visual aids. For novice speakers, it can be helpful to begin preparation of a presentation by writing a full script for the talk (but, do not ever read the script to the audience). Practice the script out loud, and write large notes in colored ink on paper copies of the visual aids (for reference, these copies may be placed on the speaker's podium or desktop). Each time the speaker(s) practices the talk, s/he will refer less often to the notes, eventually not needing the assistance at all.

Avoid the temptation to prepare note cards to hold during the talk. Such props often distract the speaker and the audience, particularly when the speaker reads directly from the cards. Reading from note cards makes it difficult for the speaker to maintain eye contact with the audience. Also, holding the cards hinders the speaker from gesturing to slides.

The following suggestions for delivery are fairly basic, but they are not always easy to follow. Clarity in speaking only comes when the message and the presentation are adequately prepared. The primary emphasis is placed on comprehensibility and economy of words. Part of clarity is to not distract the audience with unnecessary visual aids or mannerisms.

### **Convey Information Through Body Language**

Consider where to stand to not block overheads. Many people are uncomfortable giving talks, and as a result, they stand far away from the screen, which is where they want the audience to actually look. This positioning causes the audience to look first at the speaker and then at the screen. Instead, the speaker should take control of the audience by using his/her hands to direct the audience's attention. Stand close to the screen, and point at the item on the screen that is being discussed; the eyes of the audience are sure to follow. Also, it is important to stand comfortably without swaying.

The speaker should use his/her hands for specific, descriptive gestures that illustrate what is being discussed. This activity keeps the speaker's hands usefully employed and "out of mischief," as well as helps get the point across.

Maintain eye contact with the audience. Since it makes them feel involved, members of the audience appreciate direct looks from the speaker. His/her gaze should address all audience members.

Lastly, smile and exhibit confidence when speaking. When the speaker looks comfortable and confident, the audience focuses more on what is being said rather than on what is being done.

### **Convey the Message Through Speech**

Make the tone of the presentation appropriate for the audience, and maintain a suitable speak-

ing volume. Also, remember to speak at a reasonable pace and articulate. Also, practice varying voice and rhythm to maintain the audience's interest.

Avoid verbal distractions, such as “uh,” “um,” “you know,” “ok,” “well,” etc. If there exists a problem with repetitive habits, especially of saying “ah” or “um” before each sentence, there is only one cure: ask a practice audience for “The Um Alert.” Whenever the speaker says “um,” the audience also says “um.” This exercise is excruciating and quickly leads to avoidance of the pain stimulus.

### **Conduct a “Dry Run”**

The most important thing that can be done to improve a talk is to practice. If giving a group presentation, practice together as a group, so that each person knows what the other will say. Coach each other on style, give positive feedback and be specific on unclear points. The audience in this case consists of peers, so practice in front of them. Have someone sit in various corners of the room to determine if the slides are visible and if the speaker is easily heard.

Practice sticking to the allotted time slot. If the speaker runs over, the audience begins to worry about when the talk will end rather than what is being said. The only way to make sure that the talk fits into the scheduled time is to practice, out loud, with visual aids.

Learn how to operate the presentation equipment (pointer, projector, computer, microphone, light switches, extension cord, etc.) to eliminate operating mistakes that could be diminish the value of the presentation in the audience's eyes.

Remember: never end a talk with “That's all. Are there any questions?” This ending results in an awkward, dead silence as the audience tries to decide if they should clap or grill the speaker. Instead, use the magic phrase that always works: “Thank you,” which gracefully signals the end of the talk. The audience then applauds. The tension is broken, and questions can be presented and answered.

Discuss how each group member will participate in the question and answer session. Prepare a few anticipated questions, and practice answering them.

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## **EVALUATION OF THE PRESENTATION**

One of the most effective ways to evaluate an oral presentation is to videotape either a practice or final presentation. Review the recording with the entire student team, and use the following questions to help evaluate the delivery techniques and visual aids:

- ◆ Organizationally, what could have been done to make the presentation flow more smoothly?
- ◆ How effective were the visual aids? What changes could be made in either the slides themselves or in the presentation of the slides?
- ◆ How good were the delivery techniques? Were there any annoying gestures or verbal distractions? If so, what were they?
- ◆ What was the best (most effective) aspect of the presentation?
- ◆ What needs to be improved before the next presentation?

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**INTRODUCTION**

The primary purpose of a display poster is to report information. This can be done effectively by:

- ◆ Catching the viewer's interest and attention.
- ◆ Making the poster easy to read and understand.
- ◆ Telling a story.

Always keep in mind that if a viewer has to work hard to understand the message, s/he will not invest the energy to do so, and the poster will not be effective nor entice the audience.

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**POSTER DESIGN**

Be creative when designing a poster. Consider including the following visual elements to effectively illustrate information and provide viewing interest:

- ◆ Headlines
- ◆ Diagrams
- ◆ Tables
- ◆ Flow Charts
- ◆ Tactile Samples (material, parts, etc.)
- ◆ Cartoons
- ◆ Photographs
- ◆ Graphs
- ◆ Captions
- ◆ Illustrations
- ◆ Schematics

Be complete, but concise. Include enough information to provide a summary of the whole story, but not so much information that it looks like a report was glued to the board! The viewer is depending on the poster to summarize the important, essential points to tell a brief and interesting, yet factual and convincing, story. Consider the audience: a presentation for third-graders would be different than for scientists who are familiar with the topic. An effective technique to focus poster design is to think through how to briefly explain the objective, approach and solution to a friend not engaged in

the project.

### **Poster Size**

A recommended poster size is a freestanding, tri-fold poster with the central frame dimensions of 24 in. x 36 in. Standard posterboard works well if the poster will be mounted to a wall or bulletin board. If the poster is going to be propped on an easel, leaning against a wall or freestanding, use foamcore board that is stiffer.

### **Proofread Text**

Read the written text out loud to assure it makes sense. Edit and choose words carefully for clarity. Assume that the opportunity to further explain or clarify does not exist. Remember to label graph axes with descriptions and units of measure. To assist a viewer who wants to learn more, include all team members' names, the instructor's name and the date at the bottom of the poster.

### **Typeface**

Using a variety of typeface sizes can relieve boredom for the reader and provide a tool to express the message. For a 24 in. x 36 in. poster, a minimum of 18 point lettering size for text and/or descriptions is suggested. Headlines should be even larger. Make no text so small that a viewer would have to squint and move in very close to read it. Can a viewer easily read the units on the X and Y graph axes? Look for awkward automatic hyphenation of words, especially in large headlines, and modify them to make natural, easy-to-read breaks in phrases.

Selectively use **bold** and *italic* typefaces to create emphasis, but do not overuse. Also, beware **OF** providing too **MUCH** variety in **typeface styles** as it **OFTEN distracts** the viewer and decreases **LEGIBILITY**.

As a final review, stand back five feet from the poster and make sure every headline and text paragraph is easy to read. Some details (such as graph and image captions) may be acceptable with legibility at a closer distance of three feet.

### **Color**

Introduce color to direct the viewer's eye throughout the poster. Work with a limited pallet of compatible colors, and use the concept of "color jump" to repeat the same colors throughout the poster. Consider alternate color(s) for the background of the board—it does not have to be white!

### **Poster Composition**

Assess the composition and flow of the information presented on the poster. Does the viewer's eye naturally flow from the headline of the poster to the more detailed information *as if the story were being told in person*? Arrange the poster elements and use bullets, arrows and framing cut from colorful paper to help direct the viewer's eye and keep the process interesting.

### **Contrast**

Provide enough contrast between text and its background for easiest readability. For example,

black letters on a white background (or vice versa) provide excellent contrast. Black letters on yellow also work well; but red letters on black may not provide enough contrast for easy reading. In the latter case, the letters do not “pop” enough to work well. Step back from the poster and see how easy (or difficult) it is to read.

### **Neatness and Organization**

Neatness counts! Avoid the use of visible tape. Instead, use artist’s spray-mount adhesive, glue sticks or hidden tape (double-stick or rolls). Make sure every piece is well adhered to the poster. Although posters are most impressive when headlines and information are lined up squarely, the occasional placement of headlines and other poster components at intentional angles or curves can be dramatic and effective.

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## **CONCLUSION**

Using logic, creativity and consistency, posters can be an effective means of communication. If well planned and properly designed, posters can be fun, inexpensive and efficient to create. Although posters are not easy to transport, they are of great value when they “speak for themselves” in a crowded room.



# The Basics of Engineering Mechanics

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## INTRODUCTION

Engineering mechanics is an important analytical tool that allows an engineer to optimize a design, creating one that is strong and rigid enough to do the job, but not overly heavy and expensive. A thorough study of mechanics requires some knowledge of calculus and vector mechanics that many students do not ordinarily complete until the end of their sophomore year. Such a course is an essential component of many engineering disciplines, including mechanical, aerospace and civil engineering. The purpose of this chapter is to provide introductory engineering students with some important, basic analysis tools that can be applied to many design projects.

Virtually any physical device in the “real world” is acted on by forces, which can include gravitational, pressure, magnetic, electrostatic, centrifugal and impact forces. Engineering mechanics studies the effects that forces have on materials, allowing engineers to theorize how a design will react before it is built. Engineers may then optimize designs on paper (or with a computer), without having to build and test multiple versions of a product. Using mechanics, better products can be designed and built faster and more cost effectively.

This chapter has four major topics: In *Statics*, the first step in analyzing many physical structures, assumptions are made that all bodies are completely rigid and that they are strong enough to withstand the forces applied. *Mechanics of materials* considers how forces act upon actual bodies in bending, twisting or breaking them (of course, the goal of the designer is to create designs that do *not* bend too much or break). Engineers use various *design criteria* to create physical products, including design for strength, factor of safety and design for stiffness. Finally, *units* that are commonly used in mechanics are presented.



## STATICS

### Scalars and Vectors

One characteristic of engineers is that they quantify the world around them. *Scalars* are quantities that can be expressed solely in terms of magnitude, such as:

- ♦ Area
- ♦ Length
- ♦ Mass
- ♦ Moment of inertia
- ♦ Energy
- ♦ Power
- ♦ Volume
- ♦ Work

However, for some quantities, it is necessary to know both a magnitude *and* a direction to describe them completely. These quantities are known as *vectors*. Examples of vector quantities include:

- ♦ Force
- ♦ Moment
- ♦ Momentum
- ♦ Displacement
- ♦ Velocity
- ♦ Acceleration

While scalar quantities can be combined arithmetically, vectors require geometric and/or trigonometric manipulation. Vectors are usually depicted as arrows in a three-dimensional space. As shown in Figure 14.1, the magnitude of a vector is proportional to its length, and the direction of the arrow gives its orientation.

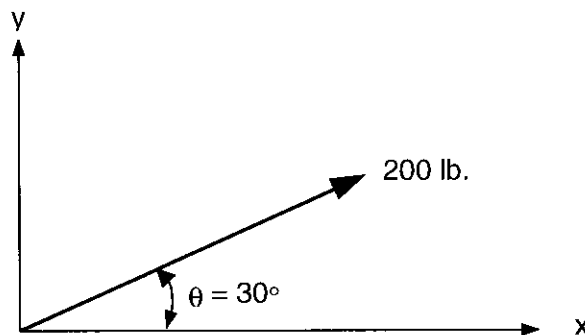


Figure 14.1. Representation of a 200-lb force at an angle of  $30^\circ$  with the x-axis.

Vectors can be added or subtracted geometrically and/or trigonometrically. For example, consider two force vectors **A** and **B** that are added together to give the vector sum  $\mathbf{C} = \mathbf{A} + \mathbf{B}$  (Figure 14.2)<sup>1</sup>. Geometrically, vector **B** is moved so that its tail coincides with the tip of vector **A**, while retaining its magnitude and direction. A line from the tail of vector **A** to the tip of vector **B** gives the vector sum **C**, also known as the *resultant*.

1. Quantities printed in **bold** are vector quantities, while scalar quantities are printed in normal font.

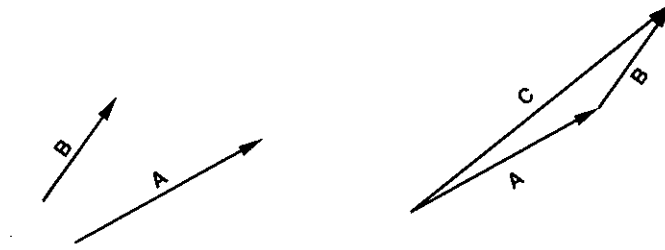


Figure 14.2. The geometric interpretation of the vector sum  $\mathbf{C} = \mathbf{A} + \mathbf{B}$ .

By moving vector  $\mathbf{A}$  instead of vector  $\mathbf{B}$ , it becomes evident that one important property of vector addition is that the order is immaterial; i.e.,  $\mathbf{C} = (\mathbf{A} + \mathbf{B}) = (\mathbf{B} + \mathbf{A})$ .

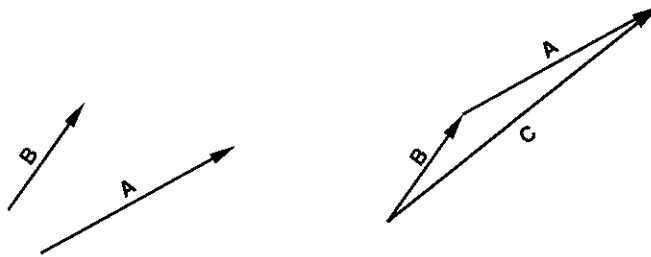


Figure 14.3. The geometric interpretation of the vector sum  $\mathbf{C} = \mathbf{B} + \mathbf{A}$ .

Mathematically, the simplest way to manipulate vectors is to utilize a Cartesian<sup>2</sup> coordinate system, which consists of three mutually orthogonal axes, usually designated  $x$ ,  $y$  and  $z$ . A vector can then be resolved into three components that lie along those three axes:

$$\mathbf{F} = F_x \mathbf{i} + F_y \mathbf{j} + F_z \mathbf{k}$$

where  $F_x$ ,  $F_y$  and  $F_z$  are the Cartesian components (scalar quantities) of the force vector  $\mathbf{F}$ . They are computed by:

$$F_x = F \cos(\theta_x)$$

$$F_y = F \cos(\theta_y)$$

$$F_z = F \cos(\theta_z)$$

where  $\theta_x$  = angle that  $\mathbf{F}$  makes with the  $x$ -axis, etc.

Note that the magnitude ( $F$ ), of the force vector  $\mathbf{F}$ , can be expressed in terms of its Cartesian components by:

$$F = [F_x^2 + F_y^2 + F_z^2]^{1/2}$$

2. Named after René Descartes (1596-1650), a French mathematician regarded as "the father of modern philosophy," who established the philosophical movement called "rationalism." His theories swept aside the metaphysics of previous philosophers, as he believed the mind possessed a "clear and distinct" idea of self. As he said, "I think, therefore I am" and "It is not enough to have a good mind. The main thing is to use it well."

The unit vectors  $i$ ,  $j$  and  $k$  each have a magnitude equal to one, with directions aligned with the  $x$ -,  $y$ - and  $z$ -axes, respectively (Figure 14.4).

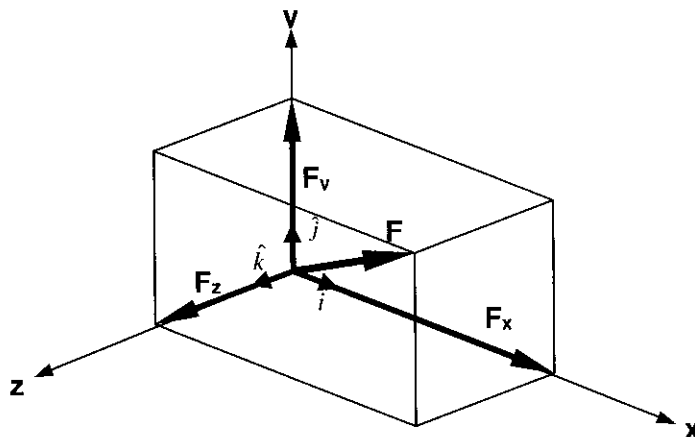


Figure 14.4. Force vector  $F$  and its Cartesian components.

Adding vectors then becomes a matter of simply adding up all the  $x$ ,  $y$  and  $z$  components arithmetically.

**Example 14.1**

Consider the vector sum  $C = A + B$  shown earlier. If we know that vectors  $A$  and  $B$  have magnitudes and directions as shown in Figure 14.5, we can resolve them into their Cartesian coordinates:

$$A = (20) \cos(30^\circ)i + (20) \cos(60^\circ)j = 17.32i + 10.00j$$

$$B = (15) \cos(50^\circ)i + (15) \cos(40^\circ)j = 10.64i + 11.49j$$

The resultant sum  $C$  can be computed by summing up the  $x$  and  $y$  components of  $A$  and  $B$ :

$$C_x = 17.32 + 10.64 = 26.96$$

$$C_y = 10.00 + 11.49 = 21.49$$

Vector  $C$  can be combined back into a single vector:

$$C = [C_x^2 + C_y^2]^{1/2} = [(26.96)^2 + (21.49)^2]^{1/2} = 34.48$$

$$\theta_x = \tan^{-1}(C_y/C_x) = \tan^{-1}(21.49/26.96) = 38.56^\circ$$

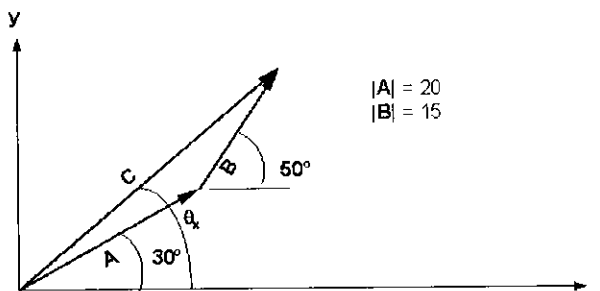


Figure 14.5. Vector sum  $C = A + B$ .

## Forces

As mentioned above, forces are vector quantities; i.e., it is necessary to know both their magnitude and direction. Some forces develop under static conditions, such as gravitational, magnetic, pressure and electrostatic. Other forces, such as centrifugal and impact forces, develop because of a dynamic condition.

One important property of force vectors is that they can be moved anywhere along their line of action. For example, the rigid body shown in Figure 14.6 is in equilibrium regardless of whether the force,  $F_1$ , is pushing (a) or shifted along the line of action so that it is pulling (b).

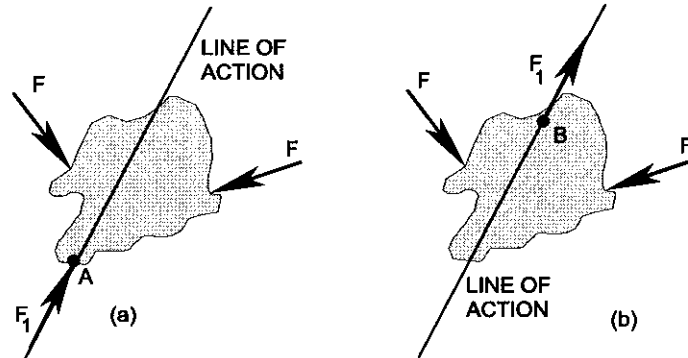


Figure 14.6. A rigid body remains in equilibrium as force  $F_1$  is shifted along its line of action from point A to point B.

Forces may be *external forces* that are applied to a structure, or *internal forces* that develop inside the structure. External forces include active forces applied to a structure as well as the reaction forces that develop at the supports. In Figure 14.7, a simply supported beam is loaded with a concentrated load (a). In (b), the beam is loaded by a uniformly distributed load spread over the top of the beam, or the weight of the beam itself loads the beam. In (c), the supports have been replaced by the reaction forces,  $R_1$  and  $R_2$ , which must be present at the supports to maintain equilibrium; this is known as a *free-body diagram*, which is an important tool for visualizing the complete loading state of a structure.

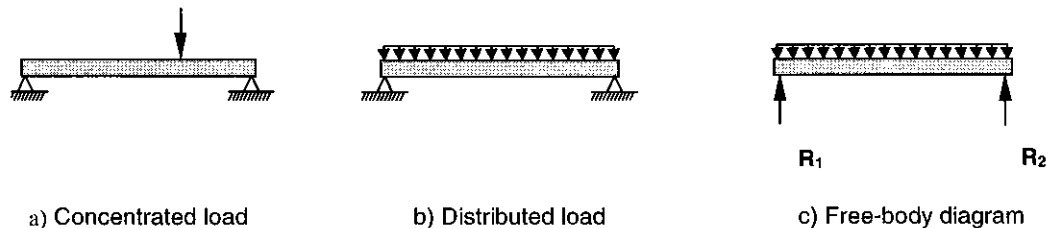
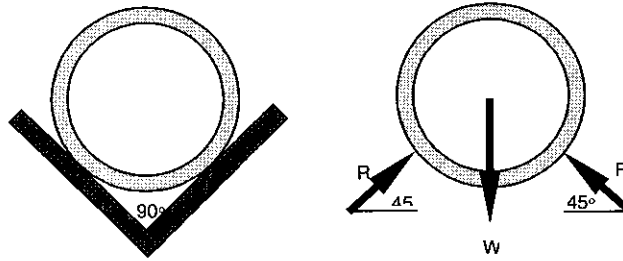


Figure 14.7. External forces applied to a simply supported beam.

**Example 14.2**

Consider a circular pipe supported in a right-angled rack as shown below. In the free-body diagram on the right, the rack is removed and replaced by the reaction forces  $R$ , each of which acts at  $45^\circ$  to the horizontal. (It can also be shown that the reaction forces must pass through the center of the circle, which provides a convenient way to find the center of circular objects.)

Internal forces develop within a structure due to the action of the external applied and reaction forces. Although these internal forces are invisible, they can be visualized by making imaginary cuts through a member and solving the equations of equilibrium. For example (Figure 14.8), consider a weight being supported by a rope (a). In the free-body diagram (b), the weight is replaced by a force vector,  $W$ , acting downward, and the reaction force,  $R_1$  acting upward. By making an imaginary cut through the rope, the internal force,  $P_{int}$ , can be found, and can be seen to be equal in magnitude to  $W$  but opposite in direction.

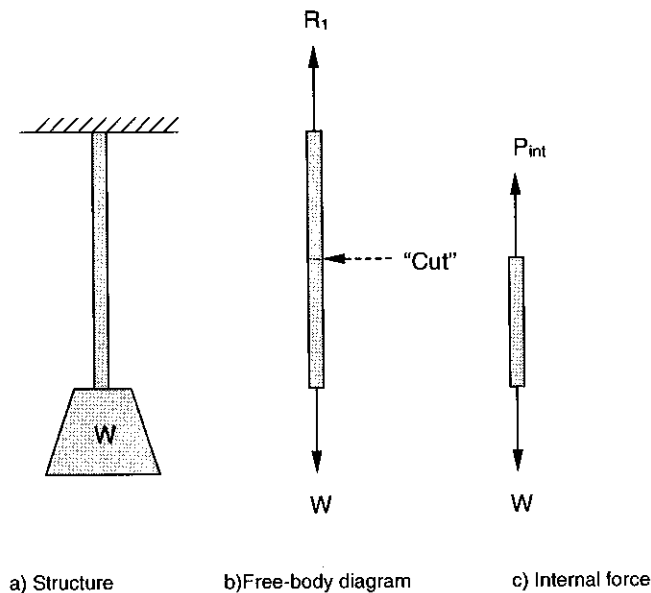


Figure 14.8. Internal forces are computed by making an imaginary cut in a member.

## Moments

A moment is the result of a force acting offset from a point. As shown in Figure 14.9, the force  $F$  tends to make the body rotate clockwise about point  $O$ . The magnitude of the moment created by this situation can be calculated by:

$$M_O = Fd$$

where  $d$  = the perpendicular distance to the line of action of  $F$ .

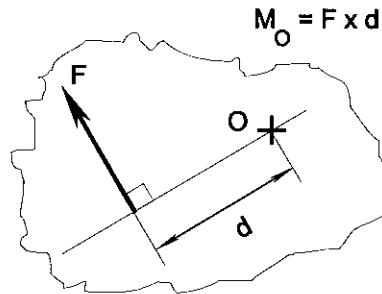


Figure 14.9. The moment produced by a force depends on the position of point  $O$ .

The units of moment are given as N-m in the SI system or lb-ft in the US system. Incidentally, a moment that tends to bend a bar in its plane of symmetry is referred to as a *bending moment*, and one that tends to twist the bar about its long axis is usually termed as *torsion* (Figure 14.10).

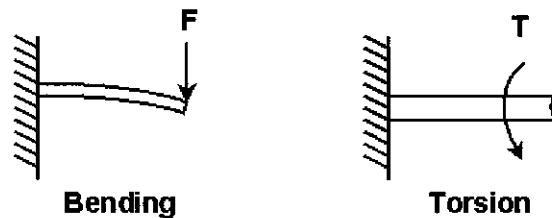


Figure 14.10. Bending moment and torsion.

## Equilibrium

The basic principle used in statics to solve for all of the forces and moments acting on a rigid body is based on Newton's<sup>3</sup> First Law, which states that if the sum of all forces acting on a body is zero (i.e.,  $\Sigma F = 0$ ), the body will either remain at rest or continue moving with constant velocity. This condition is referred to as *equilibrium*.

### External Forces

Unless it is accelerating or has fractured, a structure with applied external forces is in a state of equilibrium, which means that it must satisfy the equations of equilibrium:

3. Sir Isaac Newton (1642–1727) developed the branch of mathematics known as calculus when he was only 24. He later turned his attention to planetary motion, formulating his famous three laws of motion. Engineering mechanics is commonly referred to as Newtonian Mechanics.

$$\Sigma F = 0$$

$$\Sigma M = 0$$

These equations are given in vector format, but it is usually more convenient to solve statics problems by representing the forces and moments in Cartesian components:

$$\Sigma F_x = 0, \quad \Sigma F_y = 0, \quad \text{and} \quad \Sigma F_z = 0 \quad (\text{Equation 14.1})$$

$$\Sigma M_x = 0, \quad \Sigma M_y = 0, \quad \text{and} \quad \Sigma M_z = 0 \quad (\text{Equation 14.2})$$

It is useful to classify the force system that is acting on a structure, then choose the appropriate sets of the above equilibrium equations to solve for any unknown forces. As shown in Table 14.1, different classifications of force systems require different subsets of Equations 14.1 and 14.2.

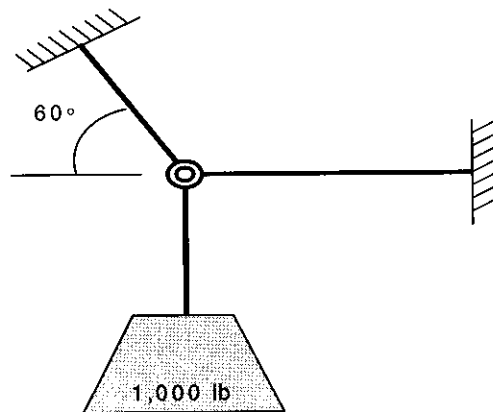
Table 14.1. Classifications of force systems and appropriate equilibrium equations.

Force System Classification	Equations of Equilibrium
Coplanar and concurrent	$\Sigma F_x = 0$ $\Sigma F_y = 0$
Coplanar and non-concurrent	$\Sigma F_x = 0$ $\Sigma M_z = 0$ $\Sigma F_y = 0$
Non-coplanar and concurrent	$\Sigma F_x = 0$ $\Sigma F_y = 0$ $\Sigma F_z = 0$
Non-coplanar and non-concurrent	$\Sigma F_x = 0$ $\Sigma M_x = 0$ $\Sigma F_y = 0$
	$\Sigma M_y = 0$ $\Sigma F_z = 0$ $\Sigma M_z = 0$

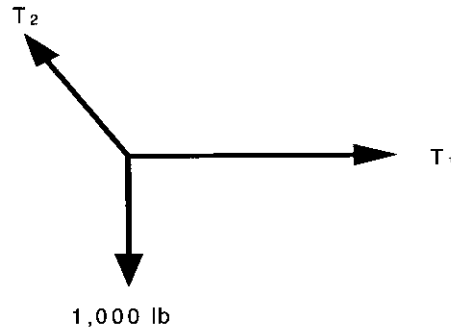
The following example illustrates a simple six-step procedure for solving for the unknown forces in a coplanar, concurrent force system.

**Example 14.3**

Consider a 1,000-lb weight suspended from two cables as shown.



Step 1. Prepare a complete free-body diagram of the system as shown above.

**Example 14.3 (Continued)**

Step 2. Classify the force system. In this problem, the force system is *coplanar* and *concurrent*.

Step 3. Write the applicable equations of equilibrium. In this case, only two of the six equations of equilibrium are applicable.

$$\Sigma F_y = 0 \qquad \Sigma F_x = 0$$

Step 4. Substitute the unknowns from the free-body diagram into the applicable equations of equilibrium.

$$\begin{aligned} \Sigma F_y = 0 & & \Sigma F_x = 0 \\ T_2 \sin(60^\circ) - 1000 = 0 & & T_1 - T_2 \cos(60^\circ) = 0 \end{aligned}$$

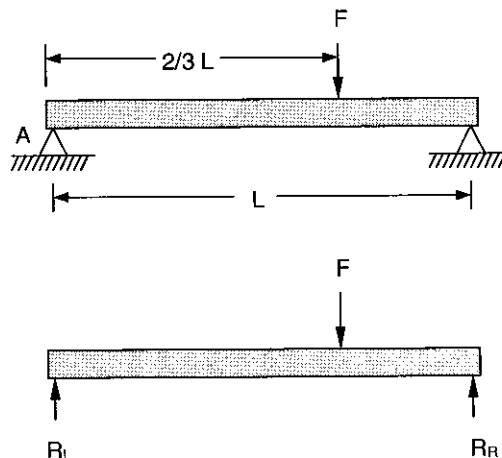
Step 5. Solve the equations.

$$T_2 = 1000 / \sin(60^\circ) = 1155 \text{ lb} \qquad T_1 = T_2 \cos(60^\circ) = 577 \text{ lb}$$

Step 6. Check the solution and interpret the results. The simplest way to verify the solution is to resolve  $T_2$  into its x- and y-components and notice that the forces sum to zero in both directions.  $T_2$  should be greater than  $W$  – is it?

**Example 14.4**

Consider a simply supported beam with a concentrated load as shown below.





**Example 14.4 (Continued)**

Step 1. Prepare a complete free-body diagram.

Step 2. Classify the force system, which in this case is *coplanar* and *non-concurrent*.

Step 3. Write the applicable equations of equilibrium (see Table 14.1).

$$\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \Sigma M_A = 0$$

The moment equation can be taken about any arbitrary point. In this case, point A is selected because it eliminates the moment due to  $R_L$ , which simplifies the resulting equations.

Step 4. Substitute the unknowns from the free-body diagram into the equations of equilibrium.

$$\Sigma F_y = R_L + R_R - F = 0 \qquad (a)$$

$$\Sigma M_A = R_R L - F(2/3)L = 0 \qquad (b)$$

Step 5. Solve the equations. Because only one unknown is involved, it is simplest to solve Equation (b) first:

$$R_R = 2/3 F$$

which is substituted into Equation (a) to give:

$$R_L = 1/3 F$$

Step 6. Check the solution and interpret the results. Suppose that  $L = 15$  ft and  $F = 9000$  lb. Substituting these values into the solutions above yields:

$$R_R = 2/3 F = 6000 \text{ lb}$$

$$R_L = 1/3 F = 3000 \text{ lb}$$

Clearly,  $R_R + R_L = F$ . In addition, it should seem intuitively logical that

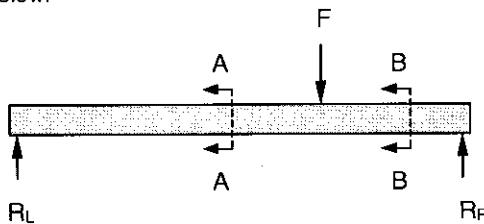
$R_R$  is greater than  $R_L$  because the force is located at  $2/3 L$ .

**Internal Forces and Moments**

In order to be able to accurately analyze many structural elements (e.g., beams that are in a state of bending), it is necessary to be able to calculate internal forces and moments. As shown in the following example, this is performed by constructing a series of imaginary slices through the element, and then applying the appropriate equations of equilibrium.

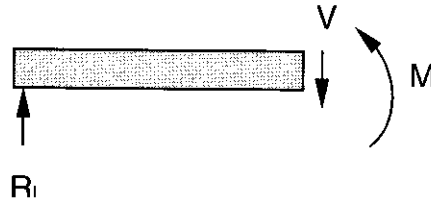
**Example 14.5**

Calculate the internal forces and moments in the beam analyzed in Example 14.4. The complete free-body diagram, showing all the applied and reaction forces, is shown below:



**Example 14.5 (Continued)**

An imaginary cut is made at A-A, located a distance  $x$  from the left support, but not past the applied load  $F$ . The right-hand portion of the beam is removed, and a free-body diagram of the left-hand remainder is drawn:



Since there are no external forces in the  $x$ -direction, the only forces will be in the  $y$ -direction. In order to satisfy equilibrium, there must be another vertical force to balance the reaction force  $R_L$ . The force  $V$  (referred to as a *shear force*) is drawn on the right end of the sectioned portion of the beam. Because  $V$  and the vertical reaction force,  $R_L = 3000$  lb, are offset by the distance  $x$ , they both create a moment. Therefore, there must also be an internal moment,  $M$ , to counteract the applied moment. By applying the equilibrium equation:

$$\Sigma F_y = 0 = R_L - V$$

it is evident that  $V = R_L = 3000$  lb

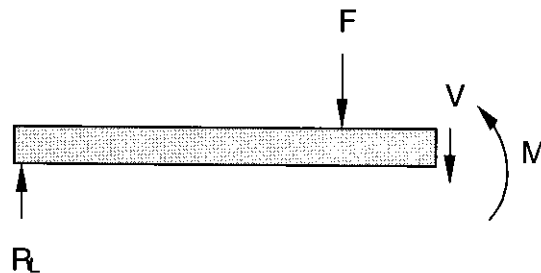
In other words, there is a constant vertical shear force,  $V$ , which is equal in magnitude, but opposite in direction to  $R_L$  anywhere along the left-hand portion of the beam. By applying the other equilibrium equation:

$$\Sigma M_{A-A} = 0 = -R_L x + M$$

It can be seen that the internal bending moment increases linearly with  $x$ :

$$M = R_L x \quad 0 < x < 10 \text{ ft}$$

A similar imaginary cut along section B-B, to the right of the applied load, yields a similar free-body diagram.



Applying the first equilibrium equation:

$$\Sigma F_y = 0 = R_L - F - V$$

$$3000 - 9000 - V = 0$$

which leads to  $V = -6000$  lb

The negative sign indicates that the assumption that  $V$  points downward is incorrect, and in fact,  $V$  is an upward shear force in this portion of the beam.

**Example 14.5 (Continued)**

To find the internal bending moment in this portion of the beam, again, write a moment equation:

$$\Sigma M_{A-A} = 0 = -R_L x + F(x-10) + M$$

$$-3000x + 9000(x-10) + M = 0$$

$$\text{which leads to } M = 90000 - 6000x \quad 10 < x < 15 \text{ ft}$$

These results can be summarized graphically in shear and bending moment diagrams (Figure 14.11). The main point to notice is that the bending moment is maximum under the applied load and is zero at the supports.

Shear and bending moment diagrams for several common loading conditions are shown in Appendix 13.A, located at the end of this chapter. Detailed equations for deformation and stress of more complex structures and/or loading situations may be found in other references [1].

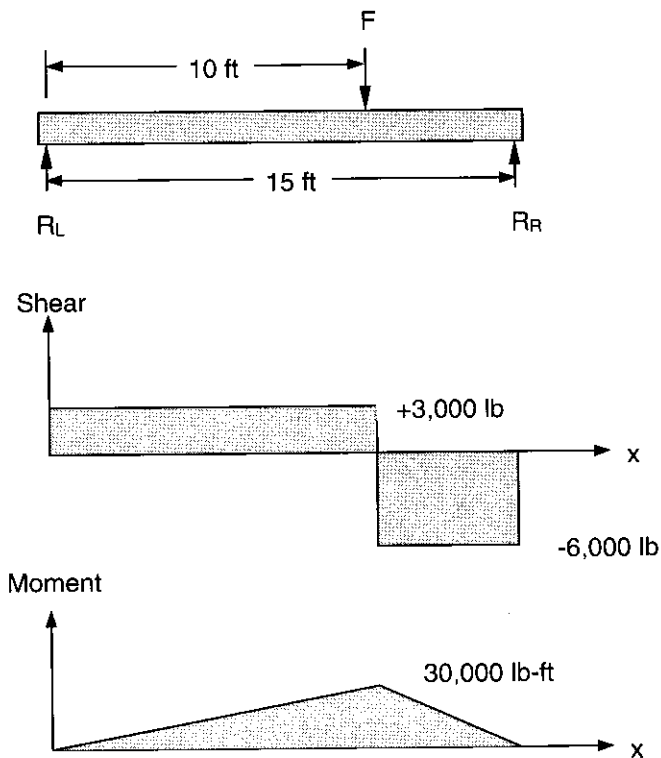


Figure 14.11. Shear and bending moment diagrams for a simply supported beam.

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## MECHANICS OF MATERIALS

In analyzing problems from a statics viewpoint, structures are considered to be ideal rigid bodies that neither deform nor fail. Statics is a useful tool that allows all the external and internal forces to be calculated. In reality, of course, structures deform and fail, depending on the material they are made from and the loads applied. In order to analyze how materials actually behave under load, it is

necessary to introduce the concepts of stress and strain. In order to analyze structures from this point of view, it is necessary to first use statics to solve for all the external and internal forces that act on a body.

## Stress

Internal forces that develop within a structural member when it is subjected to external loads generate stresses in the material. Although the state of stress in most real structures is complex and beyond the scope of this text, some simple concepts are useful tools for analyzing many engineering designs.

### Tension

The simplest state of stress arises in uniaxial tension (e.g., a rope). In this case, a *normal stress*<sup>4</sup> is uniformly distributed across the circular cross section of the rope (Figure 14.12). Normal stress is calculated by:

$$\sigma = P/A \quad (\text{Equation 14.3})$$

where

$P$  = internal force at any point [lb] or [N.]

$A$  = cross-sectional area [ $\text{in.}^2$ ] or [ $\text{mm}^2$ ]

The units of stress are usually pounds per square inch (psi), or Newtons per square millimeter, more commonly called megapascal (MPa)<sup>5</sup>.

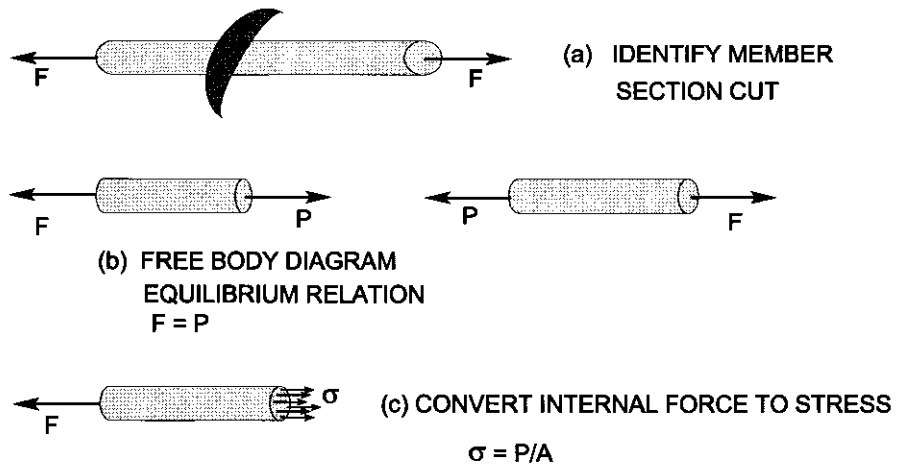


Figure 14.12. Normal stress due to uniaxial tension.

4. "Normal" means perpendicular to the circular cross-section, as opposed to "usual."
5. Blaise Pascal (1623-1662), the French thinker and mathematician worked intensely on scientific and mathematical questions during his short life. He invented a mechanical calculator to help his father, a tax collector. He became interested in probability while calculating odds when gambling. The Pascal programming language is named after him, and the unit, a Pascal, is one Newton per square meter.

### Compression

Uniaxial compression is opposite to tension; i.e., a material is being squeezed together instead of pulled apart. The normal stress for this type of loading is also calculated by Equation 14.3. However, engineers should be aware that any member in compression may suddenly buckle laterally, especially if it is long and slender (Figure 14.13). A more complete reference should be consulted if buckling is suspected [2].

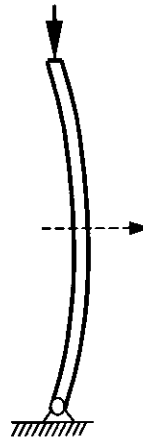


Figure 14.13. Long, slender members in compression may buckle laterally unexpectedly.

#### Example 14.6

Calculate the compressive stress underneath a 150-lb woman wearing a “spike” high-heeled shoe with a  $\frac{1}{4}$  in. circular diameter.

The area of a circle is:  $A = \pi D^2/4 = \pi (.25)^2/4 = .049 \text{ in.}^2$

The stress is then:  $\sigma = P/A = 150 \text{ lb}/.049 \text{ in.}^2 = 3056 \text{ psi}$

### Bending

Bending describes a more complex state of loading than pure tension or compression. In general, bodies are weaker and deflect more in bending than in pure tension or compression. For example, a paper clip can be easily straightened out by hand. But once straight, it is impossible to apply enough force by hand to stretch or pull the wire apart in tension. The state of stress for a body in bending is shown in Figure 14.14, which shows that the normal stress varies linearly across the section, from compression on one side to tension on the other.

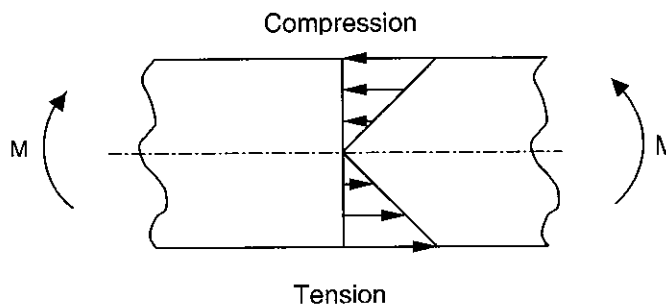


Figure 14.14. State of stress for a body in bending.

Although the stress varies linearly across the section, the designer is primarily interested in the maximum normal stress, which is given by:

$$\sigma_{\max} = \pm Mc/I \quad (\text{Equation 14.4})$$

where

$M$  = bending moment

$I$  = rectangular moment of inertia

$c$  = half the height of the beam

The plus sign signifies a tensile stress, and the minus sign a compressive stress. The rectangular moment of inertia,  $I$ , is a geometric property of the cross section. While the calculation of  $I$  for a general shape can be a complex calculation, Table 14.2 lists the formulae for  $I$  for several commonly encountered shapes.

Although each state of bending is unique, some general rules apply:

- ♦ The maximum stress occurs where the bending moment is maximum. Knowing the maximum bending moment requires a complete understanding of all the forces acting on the body (see Example 14.5).
- ♦ The state of stress for a body in bending varies from tension on one side to compression on the other, but almost all engineering analyses are based on maximum stress as given by Equation 14.4.

Table 14.2. Rectangular moment of inertia ( $I$ ) for some simple shapes.

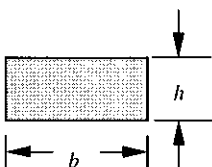
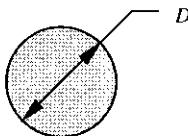
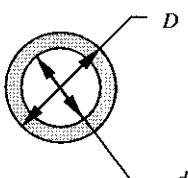
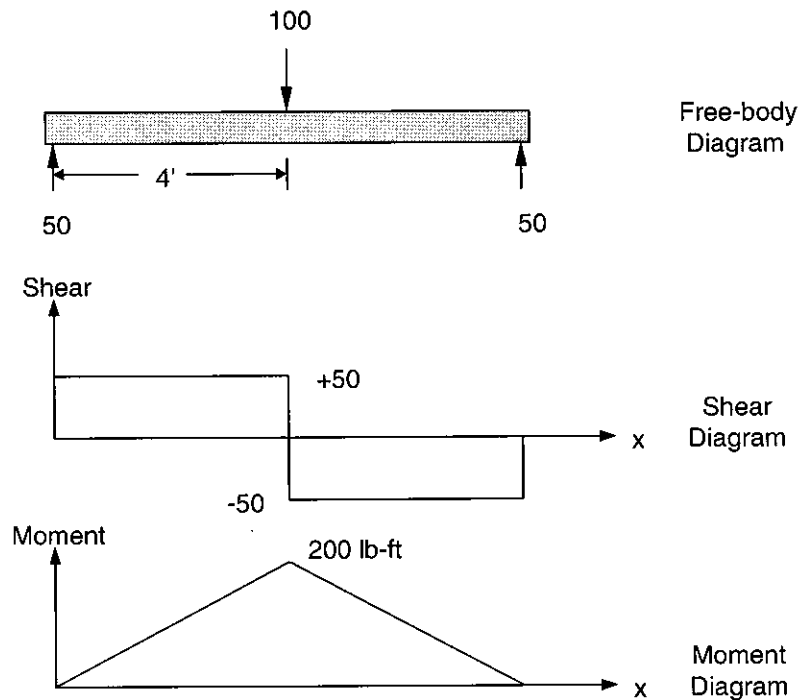
Rectangular		$I = \frac{bh^3}{12}$
Solid Circular		$I = \frac{\pi D^4}{64}$
Hollow Circular		$I = \frac{\pi(D^4 - d^4)}{64}$

Table 10.2 Rectangular moment of inertia ( $I$ ) for some simple shapes

**Example 14.7**

Calculate the maximum bending stress for a wooden "2 by 4" eight feet long supporting a 100-lb boy, if it is: a) lying flat, or b) standing on edge.

It is necessary to first compute the maximum bending moment. The free-body diagram shown below leads to the moment diagram, which reveals the maximum moment to be 200 lb-ft.



a) A 2 x 4 actually measures 1.5 in. by 3.5 in.<sup>6</sup> Therefore, the moment of inertia is given by (see Table 14.2):

$$I = 1/12 bh^3 = 1/12 (3.5)(1.5)^3 = .984 \text{ in.}^4$$

The maximum normal stress is calculated by Equation 14.4:

$$\sigma_{\max} = \pm Mc/I = \pm (200 \text{ lb-ft})(12 \text{ in./ft})(.75 \text{ in.})/(.984) = \pm 1830 \text{ psi}$$

This value for  $\sigma_{\max}$  can be compared to the strength of wood to see if it will break. Douglas fir, a common type of wood, can withstand a stress of approximately 6500 psi before it breaks. This allows us to calculate the factor of safety (described in more detail later):

Factor of Safety (FS) = Strength/Stress, or

$$FS = 6500/1830 = 4.8$$

Since  $FS > 1$ , we can predict that this board will *not* fail.

6. When lumber was first used for construction, it was rough-sawn into various rectangular shapes, including one that measured 2 in. by 4 in. Later, lumber was given a smooth finish cut, reducing its overall size to 1.5 in. by 3.5 in., but the original name of "2 by 4," or "2 x 4," is still used.

**Example 14.7 (Continued)**

b) When the board is standing on edge, it is necessary to use different values to calculate  $I$  and  $c$ :

$$I = 1/12 bh^3 = 1/12 (1.5)(3.5)^3 = 5.36 \text{ in.}^4$$

which gives rise to a bending stress of:

$$\sigma_{\max} = \pm Mc/I = \pm (200 \text{ lb-ft})(12 \text{ in./ft})(1.75 \text{ in.})/(5.36) = \pm 784 \text{ psi}$$

Notice that the bending stress when the board is standing on edge is less than half what it is when lying flat. Since most of the loads in buildings are due to gravity, boards that support floors ("joists") or roofs ("rafters") are always mounted on edge.

**Torsion**

Torsion describes the situation when a long, slender component is twisted about its long axis. As shown in Figure 14.15, a circular shaft in torsion develops a *shear stress* ( $\delta$ ) that varies linearly from zero at the center to a maximum at the outer diameter of the shaft.

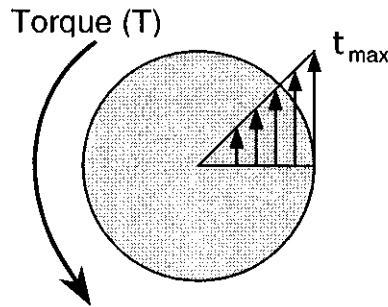


Figure 14.15. Distribution of shear stress in a shaft in torsion.

The maximum shear stress can be calculated by:

$$\delta_{\max} = \pm Tc/J \quad (\text{Equation 14.5a})$$

where

$T$  = applied torque

$J$  = polar moment of inertia

$c$  = half the diameter of the shaft

Since most shafts are circular, we know that the polar moment of inertia is given by:

$$J = \pi d^4/32$$

Substituting into Equation 14.5a, we can obtain the following equation for maximum shear stress:

$$\delta_{\max} = \frac{16T}{\pi d^3} \quad (\text{Equation 14.5b})$$

When computing factor of safety, one needs to compare the maximum shear stress with the allowable shear strength for the material. Finding this material property is beyond the scope of this text, but for now, use half the published value for ultimate tensile strength.



## Strain

If bodies were perfectly rigid, they would not deflect when loads were applied to them. However, most engineering materials are *elastic*, which means that they deform linearly under load according to Hooke's Law<sup>7</sup>:

$$\sigma = E \epsilon \quad (\text{Equation 14.6})$$

$\sigma$  = normal stress [psi] or [Mpa]

where  $E$  = material property known as the modulus of elasticity  
[psi] or [Mpa]

$\epsilon$  = strain in the material [in./in.] or [mm/mm]

## Tension or Compression

By substituting the definitions of stress and strain into Equation 14.6, the deformation for a body in pure tension or compression (assuming it does not buckle laterally) is given by:

$$\delta = PL/AE \quad (\text{Equation 14.7})$$

where  $P$  = applied load [lb] or [N]

$L$  = length of wire [in.] or [mm]

$A$  = cross-sectional area of wire [in.<sup>2</sup>] or [mm<sup>2</sup>]

## Torsion

A common engineering component is a circular shaft used to transmit torque. For example, the engine in an automobile delivers torque to the driving wheels through a drive shaft. A shaft in torsion (Figure 14.16) twists through an angle that can be calculated by:

$$\theta = TL/JG \quad (\text{Equation 14.8a})$$

$\theta$  = angle of twist [rad]

where  $T$  = applied torque [lb-in.] or [N-m]

$L$  = length of shaft [in.] or [mm]

$J$  = polar moment of inertia ( $J = \pi d^4/32$  for circular shafts)

$G$  = shear modulus of material (see Table 14.3)

Since most shafts *are* in fact circular, we can rewrite Equation 14.8a to be:

$$\theta = \frac{32TL}{\pi d^4 G} \quad (\text{Equation 14.8b})$$

7. Robert Hooke (1635–1703), one of the greatest experimental scientists of the 17<sup>th</sup> century, was a generalist of astonishing scientific scope who made lasting contributions to our understanding in optics, mechanics, geography, architecture, materials science, clock-making, paleontology and microbiology. He is less known for his realization—250 years before Darwin—that fossils document the changes to organisms on the planet.

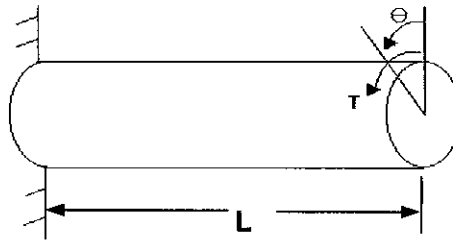


Figure 14.16. Shaft in torsion.

### Bending

Beams in bending are more common in most engineering designs than pure tension or compression. Bending deflection is a complex phenomenon that is beyond the scope of this text. However, the equations in Appendix 14.A can be used to calculate many commonly encountered loading conditions.

Table 14.3. Properties of some common materials.

Material	Modulus of Elasticity (E) GPa (Mpsi)	Modulus of Rigidity (G) GPa (Mpsi)	Yield Strength ( $S_y$ ) MPa (Kpsi)	Ultimate Strength ( $S_{ut}$ ) MPa (Kpsi)
1018 Steel	207.0 (30.0)	79.3 (11.5)	220 (32.0)	341 (49.5)
303 Stainless Steel	190.0 (27.6)	73.1 (10.6)	267 (40.0)	601 (87.3)
2024-T4 Aluminum	71.0 (10.3)	26.2 (3.8)	296 (43.0)	446 (64.8)
Copper	119.0 (17.2)	44.7 (6.5)	69-304 (10-44)	221-331 (32-48)
Wood (Douglas Fir)	11.0 (1.6)	4.1 (0.6)	24.8 (3.6)	45 (6.5)
Plexiglass (Acrylic)	2.6-3.5 (.37-.5)	-	N/A	62-86 (9-12.5)
ABS Plastic (GP)	2.1 (.31)	-	N/A	41 (5.9)
PVC Plastic	2.1-3.5 (.3-.5)	-	N/A	35-55 (5-8)
P1500 Polyester <sup>a</sup>	.83 (.13)	-	N/A	19 (2.8)

a. This material is used in the Genisys rapid prototyping machine.

#### Example 14.8

Calculate the amount of bending for the 2 x 4 boards from Example 14.7. From Appendix 13.A(c) the deflection for a simply supported beam is given by:

$$y = Pl^3/48EI$$

a) Therefore, for the board lying flat, the deflection is calculated to be:

$$y = (100 \text{ lb})(96 \text{ in.})^3/(48)(1.6 \times 10^6 \text{ psi})(.984 \text{ in.}^4) = .293 \text{ in.}$$

b) When the board is on edge, the deflection is found to be:

$$y = (100 \text{ lb})(96 \text{ in.})^3/(48)(1.6 \times 10^6 \text{ psi})(5.36 \text{ in.}^4) = .054 \text{ in.}$$

Notice that the deflection is also considerably less when the board is on edge, as well as the stress.

## DESIGN CRITERIA

### Design for Strength

As shown earlier, forces acting on a body induce internal stresses. If the stresses become too large, the material can no longer resist them, and it will either permanently deform, or even fracture. Consider a straight length of wire with a tensile force,  $P$ , applied to it and then increased. Some materials, like ceramics and many plastics, are classified as *brittle*, which means that they have relatively little deformation and fail abruptly. A good example of brittle failure is a piece of chalk, which does not show any apparent signs of bending, and then suddenly snaps. A stress-strain plot, shown in Figure 14.17, shows that a brittle material will fracture when the stress exceeds the ultimate tensile strength of the material,  $S_{ut}$ .

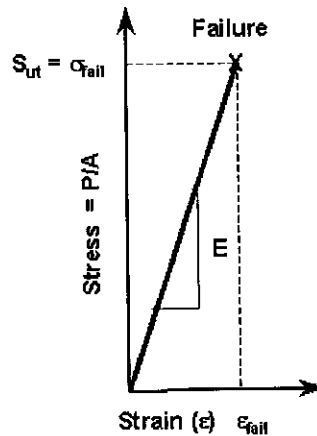


Figure 14.17. Stress-strain graph for a brittle material.

Since tensile stress for pure tension was previously defined to be:

$$\sigma = P/A$$

We can predict that this material will fail when the stress exceeds the strength, or when:

$$P > A S_{ut}$$

Strengths for various commonly used materials are given in Table 14.3.

Although bending is characterized by a variation in stress across the section of a part, the same criterion can be used to predict failure; i.e., when the maximum stress, which occurs at the outside “fiber” of the part, exceeds the material’s ultimate tensile strength.

Other materials, like most metals, exhibit *ductile* behavior. When the stress becomes sufficiently high, the material begins to *yield*, as shown in Figure 14.18. If the load is relaxed after the material yields, it will be permanently deformed. For example, a paper clip can be bent with enough force, and it will stay bent when the force is removed. The material property that quantifies a material’s ability to withstand yielding is termed *yield strength*,  $S_y$  (see Table 14.3).

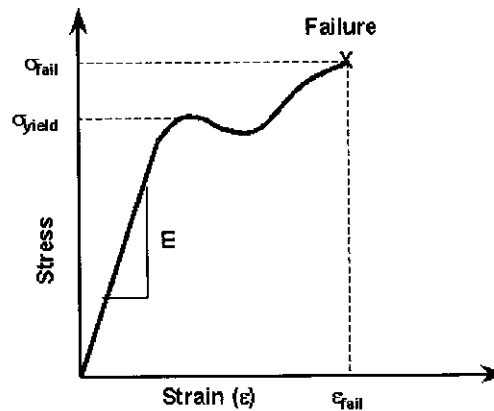


Figure 14.18. Stress-strain plot for a ductile material.

Even if a part has been bent but has not actually fractured, it can no longer do the job for which it was designed. Therefore, yield strength is usually used as the design criterion for strength of ductile materials. Brittle materials, which do not exhibit yielding, are designed using ultimate strength as the design criterion.

### Factor of Safety

The equations presented earlier are idealized models that describe material behavior. The material properties (e.g., yield strength) listed in Table 14.3 are typical values for a given material. However, there is always some uncertainty about the actual strength of a material. Similarly, there is always some uncertainty about the actual loads that a part will encounter. For example, assume an engineer has designed a chair to support someone's weight of *exactly* 250 lb. But if a 250-lb person sits down abruptly, and the impact causes the chair to collapse, is it the user's fault, or the engineer's? Or, perhaps the engineer specified a material with a yield strength of 60,000 psi, but one particular batch of steel only had a strength of 57,000 psi. That chair will not support even a static load of 250 lb.

Therefore, *all* designs should include an appropriate factor of safety, which can be calculated by:

$$FS = \text{Material Strength} / \text{Applied Stress} = S / \sigma$$

Note that  $FS > 1$ . An appropriate standard or code may specify the actual factor of safety.

For example, the State of California mandates that the factor of safety for the wire rope that suspends a passenger elevator must be from 7.6 to 11.9, depending on the speed of the elevator [3]. In other words, an elevator should be able to support up to 11.9 times its rated load before it fails. In other cases, it is up to the engineer to decide the appropriate factor of safety to use, which is a function of:

- ◆ Degree of certainty in material properties
- ◆ Degree of certainty in loading conditions
- ◆ Consequence of failure

It may be surprising to know that the structure of an airplane is typically designed with a factor of safety of only 1.5! Although the consequence of a wing falling off is extremely severe, both the loads that an airplane experiences and the materials from which it is made are extremely well known. If a plane were made with the same factor of safety as an elevator, it would be too heavy to get off the ground.

### Design for Rigidity

Rigidity is usually a more common design goal than strength. For example, it is possible to design the floor of a house so that it will safely withstand the force of someone walking across it. Yet, if the floor is too springy (i.e., it deflects noticeably when a person walks across it), it will be perceived as unsafe, even though it is actually not. This criterion is usually specified as the maximum amount of deflection that a structure may have.

#### Example 14.9

Assume a 50-in. rod must support a load of 100 lb and not extend more than .050 in. If an aluminum ( $E = 10,000,000$  psi) rod is chosen, Equation 14.12 can be solved for the required rod diameter,  $D = .113$  in. But, recall that one of the basic design rules is to "use standard sizes," and this diameter rod is not available, at least not at reasonable cost. Therefore, 1/8 in. (.125) should be selected. Equation 14.12 predicts that the actual deflection will be .041 in., which is within the design requirement of .050 in. maximum deflection.

If even less deflection is required, the designer has two options: use a stiffer material (e.g., steel, which has an elastic modulus three times that of aluminum, or use a larger diameter rod).

The engineer should also check the stress in the rod to ensure that it can handle the 100-lb load. Using Equation 14.9, the stress is found to be 8,150 psi, which is well below the yield strength of aluminum given in Table 14.3.

## UNITS

In the study of mechanics, there are four basic quantities as shown in Table 14.4 (the gravitation constant,  $g$ , relates the units to each other but is not a quantity of measurement in itself).

Table 14.4. Basic quantities and units.

Unit of Measure	US Customary (FPS)	International System of Units (SI)
Length	Foot (ft)	Meter (m)
Time	Second (s)	Second (s)
Mass	Slug ((lb•s <sup>2</sup> )/ft)	Kilogram (kg)
Force	Pound (lb)	Newton (N) (kg•m)/s <sup>2</sup>
Gravitation Constant $g$	32.17 ft/s <sup>2</sup>	9.807 m/s <sup>2</sup>

Two of the units (length and time) are independent. However, in order for force and mass to be dimensionally homogenous, they are related to each other by Newton's second law:

$$\Sigma F = ma$$

In the International System of Units (SI), the units for length, time and mass are specified, and then used to derive the remaining basic unit for force. Length is given in meters (m), time in seconds (s), and mass in kilograms (kg). The unit for force is called a Newton (N) in honor of Sir Isaac. The Newton is derived from Equation 14.16 so that a force of 1N will impart an acceleration of  $1 \text{ m/s}^2$  to a mass of 1 kg [i.e.,  $1 \text{ N} = (1 \text{ kg})(1 \text{ m/s}^2)$ ]. For dimensional homogeneity, it is clear that  $\text{N} = (\text{kg}\cdot\text{m})/\text{s}^2$ . In the SI system, the gravitation constant  $g = 9.807 \text{ m/s}^2$ . With this value of the acceleration due to gravity on Earth, the weight of a mass of 1 kg is:

$$W = mg = (1\text{kg})(9.807 \text{ m/s}^2) = 9.807 \text{ N}$$

In the US Customary System, length is given in feet (ft), time in seconds (s) and force in pounds (lb). The unit for mass is called a slug, which is derived from Equation 14.16 so that a force of 1 lb will impart an acceleration of  $1 \text{ ft/s}^2$  to a mass of 1 slug [i. e.,  $1 \text{ lb} = (1 \text{ slug})(1 \text{ ft/s}^2)$ ]. For dimensional homogeneity, it is clear that a slug =  $(\text{lb}\cdot\text{s}^2)/\text{ft}$ . In the US Customary System, the gravitation constant  $g = 32.17 \text{ ft/s}^2$ .

In addition to the quantities presented in Table 14.4, several other quantities are useful for statics and strength of materials, listed in Table 14.5.

Table 14.5. Units of other frequently used quantities.

Unit of Measure	US Customary	SI Equivalent
Moment M	foot-pound (ft•lb)	newton-meter (N•m)
Stress $\sigma$	pound/square foot (lb/ft <sup>2</sup> )	Pascal (Pa = (N/m <sup>2</sup> ))
Strain $\epsilon$	dimensionless	dimensionless

The quantities in Table 14.5 are given in terms of the basic units for length, time and force. However, in practice other units are often employed. For instance, moment may be expressed as in•lb instead of ft•lb, and stress expressed as MPa (mega Pascal) instead of Pa ( $1 \text{ MPa} = 1,000,000 \text{ Pa} = 1 \text{ N/mm}^2$ ) or psi (lb/in.<sup>2</sup>) instead of (lb/ft<sup>2</sup>). Conversions between the two systems are listed in Table 14.6.

Table 14.6. Unit conversion factors.

Unit of Measure	US Customary	SI Equivalent
Acceleration	ft/s <sup>2</sup>	0.3048 m/s <sup>2</sup>
	in./s <sup>2</sup>	0.0254 m/s <sup>2</sup>
Area	ft <sup>2</sup>	.0929 m <sup>2</sup>
	in. <sup>2</sup>	645.2 mm <sup>2</sup>
Energy	ft•lb	1.356 J

Table 14.6. Unit conversion factors. (Continued)

Unit of Measure	US Customary	SI Equivalent
Force	Kip	4.448 kN
	lb	4.448 N
Impulse	lb•s	4.448 N•s
Length	ft	0.3048 m
	in.	25.40 mm
	mi	1.609 km
Mass	lb mass	0.4536 kg
	slug	14.59 kg
	ton mass	907.2 kg
Moment	ft•lb	1.356 N•m
	in.•lb	0.1130 N•m
Area Moment of Inertia	in. <sup>4</sup>	0.4162 x 10 <sup>6</sup> mm <sup>4</sup>
Power	ft•lb/s	1.356 W
	hp	745.7 W
Stress and pressure	lb/ft <sup>2</sup>	47.88 Pa
	lb/in. <sup>2</sup> (psi)	6.895 kPa
Velocity	ft/s	0.3048 m/s
	in./s	0.0254 m/s
	mi/h (mph)	0.4470 m/s
Volume	ft <sup>3</sup>	0.02832 m <sup>3</sup>
	in. <sup>3</sup>	16.39 cm <sup>3</sup>
	gal	3.785 l
Work	ft•lb	1.356 J

## CONCLUSION

One of the characteristics of *engineering design*, as opposed to trial-and-error, is the use of *analysis*, which allows the engineer to make design decisions based on analysis, before parts are built. Engineering mechanics is an important analysis tool that can predict how physical parts of a design will react to forces. While a thorough understanding of this complex topic requires several semesters of in-depth study, the purpose of this chapter is to provide enough details to allow students to design parts that will neither break, nor bend too much.

The following method applies to many design situations:

1. Use *statics* to understand the complete state of external and internal forces and moments that act on a body, assumed for the moment to be rigid.
2. Calculate the *stress* (e.g., Equations 14.3, 14.4) that develops inside a body when forces act on it.
3. Compare the stress to the strength of the material and calculate the factor of safety.
4. Calculate how much a body will *deform* in reaction to applied forces (e.g., Equations 14.6, 14.7).
5. Adjust the dimensions or material to make sure that the part will perform as intended.

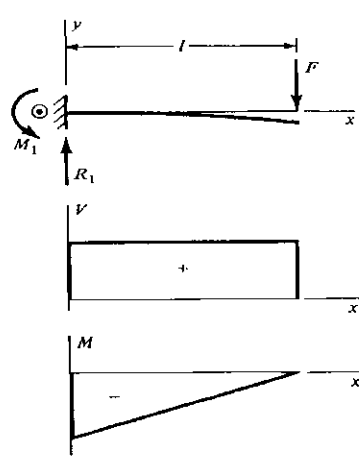
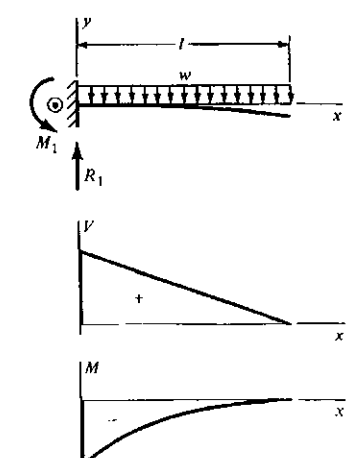
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## REFERENCES

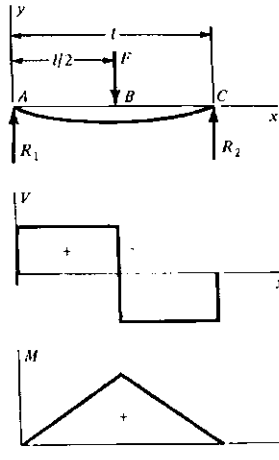
1. Young, W.C., *Roark's Formulas for Stress and Strain*, Sixth Ed., McGraw-Hill, 1989.
2. Shigley, J.E. and Mischke, C.R., *Mechanical Engineering Design*, Fifth Edition, McGraw-Hill, 1989.
3. California Division of Industrial Safety, Department of Industrial Relations, Subchapter 6. *Elevator Safety Orders*.



### APPENDIX 14.A: Shear, Moment and Deflection of Some Simple Loading of Beams.

<p>a) Cantilever beam — concentrated load</p> 	$R_1 = F$ $M_{MAX} = Fl$ $Y_{MAX} = \frac{Fl^3}{3EI}$
<p>b) Cantilever beam — uniform load</p> 	$R_1 = wl$ $M_{MAX} = \frac{wl^2}{2}$ $Y_{MAX} = \frac{wl^4}{8EI}$

c) Simple supports — center load

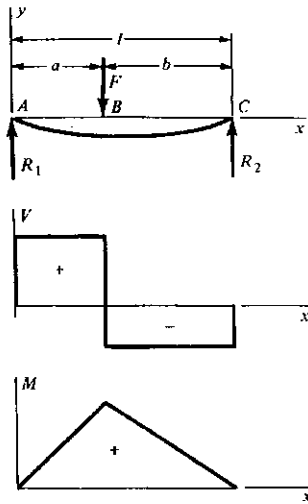


$$R_1 = R_2 = \frac{F}{2}$$

$$M_{MAX} = \frac{Fl}{2}$$

$$Y_{MAX} = \frac{Fl^3}{48EI}$$

d) Simple supports — intermediate load  
(a < b)

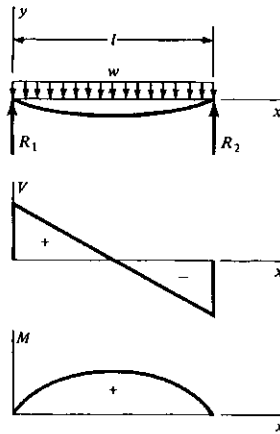


$$R_1 = \frac{Fb}{l} \quad R_2 = \frac{Fa}{l}$$

$$M_{MAX} = \frac{Fab}{l}$$

$$Y_{MAX} = \frac{Fab(a^2 + b^2 - l^2)}{6EI}$$

e) Simple supports — uniform load

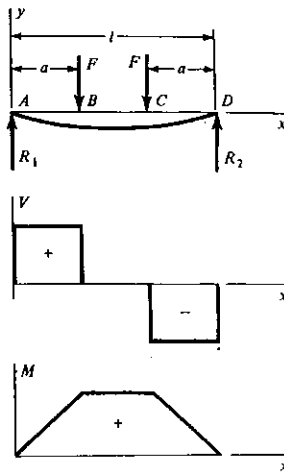


$$R_1 = R_2 = \frac{wl}{2}$$

$$M_{MAX} = \frac{wl^2}{8}$$

$$Y_{MAX} = \frac{5wl^4}{384EI}$$

f) Simple supports — axle loading



$$R_1 = R_2 = F$$

$$M_{MAX} = Fa$$

$$Y_{MAX} = -\frac{Fa}{24EI}(4a^2 - 3l^2)$$

# Measurements and Instrumentation

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## INTRODUCTION

Measurements are made for a variety of reasons, and these reasons shape the type of measurement techniques and equipment that are available. Examples include measurements of a controlled process like building heating or the manufacture of soft drinks, performance measurements such as the ultimate strength of a bolt or the efficiency of an aircraft engine, hypothesis testing for comparison to theory, such as the behavior of a chaotic forced pendulum, or the simple need to know "does it work now that I've plugged it in and turned it on?" In this introductory engineering projects course, measurements will be needed to make sure the design process goes according to plan and to test the performance of the finished product.

Prior to making any kind of measurement, there are a number of considerations that must be made before deciding on a technique.

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## Measurement Considerations

### Static vs. Dynamic

The first measurement consideration, is the quantity being measured changing with time? For example, if the strain in a snowboard with a rider standing still is needed, it does not matter when the measurement is made; one moment is as good as the next, as long as the conditions have not changed. This is called a *static* measurement. On the other hand, if a measurement of the maximum strain in a snowboard during landing after a jump is required, a series of measurements should be made very quickly as the board makes contact with the snow. How many measurements to make, how fast to make them and how to trigger the start of the measurement sequence will have to be decided in advance. In engineering jargon, the measurement of a time-varying quantity is called a *dynamic* measurement. The number of measurements is sometimes called record length or number of scans, and the rate of measurement (sample rate) is expressed in samples or cycles per second, with units of Hertz.

Another factor that must be considered in advance is whether or not the measurement device can respond to the quickly changing strain level. How fast a device can respond is expressed by its *frequency response*. Specifically, frequency response indicates how a device responds to a signal of sine wave shape. A device described as flat up to 1 kHz can track sine wave signals of frequencies ranging from 0 to 1 kHz, but it cannot keep up with higher frequency signals. So if a snowboard is vibrating at 2 kHz, and the strain gage is only good to 1 kHz, the output from the gage will be lower than it should be.

On a practical level, static measurements are often one-of-a-kind, and the results are as easily written in a notebook as entered into a spreadsheet. Dynamic measurements may be made so fast (MHz!) or in such large quantities (1 sample every 5 minutes for three weeks) that a computer is required to control the sample rate and record the data. Computer-based data acquisition systems generally read electrical voltages, so the measured quantity will have to be changed (transduced) into a voltage signal. Knowing ahead of time whether a static or a dynamic measurement is needed dictates what kind of measurement equipment can be used.

This chapter focuses on simple, static measurements that can be made using a self-contained measurement device. If a dynamic measurement is needed, check with the course instructor on the availability of an appropriate, existing system.

### **Resolution**

Another question to consider before choosing a measurement technique is "how good does the measurement have to be?" For example, if a measurement of the thickness of a piece of aluminum foil is needed, will an ordinary ruler do the job? Only if a very crude measurement is acceptable: the smallest quantity that a ruler can resolve is  $1/16^{\text{th}}$  of an in. The thickness of aluminum foil is smaller than that. A measurement device with much higher resolution is needed, such as a micrometer.

The term *resolution* has at least three meanings with respect to a measurement device. First, the most common meaning is the resolution in the quantity of interest, like the smallest division on the ruler. A device with high resolution is often called *high precision*. Second, a measurement also has a resolution in time; i.e., if it takes several seconds to make a measurement, and the measured quantity changes during that time, then the measurement is poorly resolved in time. Similarly, if the measurement is of a quantity that varies in space, i.e., the quantity is different from one side of the measurement device to the other, then better spatial resolution is needed. For example, if the speed of water at different locations across the diameter of a pipe is needed, then a device that only measures the average water speed will not be useful.

### **Uncertainty**

Another aspect of "how good does the measurement have to be?" has to do with the fact that no measurement is 100% perfect; there is always the possibility of error—a difference between the measurement and the true value. Error might be due to inaccurate calibration, such as a speedometer that consistently reads high. This type of error is known as *bias* or *systematic* error. A device with a low bias error is often termed *highly accurate*, although not necessarily *precise*, which relates to

the resolution of the device or the repeatability of the measurement. Another type of error might be due to uncontrollable variables, such that every time the same measurement is made, it is a little different. This second type is called *random* error. In any case, when a measurement is made, the exact size of the errors is never known, so the true value of what is measured is uncertain. However, the likely range of possible errors can always be estimated to some degree. This is called *uncertainty analysis* [1, 2]. This topic is covered in first-year chemistry and physics courses, but for now keep in mind that it is a good idea to check the calibration of measurement tools (measure known values now and then) and make several repeated measurements, just to see if there is a range of values.

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## MEASUREMENT TOOLS

### Dimensional (Size) Measurements

Ordinary rulers measure flat objects a maximum of one foot in length, with a resolution of  $1/16^{\text{th}}$  in. or 1 mm. To measure larger dimensions, a yardstick could work, but its resolution may be only  $1/8^{\text{th}}$  in. A tape measure can be up to 50 ft in length, with a resolution of  $1/16^{\text{th}}$  in. at best. Measurement of larger objects requires surveying tools. Going in the other direction, a machinist's rule represents the next step up in accuracy. Usually these are made of flexible steel, are 4 to 6 in. in length and have a maximum resolution of .01 in.

Even more accurate are measuring calipers, which measure things up to 8 in. with a resolution of  $\pm 0.001$  in. ( $\pm 0.03$  mm). Calipers are excellent for measuring the inner and outer diameters of round objects and the depths of small holes. They may have a dial readout, a digital readout or a vernier scale [3]. The highest accuracy common device, a micrometer, has a range limited to an inch or two, but an accuracy of  $\pm 0.0005$  in. ( $\pm 10$   $\mu\text{m}$ ). Measurements of such high precision (a human hair is approximately 0.002 in.) are sensitive to applied pressure, temperature and surface cleanliness — factors that must be controlled for precision measurements. Micrometers have a ratchet tightening screw to provide a standard pressure between the tool and the part. Note that all of these dimensional measurement techniques are good for static measurements only. Time-varying dimensional measurements require much more sophisticated techniques.

### Force

Force can be defined as a directed push or pull. The most common force experienced is weight due to gravity. Thus, a scale used to measure the weight of fish in pounds can also be used to measure force in pounds. In fact, fish scales are common, available at hardware and sporting goods stores. They often have hooks on either end, and can measure tensile forces up to 50 lbf, with an accuracy of 2 oz. For measurement of compressive forces up to 5 lbf, a postal scale might be appropriate. A bathroom scale can go up to a few hundred pounds, but with low accuracy and repeatability. High quality laboratory scales for weight measurement are common, but are usually designed to measure small quantities of chemicals with great accuracy, so they are generally not appropriate for

force measurement. Higher quality force measurement techniques require electronic transducers and signal processing [4]. If the application of a known force is needed (for example, to pull on something with a force of 2 lbf), it may be possible to hang calibrated weights to exert the correct force.

### **Temperature**

Liquid-in-glass thermometers are commonly used to measure body temperature (fevers) and for cooking purposes. Mercury, often used as the encapsulated fluid, presents a toxic waste cleanup problem if the thermometer breaks. Alcohol is also common, but is limited at the high temperature end of the scale. A typical high-quality thermometer provides a range from -4 to 300°F with a resolution of 0.1°F. Thermometers are designed to be either fully or partially immersed in a fluid (either gas or liquid); thus, they are less appropriate than thermocouples or thermistors [5] for the measurement of temperature in a solid.

Digital thermometers are increasingly common for laboratory purposes. These devices measure temperature electronically and are packaged with a digital readout. Generally, only the sensor element need be immersed. Accuracies of 2°F are typical, so they are easier to use than liquid-in-glass thermometers, but less accurate.

### **Flow**

A measurement of the flow rate of liquid moving in a pipe can be made using a bucket and a stopwatch. The time it takes to fill the bucket is recorded, and then divided into the mass of fluid measured on a weight scale to yield mass per unit time. As the accuracy of this technique is dependent on a person using a stopwatch and the accuracy of the weight-measuring device, it is better to record over a long period of time, if possible. This method may seem crude, but automated versions of this technique are used by the National Institute of Standards and Technology to calibrate the highest accuracy flow instruments.

If the velocity of a stable air stream is needed, a simple device called a *pitot* (pronounced pea-toe) *static tube* can be used [6]. The pitot-static tube is a double-walled probe that is inserted into the air stream as shown in Figure 15.1. This use of the term "static" has a different meaning than discussed earlier with respect to time-constant quantities. The difference in pressure between the central tube and the side holes is related to the velocity:

$$V = \sqrt{\frac{2(P_{stag} - P_{static})}{\rho}}$$

where  $V$  = velocity,  $p_{stag}$  is the stagnation pressure (measured in the central tube),  $p_{static}$  is the static pressure (measured at the side holes), and  $\rho$  is the air density. When applying this equation, be sure to use the appropriate conversion factor to make the units cancel.

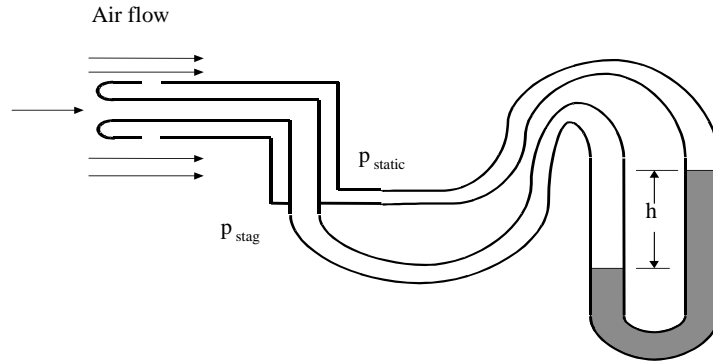


Figure 15.1. Pitot-static tube with manometer.

The pressure difference,  $p_{stag} - p_{static}$ , can be measured using a manometer. This is simply a U-tube partly filled with a liquid of known density (usually a special oil) as shown in Figure 15.1. The different pressures acting on the two surfaces of the liquid in the tube causes one surface to rise, and the other to fall. The difference in height,  $h$ , can be related to the pressure difference  $\Delta p$ :

$$\Delta p = \rho_{liquid} gh$$

where  $g$  is the acceleration of gravity. Again, use units conversion factors as needed. Pitot-static tube/manometer combinations are best used when the air velocity is constant with time, or if an average velocity is desired. Depending on the quality of the manometer, accuracies in pressure measurement of one percent can be expected.

Hand-held electronic velocity meters are commonly used in industry. However, they are often expensive (\$500 or more), may require calibration and are no more accurate than a pitot-static tube/manometer measurement.

## Voltage

Measurement of voltages up to 20V is easy and safe with a hand-held or tabletop digital multimeter (DMM or DVM) [7]. If the voltage is not varying with time, set the meter on DC (direct current). This is appropriate for measuring battery voltages, for example. You may have to choose an expected voltage range, but many meters are auto ranging. If the voltage is varying in a periodic fashion, set the meter on AC (alternating current).

For example, if household AC is measured, it will read 110VAC. Be very cautious when measuring any voltage higher than 20V, AC or DC. The body can easily become a conducting path, and the outcome could be fatal. One safety technique is to first turn off power to the device being studied. Then connect the DMM using clips, stand back and turn the power back on. In any case, the maximum voltage of most DMMs is 200V.

Oscilloscopes are common laboratory tools for measuring a time-varying voltage when an AC measurement provides insufficient information [8]. A screen displays the input voltage as a function of time, as shown in Figure 15.2. The trace is triggered to start the next time the voltage reaches a particular level, at some point during the next cycle of a periodic waveform. Modern scopes provide



an auto-scaling feature, but they are not foolproof. If the expected result does not show on the screen, adjust the rate at which the signal is displayed. This control may be labeled *timebase* or *time/division* where division refers to the squares into which the scope screen is divided. If that does not work, adjust the trigger level.

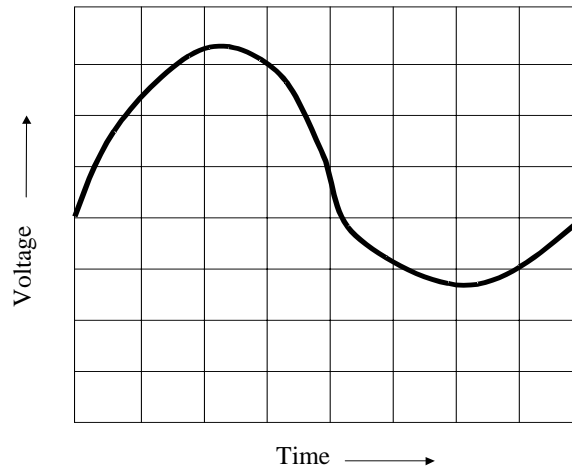


Figure 15.2. Oscilloscope screen.

### Tension / Compression Testing of Materials and Structures

Testing machines that stretch or crush samples are often used to determine the strength of materials and/or structures. As shown in Figure 15.3, a sample is held in the machine by grips. The crossbeam is then programmed to move up or down at a specific speed, and the resulting tensile or compressive loads on the sample are measured by the load cell. The deformation of the sample is called *strain* and is measured in units of inches shortened per inch length of original sample.

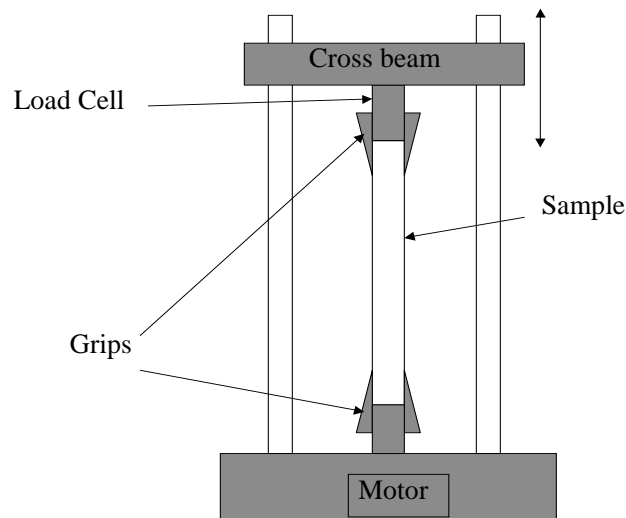


Figure 15.3. Stress-strain testing machine.

The strain is determined by the motion of the crossbeam and can be considered an independent parameter, set by the user. The load cell measures the resulting force, which is thus a depen-

dent parameter. When the force is divided by the area that the force acts over, the result is *stress*. A typical stress-strain curve for a metal that has been pulled to failure is shown in Figure 15.4.

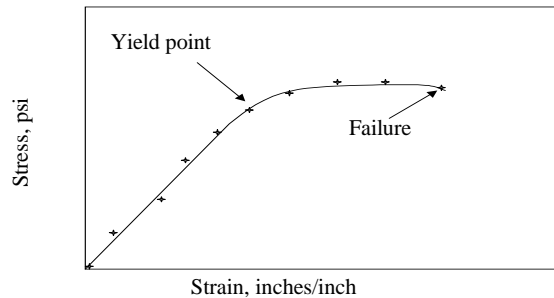


Figure 15.4. Typical stress-strain curve for a metal sample pulled to failure. Data points: +

As the crossbeam begins to move, stress builds up linearly and elastically. Once the strain passes the yield point, the sample will be permanently deformed. It takes little additional stress to continue the deformation. Eventually, the part breaks.

When using such a machine, a number of decisions must be made in advance. The range of expected load (force) must be set. If the load exceeds this range, data could be lost. The rate of strain (how fast the cross bar moves) must be specified too. The time to failure at that strain rate must be estimated, and the number (record length) and rate of load cell samples (data rate) must be programmed in advance as well. Having the strain rate too high and the load cell sample rate too slow could result in having only one or two samples on the chart.

## REFERENCES

1. J.P. Holman, *Experimental Methods for Engineers*, Section 3.4, Uncertainty Analysis, 1994, McGraw-Hill.
2. Ronald H. Dieck, *Measurement Uncertainty Methods and Applications*, 1992, Instrument Society of America.
3. <http://me.mit.edu/lectures/machine/measure/intro.html> This website has a nice description of the use of calipers and micrometers, as well as instructions on basic machine shop techniques.
4. J.P. Holman, *Experimental Methods for Engineers*, Chapter 10, Force Torque and Strain Measurements, 1994, McGraw-Hill.
5. J.P. Holman, *Experimental Methods for Engineers*, Chapter 8, Measurement of Temperature, 1994, McGraw-Hill.
6. R.W. Fox and A.T. McDonald, *Introduction to Fluid Mechanics*, Fourth Edition, pp 241-242, 1992, Wiley and Sons.
7. J.P. Holman, *Experimental Methods for Engineers*, Section 4.5, Basic Digital Meters, 1994, McGraw-Hill.
8. J.P. Holman, *Experimental Methods for Engineers*, Section 4.15, The Oscilloscope, 1994, McGraw-Hill.



# Engineering Analysis

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## INTRODUCTION

Analysis is the breaking down of an object into its basic elements to get to its essence. This process is a means of studying the nature of something and identifying its essential features and their relationships. Analysis is the opposite of synthesis, which is identifying common features in separate entities. The tools for analysis are based upon logic and the application of logical systems (e.g., mathematics, physics and mechanics). The role of analysis in design is a critical one and can be considered the internal guidance system of a project. A project without analysis is like a sports team without a coaching staff or a ship without a rudder.

## The Role of Analysis

A focus of this section is to explore the relationship between analysis and other elements of design. The list of questions and topic areas below address the role of analysis in engineering:

- ◆ The traits of engineers and their relationship with analysis.
- ◆ What comes first: analysis or experience?
- ◆ At what point in the evolution of a design should the guidance from theory be given priority? Guidance from experiment?
- ◆ The seamless interplay between hands-on and theoretical components.
- ◆ Will the application of the tools of engineering remain static?
- ◆ What happens when theory and experiment do not agree?
- ◆ How is it known that an analysis is flawed?
- ◆ How is a design analyzed?
- ◆ What are the types and levels of analysis?
- ◆ Where does analysis begin?
- ◆ Does a project ever begin based solely upon analysis?

- ♦ Try to think of a situation where analysis is the very last thing done.
- ♦ List a few examples of the critical role that analysis has played in engineering design.

## THE TRAITS OF ENGINEERS AND THEIR RELATIONSHIP WITH ANALYSIS

### Engineer Traits

Gibney [1] considers the creative process in the context of improving abilities to generate fresh approaches and products. She reviews four educational programs working in this area, including work in progress at Stanford University by R. Faste, where engineers are encouraged to use “ambidextrous” thinking, or both the left and right hemispheres of the brain. Linear, logical processes and verbal abilities derive primarily from the left side of the brain, and visual-spatial properties, intuition and qualitative assessment skills derive primarily from the right side. An eventual goal as an engineer’s skill evolves is to move towards “whole brain” thinking.

Often, first-year students have significant analytical or creative skills, but have not yet developed the broad set of abilities needed in engineering. University goals are to nurture existing talents as well as to broaden the range of talents. Engineering graduates should have an integrated knowledge of their profession, viewing sub-disciplines and engineering tools as problem-solving resources. Engineers should respect the need for complementary talents in the design process. This respect should naturally extend to other engineers and team members who will typically possess valuable abilities in disparate areas. Figure 16.1, a conceptual figure summarizing these thoughts, indicates initial focus and an idealized broadening of capabilities.

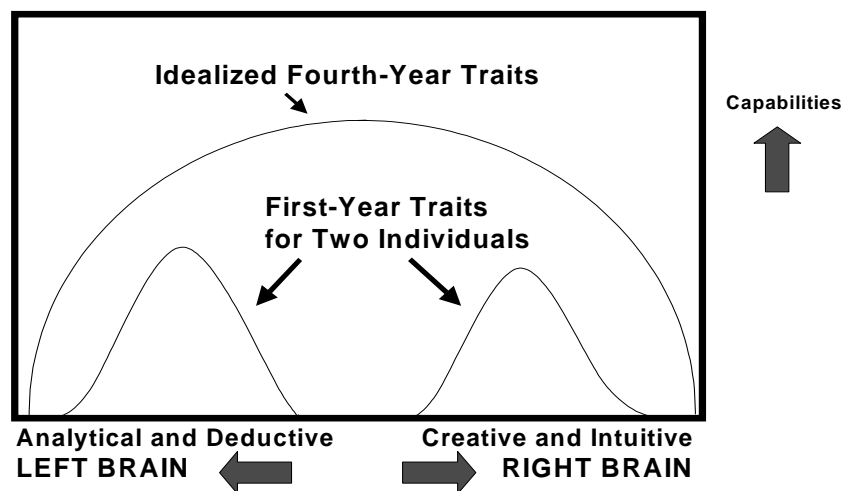


Figure 16.1. First-year vs. fourth-year traits of engineering students.

Two individuals with such focused talents early in their careers will complement one another quite well. Most people will have far more complex distributions of talents than this extreme example. An important moment in the process of improvement is identifying and admitting the need to fill “ability gaps.”

Thus far, this section has discussed analysis in the context of traits and abilities—a philosophical approach. Next, a more practical perspective is taken, in the context of the design process.

## THE ROLE OF ANALYSIS IN THE DESIGN PROCESS

### Complementary Roles

The design process requires different abilities and perspectives at various stages. Several models of this process presented here derive from different engineering disciplines or viewpoints. Though the modes of presentation differ, the fact that the process described is almost identical should give confidence that these models capture the basic elements of the evolution of designs. The diagram in Figure 16.2 captures the design process and considers the complementary roles of different traits of engineers.

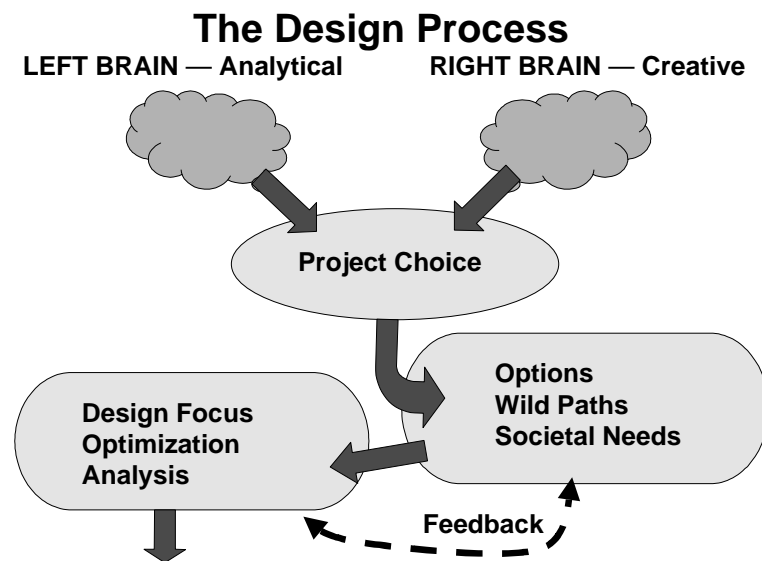


Figure 16.2. The design process, with consideration of the complementary roles of different traits of engineers.

This flow diagram follows the design process in emphasizing how traits derived from both the left and right hemispheres of the brain have critical roles at different times. In the beginning, either or both perspectives can drive the choice of a project. Even this initial choice may require fine-tuning as the sequence of steps continues. The following stage is one where creative brainstorming suggests paths to be investigated. The next stage involves a critical assessment of the possibilities and a first level of analysis, usually resulting in a prioritized list of choices and rational. After this first crack at analysis, there is typically some iteration and another review to make sure additional avenues are considered. Usually, a clear design focus is an outcome of this part of the sequence.

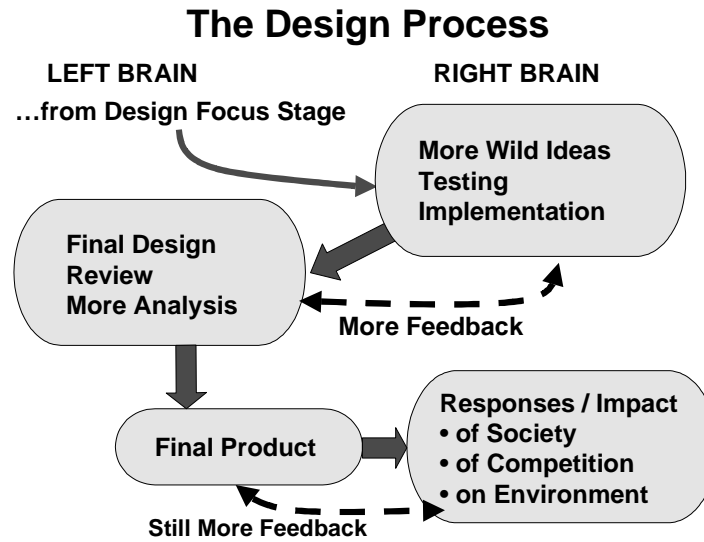


Figure 16.3. The design process continues with iterative stages involving prototypes and final product design.

Next (see Figure 16.3), a creative review of the ways of constructing, testing and implementing the design usually leads to a prototype, or frequently prototypes. This part of the process is more open to new approaches before the design and test results are critically reviewed and analyzed. The elements of the final design—together with recommendations for production, use and marketing—are a key product of this review phase. Again, there is an opportunity for iterative fine tuning to make sure key innovations are incorporated.

Even after the final product is produced, there exists a continual need to monitor the responses to and impacts of the product. A minor design flaw might show up during use, and a small change in materials might make the product safer to use or more friendly to the environment.

### An Iterative Process

Radcliffe [2] presents an alternate view of the design process, which is illustrated in Figure 16.4. This sequence diagram emphasizes the iterative nature of the process. Since new information or a new insight can be discovered at any stage, it may be necessary to return to a previous point in the process. Although Radcliffe adds a problem recognition and a presentation stage, the sequence is quite similar to that presented in Figure 16.2 and Figure 16.3.

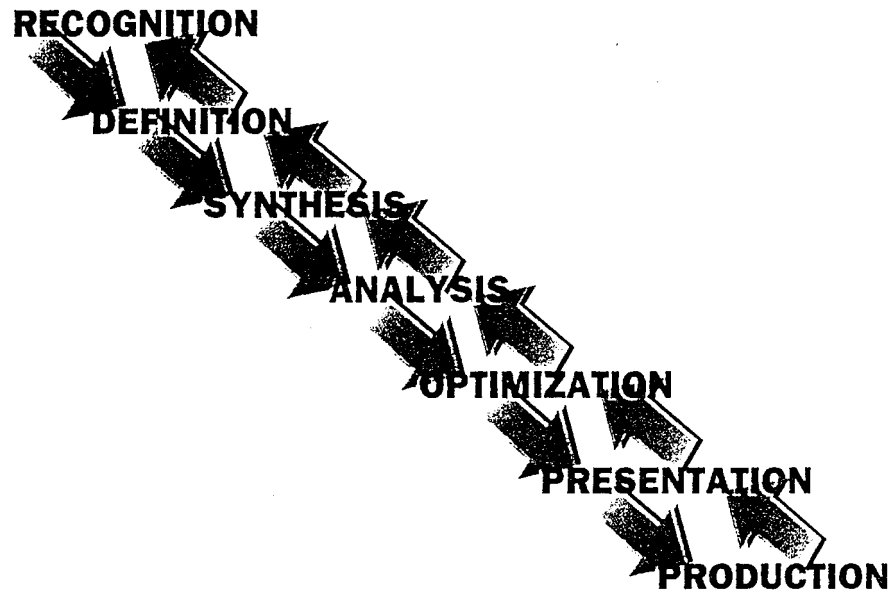


Figure 16.4. Stages in the design process: Several iterations through multiple steps are often required before arriving at a successful design. Source: Radcliffe [2].

### The Design Spiral

Designing a submarine is an especially challenging project. There are constraints of size and weight, environmental challenges (depth and pressure), critical life support needs, hull design, mission requirements, as well as propulsion and energy requirements. Decisions on each of these elements can greatly impact all or many of the other elements. Submarine engineers have developed the design spiral as a model to ensure that the various elements integrate in a methodical way [3]. This process, reproduced schematically in Figure 16.5, helps to ensure that the strong interactions between sub-components are accounted for at all stages. As one moves from the outside of the spiral to the inside each of the systems is re-visited in an interactive way, moving toward the final design. Other complex systems—such as aircraft, space vehicles and chemical plants—offer similar challenges in which each of the components explode into a design process embedded in a larger one demanding tremendous care in integration. Analysis is the umbrella that protects the total system—tying everything together and ensuring that a minor change in one sector of a design does not cause a disaster in another.



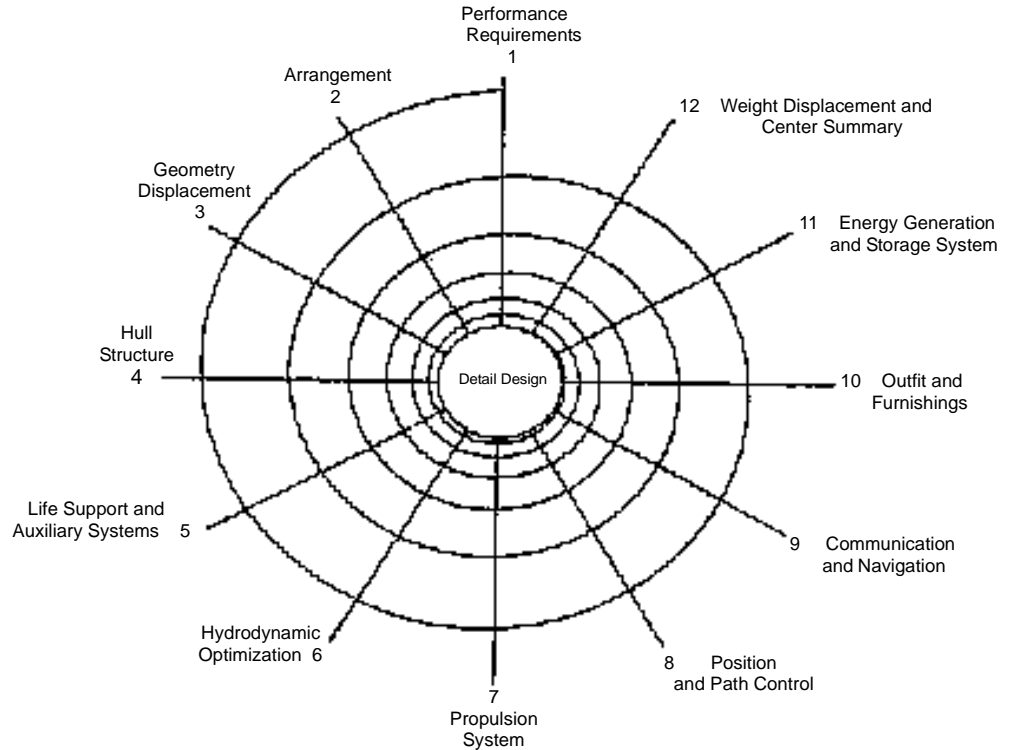


Figure 16.5. The “design spiral” model of the design process helps submarine engineers ensure that all design elements integrate in a methodical way. Source: Allmendinger [3].

### Design Definition

Dieter [4] presents an interesting set of final designs (see Figure 16.6) to emphasize the importance of the definition of the design problem. This figure also shows how critical an integrated and well-coordinated design process is to a sensible outcome.

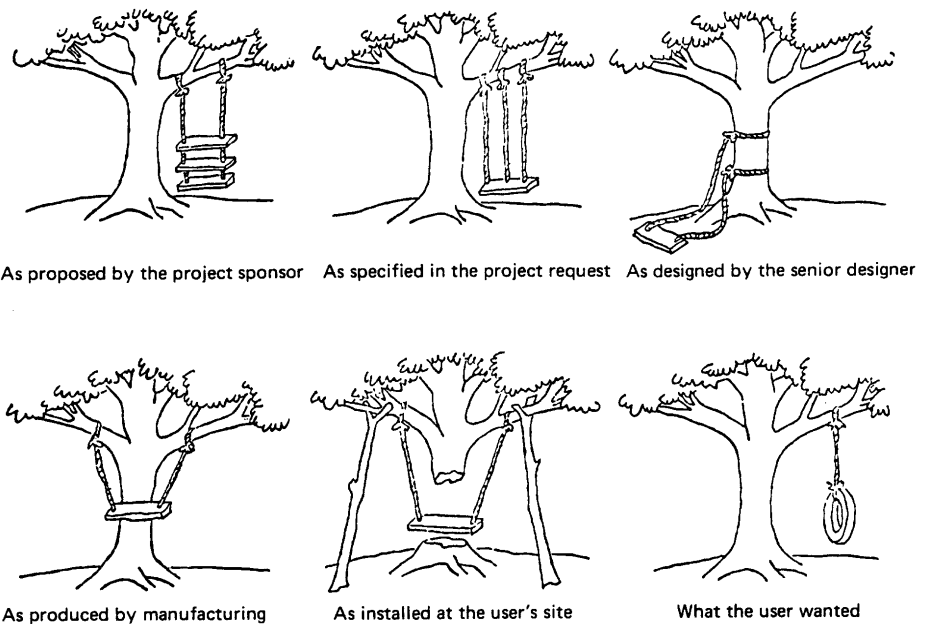


Figure 16.6. Note how the design depends on the viewpoint of the individual who defines the problem. Source: Dieter [4].

## CONTINUITY BETWEEN THEORETICAL & HANDS-ON ENGINEERING

During the design process, there should be a seamless transition between theory and experiment. An effective engineer respects and understands the relative roles of analysis and practice. An engineer should feel not only comfortable and competent in both areas, but also in transitioning between them. With experience, the choices and application of engineering skills should become a reflex. As students move through their academic careers, the critical roles of the analytical components of their courses become clear.

## EVOLUTION OF ENGINEERING ABILITIES

The evolution of skills should not be limited to an academic career, but be a life-long process. There are many examples of scientific breakthroughs having such far-reaching implications that entire disciplines changed “overnight.” The transistor is one such example, which challenges traditional electrical engineers to adapt. If one is alert to the implications of change, times of rapid transition are also times of exceptional opportunity. These comments apply to both theoretical and experimental skills and should be a strong incentive to invest in continuing education.

## INTERPLAY BETWEEN THEORY AND EXPERIMENT

Questions often arise when comparing theory and experiment, and it is not always clear where to place your confidence. Table 16.1 contrasts the typical sequence of elements involved with a theoretical development and an experiment. This should be helpful in contrasting the two approaches of investigation. Analysis is a critical element of both.

Table 16.1. Typical Developmental Sequences.

<b>Theory</b>	<b>Experiment</b>
Definition of the Problem	Definition of Goals
Assumptions	Choice of Parameters
Initial Conditions	Analysis of Approaches <ul style="list-style-type: none"> <li>◆ Full Scale</li> <li>◆ Scale Model</li> </ul>
Boundary Conditions	Choice of Methodology <ul style="list-style-type: none"> <li>◆ Sensors</li> <li>◆ Processing</li> </ul>
Approach <ul style="list-style-type: none"> <li>◆ Analytical</li> <li>◆ Numerical</li> </ul>	Analysis of Error
Presentation	Presentation
Conclusions	Conclusions
Range of Applicability	Range of Applicability

## Evaluation

Important questions arise when theory and experiment are not in agreement. There are key areas to investigate when critically assessing the results of theoretical developments or experiments. The table below lists valuable areas to use for the evaluation of theoretical and experimental results.

Table 16.2. Evaluation areas for theory and experiment

<b>Theory</b>	<b>Experiment</b>
Validity of Assumptions, Initial Conditions and Boundary Conditions	Accuracy of Measurements
Reasonableness of Any Extrapolations	Reasonableness of Any Scaling
Error Free Analysis	Repeatability of Measurements
Resolution of Phenomena is Appropriate	Difficulty in Execution

## Varied Approaches

There are also many theoretical and experimental approaches that can be taken. These vary greatly in cost and complexity and should be chosen to be appropriate to the goals of the investigation. At times, a rough estimate, a simple qualitative experiment or a demonstration answers key questions. Such “quick and dirty” estimates can give guidance or assurance at critical phases of an investigation. The fact that an approach is shown to be plausible and is not discounted can justify the expenditure of additional time and energy.

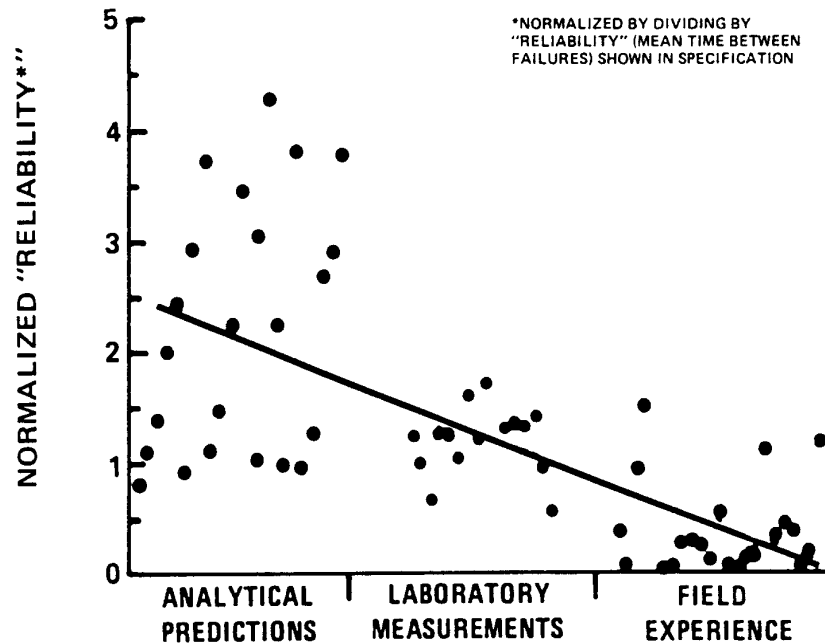
On the other hand, there are situations where in-depth calculations and/or experiments are appropriate. This could be when important, but small, differences are an issue, or when a critical decision requires a detailed justification. Often, the extent of the study required falls between these two extremes. Table 16.3 lists some of the possible analytical paths to answering questions.

Table 16.3. Paths to answering questions during the design process.

<b>Types of Theoretical Analyses</b>	<b>Types of Experiments</b>
Order of Magnitude Analysis	Simple Qualitative Experiment
Rough Estimate	Scaled Experiment
Limited Analytical Development	Limited Experiment
Complete Analytical Solution	Full Scale Experiment
Numerical Calculation	Exploratory Experiment

Often the short, “back of the envelope” estimates apply during the early stages of projects, with more detailed studies undertaken during the critical decision-making stages. Frequently, near the end or execution stages of a project, there may be a need to resolve a particular issue. At this final point, questions and problems usually can be clearly stated.

In Figure 16.6, Augustine [5] indicates the danger in relying upon initial estimates of the functioning of designed systems. Note that the actual field experience is several times worse in terms of reliability than the initial analytical estimates. This presentation would probably have looked just as gloomy if the initial estimates were based upon lab measurements alone, prior to the final design evolution. This also reinforces the need for an iterative process using complementary techniques.



BASIC DATA (1) G. KERN, "OPERATIONAL INFLUENCES ON AVIONICS RELIABILITY."  
 SOURCES: (2) DEFENSE MANAGEMENT JOURNAL, "7 MID 70's SYSTEMS."  
 (3) AUTHOR'S DATA COLLECTION

Figure 16.7. Inability of hardware to withstand real world pressures. Source: Augustine [5].

## THE ANALYSIS PROCESS

Previous sections discussed the many facets of analysis, but have not addressed the basic methodology used in performing analyses. Analysis involves more than using something learned in a math, physics or dynamics course, although the insights and tools provided by such courses are indispensable. The efforts involved with a typical analytical study are summarized below. These steps can be informal or quite formal, depending upon the scope or importance of the effort.

A typical sequence of efforts for analysis of a device or problem:

- ◆ Conceptually break down into component parts.
- ◆ Define purpose or function and desired capabilities.
- ◆ Represent components in physical or mathematical terms.
- ◆ Investigate whether or not the intended purpose is fulfilled by your logical representation (will it work?).
- ◆ Explore how parts interface and become something complete (a functional whole).
- ◆ Provide guidance concerning impact; e.g., implications, indicated changes and improvements.
- ◆ Document the details and essentials of the analysis.

## THE CRITICAL ROLE OF ANALYSIS IN ENGINEERING PROJECTS

Petroski [6] makes a point about how cautious engineers need to be during the design stage. In fact, he suggests the advantage of at least slight paranoia and imagining that the impossible will happen to a creation. It is essential to learn from failures as well as successes. Successes and failures (see Table 16.4) show that we can derive valuable lessons by analysis of a great range of designs, as described below.

Table 16.4. Engineering design successes and failures.

Successes	Failures
Radar	Tacoma Narrows Bridge
Stay-on Tabs for Aluminum Cans	Kansas City Regency Hotel
Boeing 777 Aircraft	Challenger Space Shuttle
Global Positioning System	Three-Mile Island Nuclear Power Plant

Some past engineering failures involved a history of designs following a methodology that seemed to work. However, when scale sizes or loads were extended and the designs subjected to environmental extremes, the result was numerous historical failures to analyze and learn from.

Conversely, when analyzing a design that works and has been accepted for long periods of time by a large segment of society, there are also valuable lessons to be learned. In this spirit, a review of several successful designs offers lessons worth emulating. Following this, a review of several failures will identify paths worth avoiding.

### Successes

The development of radar (RAdio Detection And Ranging) required an existing base of electronic capability to be feasible. This is a case where the supporting technology grew to a threshold that made radar possible. This development eventually led to parallel remote sensing devices using light (lidar) and sound (sonar and sodar). It took more than 30 years for these variations to appear. As illustrated in this example, a successful design exploiting one area of technology may have many fruitful derivative applications in other disciplines.

The stay-on tabs for aluminum cans that are standard now are an example of the value of being sensitive to a societal need and acting upon it. These tabs replaced throw-away tops that were wasteful and created pollution. About a trillion stay-on tabs have been produced thus far, saving more than 4 million tons of aluminum (recovered and recycled). This is an example of a simple concept having great impact.

The Boeing 777 aircraft is an example of a different type of success. The efficient and cost effective design was possible not just because of the development and application of advanced computers and software, but also because networking permitted engineers world-wide to work effectively on the same design. This demonstrated the feasibility of paperless design and concurrent engineering.

The development of Global Positioning System (GPS) technology is an example of an existing base of infrastructure and technical capabilities making a concept practical. In this case, satellite platforms and electronics enabled the execution of the concept, permitting accurate location (to within meters) world-wide. Uses for this capability continue to be discovered. This is an example of an area that is in a stage of dynamic expansion of applications. It continues to be fruitful to analyze the system and search for additional uses.

### **Failures**

The Tacoma Narrows Bridge collapsed in 1940 when exposed to relatively modest winds exciting a resonance. This is an example of extrapolated engineering, where the effects of winds were not properly considered. This example of an engineering design failure should encourage caution when extending past, seemingly successful, designs.

The walkways at the Kansas City Regency Hotel gave way in 1981, resulting in many deaths. A seemingly non-critical design change to save time and cost resulted in creating a weakness in the suspension. As illustrated by this example, there is no such thing as an unimportant design element—all details need to be considered at all stages.

The Challenger space shuttle exploded on January 28, 1986. Tufte [7] provides details of the analyses that explained the cause of the disaster that involved O-ring seals failing at low temperatures. The seals were critical elements to the sections separating different rocket stages. The decision to use multi-stages was a political one designed to make use of a vendor from a different state. A single stage would not have been possible to transport. This decision made the design more complex than necessary, which eventually led to a failure. The investigation was notable in that the reason for the failure was clearly communicated to the media using a simple, but elegant experiment illustrating how the failure occurred.

The Three-mile Island nuclear power plant failure provides an example of how a simple component can cause a major problem, also indicating the importance of working out foolproof displays of system status. The problem was that a valve failed causing an overheating problem. However, the visual display did not indicate the actual status of the valve, but rather what the valve had been “told” to do. Such attention to displays is critical for engineering systems in which operators monitor status and make decisions.

As suggested by the above examples, there is a vast body of design lessons and guidance to be gleaned from the analysis of successful and failed designs.

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## **CONCLUSION**

The intent of this review of engineering analysis is to engender appreciation of the role analytical assessment plays in the design process. To really appreciate the importance of this role, engineers need to apply analysis in their day-to-day work and experience the results over a period of time. Analysis is the essence of being an engineer. The ability to analyze distinguishes an engineer from a technician.

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## REFERENCES

1. Gibney, K., *Awakening Creativity: How Engineering Educators Help Students Unlock Their Creative Potential*, ASEE Prism, March 1998, pp18-23.
2. Radcliffe, C. J., *Cut, Copy, Paste and Engineering Design*. Syllabus, Premier Issue, 1997?, pp14-15.
3. Allmendinger, E. E., *Submersible Vehicle Systems Design*, The Society of Naval Architects and Marine Engineers, Jersey City, NJ.
4. Dieter, G. E., *Engineering Design: A Materials and Processing Approach*, McGraw Hill, 1983, 592pp.
5. Augustine, N. R., *Augustine's Laws: An Irreverent Guide to Traps, Puzzles, and Quandaries of the Defense Business and other Undertakings*, American Institute Aeronautics and Astronautics, 1983, 241pp.
6. Petroski, H., *Invention by Design: How Engineers Get from Thought to Things*, Harvard University Press, 1996, 242pp.
7. Tufte, E.R., *Visual Explanations*, Graphics Press, Cheshire, CT, 1997, 156pp.

## INTRODUCTION

Electronic circuits are all around us. From a basic timer in a microwave oven to sophisticated circuits in our home computers—all of these devices depend upon some sort of circuitry. In today's world, most circuits are very complex. However, these complex circuits are just a collection of small, basic circuits combined to create the enormous web of wires and parts.

This chapter introduces small, basic circuit components and builds upon these ideas with the introduction of general electronic principles and simple circuit examples. This introduction should help the reader see how complex circuits can be broken down into smaller, simpler systems.

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## SIMPLE CIRCUIT COMPONENTS AND CONCEPTS

In its simplest definition, a circuit is something that goes around in circles. An analogy of this can be found in rural areas where water is pumped up from a well in the ground and run through a faucet. From the faucet, the water runs down the drain and back into the ground. Over and over, the cycle is repeated.

In an electronic circuit, the same idea applies, but the basic difference is that electrons are circulating rather than water molecules. In this discussion, the analogy of a water system will be used to help understand how circuits work. Plumbing and electronic systems work similarly, and often times it is easier to visualize a water system. However, keep in mind that water and electrons are fundamentally very different from each other.

### Wires

In electronic circuits, a wire is similar to the water pipe in a water system. In the plumbing world, the diameter of the pipe determines the capacity of how many gallons of water per minute the pipe can carry. In electric circuits, the wire diameter is related to the capacity of how many electrons per



second the wire can carry—better known as amps (A)<sup>1</sup> of current. Usually, the wires in a circuit are short, and the resistance of the wires is negligible. (The concept of resistance is discussed later in this chapter in the section titled Resistors.) In the water analogy, this is like ignoring the friction in the pipe. Keep in mind that when wires are long, the resistance may no longer be negligible.

In the case of short wires used in typical circuits, the wire diameter is an indication of the wire current capacity in amps. Wire diameter is measured in units known as the American Wire Gage (AWG) standard. When using this standard, the smaller the AWG number, the larger the wire diameter, and therefore, the more electrons it can carry. Notice the reverse relationship of the AWG number to wire diameter and current capacity (see Figure 17.1).

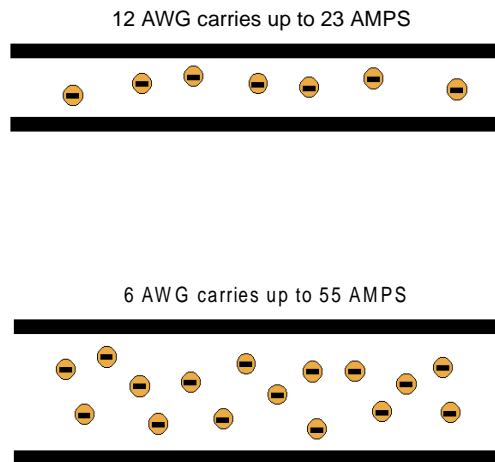


Figure 17.1. When using American Wire Gage (AWG) standard units, the smaller the wire number the more electrons it can carry. For example, a 12 AWG wire can carry 23 amps, while a 6 AWG wire is larger and carries 55 amps.

## Voltage and Batteries

Voltage is one of the most difficult electronics concepts to explain. For illustration, voltage has the same function as a hill in a physical analogy. The height of the hill has what is called gravitational potential, made possible by the presence of a gravitational field. The hill can be used to cause objects to move and flow down the hill. Likewise, voltage, also called electrical potential, is made possible by the presence of an electric field. Voltage can be used to cause the flow of electrons (current) through the electrical components in the circuit.

Voltage is caused by the separation of charge similar to how gravitational potential is caused by the separation in height for the hill. The separation of charge can be provided by a battery; therefore, a battery is a voltage source. In the presence of applied voltage, molecules are attracted to (or repelled from) each other, causing the electrons to flow in order to balance the separation of charge and return to a neutral reference value; i.e., “ground” discussed in the next section. Voltage, just like height, is a relative measurement. There is no absolute value for voltage, only a voltage difference.

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1. 1 amp =  $6.25 \times 10^{18}$  electrons per second.

Many times voltage is measured across an electric component or from a reference position like “ground.”

Referring to the water analogy again, a water pump is used to pump water through a network of pipes. The higher the pressure produced by the pump, the higher the resulting flow of water. Similarly, voltage is like an “electric pressure,” although only on a conceptual level since voltage does not have the same type of measurement units as pressure. In a circuit, the battery provides a voltage that pushes the electrons through the wire, resistors and other electrical components.

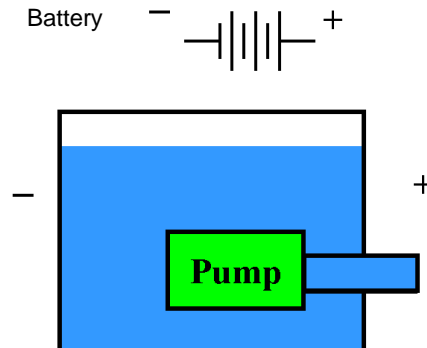


Figure 17.2. A battery pushes electrons through a network of wires, just like a water pump pushes water through a network of pipes.

Figure 17.2 demonstrates the analogous relationship between a pump and a battery. The lower diagram shows a water pump, in which the plus symbol on the right side represents the output or pressure side of the pump and the negative symbol on the other side represents the suction or pull side. The diagram just above the water pump is the standard symbol for a battery, as used in schematic diagrams. Similar to the pump, the battery has a plus side (the positive voltage or push side), and a negative side (the pull side). In many circuit applications, the negative side of the battery is connected to reference “ground,” which is discussed further in the next section.

The voltage value (V) indicates how many amps the battery can push. A battery with a higher voltage will try to push higher amps (more electrons) through the wires and electric components. Therefore, it is important to choose the correct battery voltage for the circuit—too high a voltage can burn the wire by pushing more amps through the wire than it can handle. This is parallel to a plumbing system: if too much pressure is applied, it may exceed the capacity of the pipe and burst.

Engineers must always be aware of system limitations and work within those limits. In the simple circuit described thus far, the circuit's physical limits can be met by either choosing a smaller battery voltage or a smaller gage (larger diameter) wire that can handle more current.

## Ground

“Ground” is an important concept that connects entire circuits together. It is a neutral point or a reference point. In the physical example mentioned above, the bottom of the hill is analogous to the ground (GND) in an electric circuit. Voltage is frequently measured from this reference point.

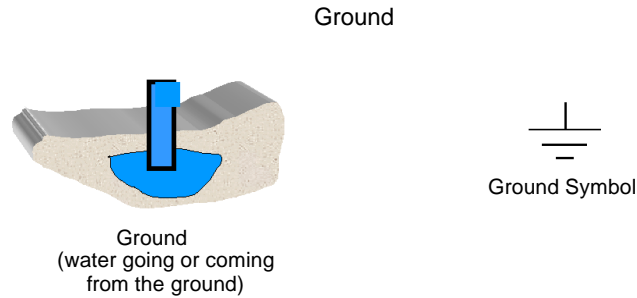


Figure 17.3. In circuit schematics, the symbol for ground is frequently used in schematic diagrams to indicate that the wires are connected to each other.

Figure 17.3 provides the schematic symbol for ground (on the right) and the water analogy for ground (on the left). In circuit schematics, *any wires connected to this symbol are connected to the same reference point (GND)*.

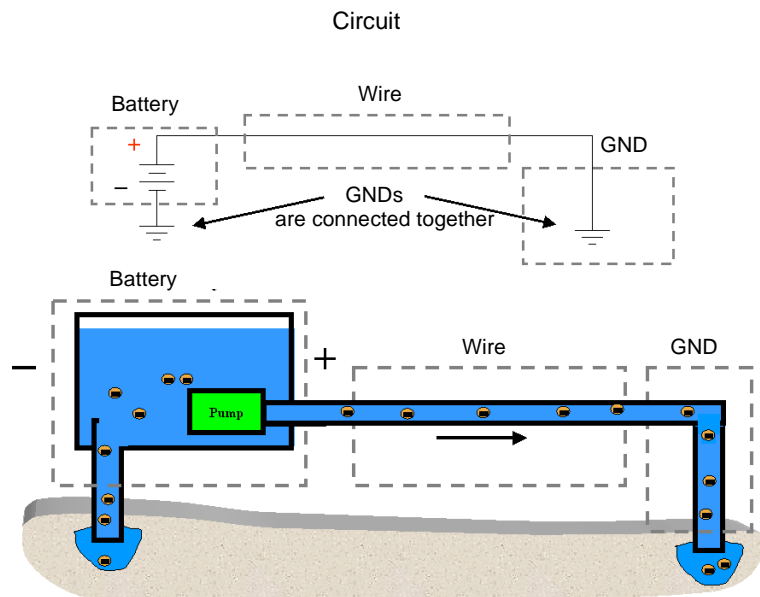


Figure 17.4. The top diagram shows an electronic circuit. The bottom diagram shows a parallel water system to illustrate what goes on inside the wires.

Plumbing and electronics often work similarly. Figure 17.4 shows how a circuit schematic (top diagram) is analogous to a water system (bottom diagram). Looking at the circuit schematic, begin at the battery and trace the electron flow through the wire and back down to ground. Notice that there are two ground symbols in the circuits diagram; this means that every point with a ground is connected together and are at the same voltage reference value—just like in the water diagram where the two ends of the pipe are at the same water level.

## Resistance

In simple terms, resistance is something that holds back or makes things harder to do; it is basically a restriction to flow. Up to this point, the described circuit system only contains wires and a bat-

tery to push electrons through the wires, which are assumed to have negligible resistance. However, when electrical components such as resistors, LEDs, light bulbs, motors, etc., are added to a circuit, resistance becomes an important issue. This is because most components do not have negligible resistance. Several electrical components will be discussed in detail in the sections below.

### Ohm's Law

The unit Ohm (symbolized by the Greek letter  $\Omega$ ) is used to measure resistance. According to Ohm's Law, *1 Ohm is a unit of electrical resistance equal to that of a conductor in which a current of one ampere is produced by an electric potential of one volt across its terminals.* Thus, the basic variables in Ohm's Law, voltage (V), resistance ( $\Omega$ ), and current (A), are closely related and cannot be determined independently. For example, if the battery voltage (V) has been selected and the resistance ( $\Omega$ ) has been calculated, the amperage (A) of current flowing in the electric components can be determined to ensure the capacity of those components is not exceeded. Likewise, Ohm's Law can be used when any two of the variables are known to calculate the value of the unknown third variable using the equations in Figure 17.5.

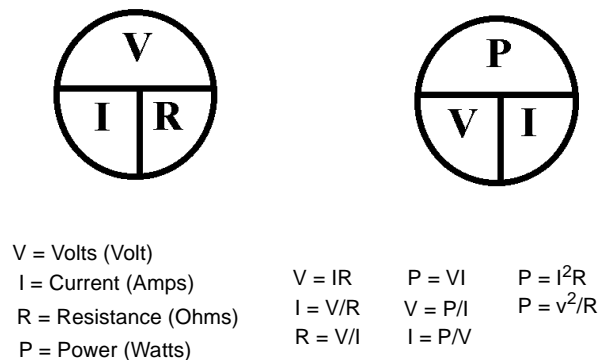


Figure 17.5. Using Ohm's Law, the values of voltage, current, resistance and power may be calculated from the above equations.

For example, to calculate the voltage (V) from known resistance (R) and current (I) values, cover the symbol for the unknown value on the circle on the left in Figure 17.5. In this case, covering the "V" indicates that current (I) must be multiplied times resistance (R) to calculate the unknown voltage value. To determine current (I), cover the "I" to realize that it can be calculated by dividing "V" by "R."

### Power

The Ohm's Law equations (Figure 17.5) also include the variable power, measured in watts (W), which is defined as *one ampere moving through an electric potential of one volt.* Power is also a unit of measure equal to the rate of energy transfer. Thus, electric components come with a power rating that informs the user what combinations of voltage and current may be safely applied without burning it up. An example is a light bulb, which is simply a resistor that gives off heat and light. A higher wattage light bulb draws more current from a given voltage, thereby transferring energy more quickly to provide a brighter light.

## Resistors

Using the water analogy, a resistor is like a kink in a water hose. When a hose is folded to make a kink, the amount of water flowing through it can be controlled. A more severe kink in the hose lets even less water flow through it.

In electronics, a resistor causes a “restriction” that controls the number of electrons that flow through the restriction and the rest of the circuit (see Figure 17.6). Resistance is important because it allows control of a variety of devices. Many devices, such as electric motors, run faster the more electrons are pushed through it.

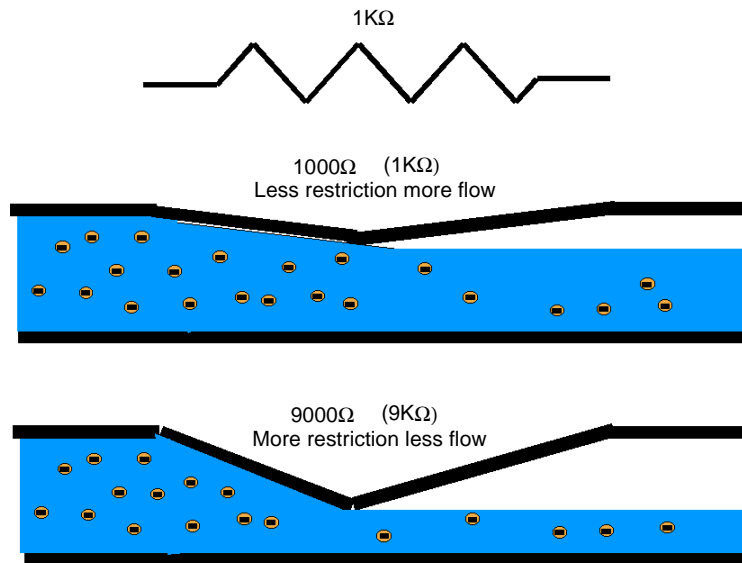


Figure 17.6. The top diagram shows an electronic symbol for a resistor. The lower diagrams illustrate how a resistor affects the flow of electrons.

Recall that the unit of measure for resistance is an Ohm ( $\Omega$ ). The more resistance a resistor has, the bigger the number value ( $\Omega$ ), and fewer electrons are allowed to flow. Thus, a  $1000\Omega$  resistor is like a kink with a bigger opening than that of a  $9000\Omega$  resistor.

Notice that the electronic symbol for a resistor (see Figure 17.6) has no polarity. Compare this to the battery symbol discussed earlier that had polarity indicated (a plus and minus symbol). In the case of the battery, it was important to know the direction of electron flow. But, in the case of a restriction, like a resistor, the function is the same no matter the flow direction.

### **Color Code System**

Because electronic components are so small, it is difficult to write all of the value information on each resistor. Therefore, a color code system indicates the resistor values.

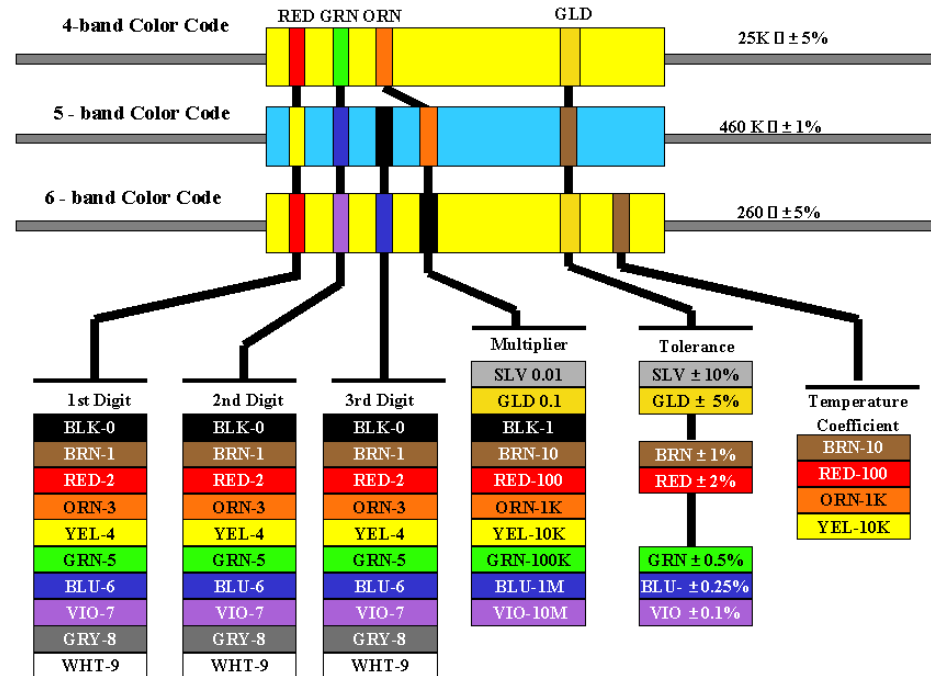


Figure 17.7. This chart illustrates the color code system used to determine the resistance value (in Ohm's) of electronic resistors. Three resistor examples are illustrated.

Using the resistor color chart in Figure 17.7, notice the three resistors with various numbers of color code bands. Three resistor examples are illustrated. The first resistor, with four color bands, provides the minimum resistor information. The second, a 5-band code, provides a little more information on the resistor. And, the third resistor, a 6-band, provides even more information.

Looking at the 4-band code resistor example, note that there are three bands close together with the fourth one located slightly separated from the first three. This far right band is the last one to be read. The first band (on the far left) is called the first digit, the second is the second digit, the third band is called the multiplier, and the final band indicates the tolerance of the resistor.

To determine the value of the 4-band resistor in Figure 17.7, note that its first band is **RED**. Following the line down the chart indicates that red represents the number **2**—the first digit. Next, the second band is **GREEN** and represents a value of **5**. The third band, the multiplier, is **ORANGE**, and indicates a value of **1K** (1K = 1000). To determine the final value, take the first two color-band digits, **25**, and multiply it by the multiplier, **1K (1000)**, resulting in the value of this resistor as 25 X 1000 = 25000 Ohms.

The fourth band indicates the tolerance. In this example, it is **GOLD**—a tolerance value of **5%**. Multiplying the resistor value (25000 Ohms) by .05 calculates this resistor's tolerance; it is a **25000W** resistor with a **5%** tolerance. Therefore, when measured, the actual value should fall between **23750W** and **26250W**.

## SIMPLE CIRCUIT COMBINATION AND SAMPLE CALCULATIONS

### Standard Units

In electronics, the numbers in many of the measurement units are usually very large or very small. To write all the zeros that represent these numbers would be cumbersome. So, like in many other technical fields, Standard Units are used as a shorter form to annotate values (Table 17.1). For example, the number **25,000,000,000** is written as **25G**, pronounced "twenty-five Gig." To obtain the full value, the number in front of the letter designator is multiplied by the value of the Standard Unit.

Examples:

$$5.6\mu = (5.6) \times (0.000001) = 0.0000056$$

$$47K = (47) \times (1000) = 47000$$

After many references to the Standard Units chart, these short-hand units will become familiar and second-nature.

Table 17.1. Standard Units.

Unit	Value
G (Giga)	= $\times 10^9$ (1,000,000,000)
M (Maga)	= $\times 10^6$ (1,000,000)
K (Kilo)	= $\times 10^3$ (1,000)
m (milli)	= $\times 10^{-3}$ (0.001)
$\mu$ (micro)	= $\times 10^{-6}$ (0.000 0001)
n (nano)	= $\times 10^{-9}$ (0.000 000 001)
p (pico)	= $\times 10^{-12}$ (0.000 000 000 001)

### Standard Electronic Units

In circuits, another standard notation is used to identify specific components since often there are many components of the same type. Table 17.2 shows all of these variables.

Table 17.2. Standard Electronic Units

Schematic Symbol Letter	Component Type	Unit of Measure	Unit Symbol
B <sub>x</sub>	Battery	Volts	(V or E, V <sub>CC</sub> , V <sub>EE</sub> )
R <sub>x</sub>	Resistor	Ohms	( $\Omega$ )
I <sub>x</sub>	Current	Ampere	(A)
P	Power	Watts	(W)

Schematic Symbol	Letter	Component Type	Unit of Measure	Unit Symbol
$C_x$	=	Capacitor	= Farads	(F)
$D_x$	=	Diode	= Peak Inverse Voltage	(PIV)

In Table 17.2, the left column indicates the letter notation found next to the schematic symbol in a circuits diagram, and the x just below provides the component number. For example,  $R_{13}$  is resistor number 13, and  $C_2$  is capacitor number 2.

### Single Resistor Circuit

Understanding some simple example problems will apply the information discussed thus far. In the left example of Figure 17.8, the voltage and resistance values are known; the current value is unknown. By taking the known voltage (12V) and dividing it by the resistance (100  $\Omega$ ), the current is calculated (120mA). In the example on the right, the problem is similar; except the unknown variable to solve for is the resistance. For example, suppose the voltage is known because the battery has been chosen. If it is then determined that 240mA of current is needed for the rest of the circuit, the appropriate size resistor of 50 Ohms is calculated.

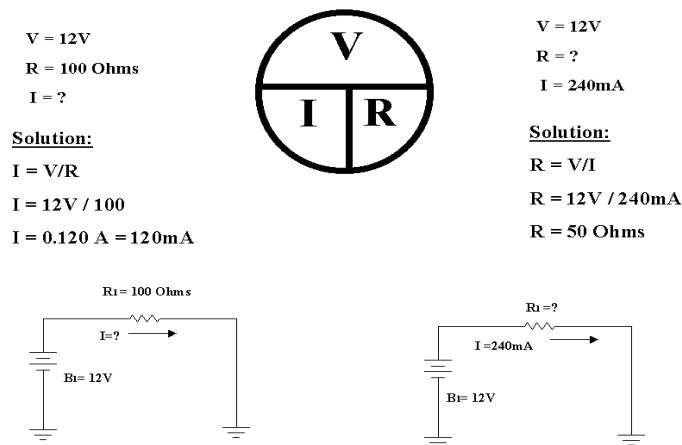


Figure 17.8. These two example problems involve circuits with one resistor each. Solve for the unknown variables.

### Power Calculations

To calculate power, refer to the first example in Figure 17.9, and use the cover-up method as described earlier. The variables are volts (V), current (I) and power (P). With a given voltage (12 V) and current (300mA), the power value may be calculated (3.6 W of power).



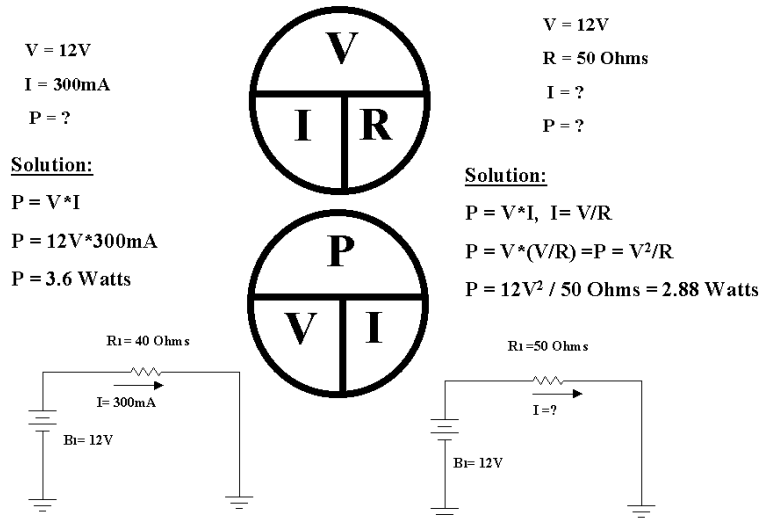


Figure 17.9. These two example problems involve calculating the unknown value of power (P) in a circuit.

The power value calculated in this example is the power that the resistor is using, or better yet, the power it absorbs. Power does not only apply to resistors, but it also applies to every component found in electrical circuits. Other components, such as batteries, generate (or output) power. Electric components either provide or absorb power.

The examples in the Figure 17.9 show that the power the battery outputs is about equal to the power the resistor absorbs. In the real world, nothing is perfect and power losses are unavoidable. In basic circuit analysis, it is commonly assumed that all circuits are ideal and any losses are negligible. Thus, the battery output equals how much power the resistor absorbs.

### Resistors in Series Circuit

Electronic terminology describes a “series” combination of resistors as those that are connected, in succession, one after another.

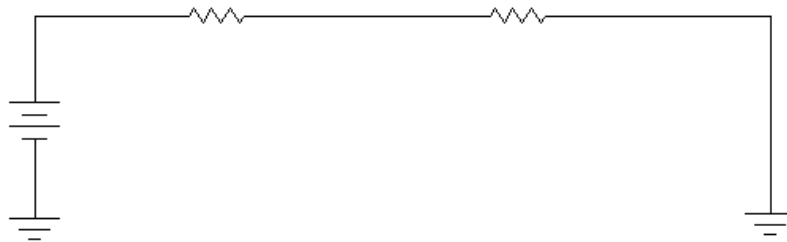


Figure 17.10. Electronic schematic circuit diagram illustrating two resistors in series.

Figure 17.10 illustrates the electronic symbol for resistors in series. In this circuit, the electron flow direction begins at the battery, proceeds through the first resistor and then flows through the second resistor.

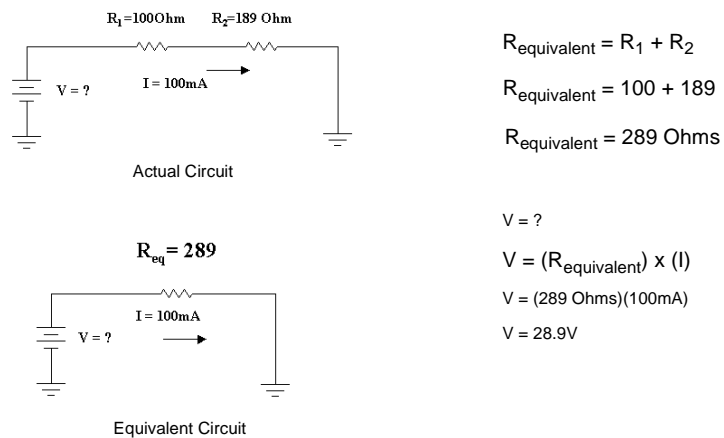


Figure 17.11. Example of a circuit with resistors in series, and the same circuit with the two resistors in series replaced with an equivalent resistance for ease of calculation.

Referring to Figure 17.11, the top diagram illustrates a circuit with a battery and two resistors in series. In a series circuit like this, the resistors may be added together:  $100\ \Omega$  plus  $189\ \Omega$  gives a value of  $289\ \Omega$ , called an equivalent resistor. For ease of calculation, the two resistors are replaced with an equivalent resistance (lower diagram).

Making an equivalent circuit makes no difference to the battery; it only feels a total resistance due to all the components in the circuit. It is like a person lifting a box with several rocks in it. She cannot distinguish that there is more than one rock inside, but she can feel the total weight (resistance) of the rocks. Once the two resistors are replaced with an equivalent resistance, it is simple to do the calculations as usual, given resistances and current, to determine the unknown battery voltage value.

Keep in mind that current in a *series circuit* is the same throughout its path. In this example, the current going through  $R_1$  is the same as the current going through  $R_2$ .

### Resistors in Parallel Circuit

Alternately, multiple resistors can also be connected “in parallel.” An example of a circuit with resistors in parallel is shown in Figure 17.12. All the input leads are connected, together and all the outputs are connected together. Basically, the circuit divides into several branches, one that contains  $R_1$  and the other that contains  $R_2$ .

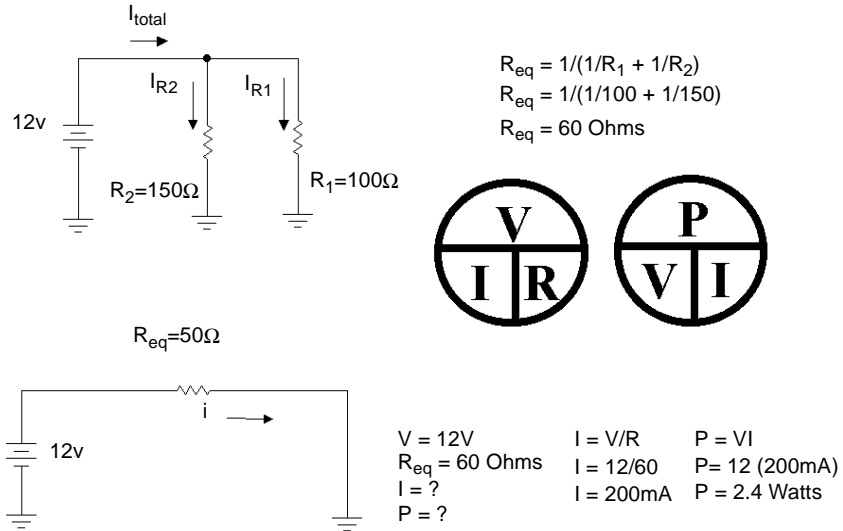


Figure 17.12. A schematic diagram of a circuit with resistors in parallel, and the same circuit with the two resistors in parallel replaced with an equivalent resistance for ease of calculations.

Using the water analogy again, resistors in parallel are similar to a situation in which a pipe brings water to both a kitchen and a bathroom sink simultaneously. The pipes for each sink come from the same pump source, and the sink drains each attach to the same drain source. In this case, each faucet feels the same pressure. The valve on the faucet provides a “resistance.” If the kitchen faucet is open more than the bathroom faucet, there is more water flow through the kitchen branch. Yet, the combined flow of both the kitchen and the bathroom faucets equals the total flow rate coming from the pump source.

Similarly, in electronics each resistor feels the same voltage, which permits the connection of several circuits to utilize the same voltage source. In the top circuit diagram of Figure 17.12,  $R_1$  and  $R_2$  each have a branch. These two branches are really separate circuits that share the same voltage source, and each resistor works *independently* from the other. Because they work independently, each will have a different current flowing through them. As in the water analogy, the sum of the currents running through each branch is the total current, provided by the battery.

Notice how the parallel configuration is different than the series configuration. Since the resistor values in each branch feel the same 12V from the battery, the current in each branch can be different. This was not the case for the series configuration, in which the voltage is shared and the current through each resistor must be the same. To calculate the current (I) value for the parallel resistors circuit in Figure 17.12, the actual circuit is simplified by replacing the two resistors with an equivalent circuit. However, since the flow in each branch is different, the resistor values cannot be simply added together to determine an equivalent resistance. Rather, the following formula has been derived to determine the equivalent resistance:

$$R_{equivalent} = 1/(1/R_1+1/R_2+\dots 1/R_x)$$

Calculate the equivalent resistance by using the given resistance values from Figure 17.12 ( $100\Omega$  for  $R_1$  and  $150\Omega$  for  $R_2$ ) in the formula. Take the reciprocals of each resistor and add them together, then take the reciprocal again to obtain a final equivalent resistance of  $60\Omega$ . Replace the resistance to get a simple circuit and calculate the current as usual. Keep in mind that this is the *total* current being calculated. Take the given voltage ( $12\text{ V}$ ) and divide it by the equivalent resistance ( $60\Omega$ ) to calculate the total current ( $200\text{mA}$ ).

The total power value may also be calculated in the same way as the resistors in series example, where the sum of the power that each resistor uses is the total power consumed by the circuit. In power calculations, whether it is a series or parallel circuit, the sum of the power used by all components is the total power used. Multiply the given voltage ( $12\text{V}$ ) by the calculated current ( $I_{\text{total}} = 200\text{mA}$ ) for a total power ( $W_{\text{total}}$ ) of  $2.4\text{ W}$ . To verify these numbers, it is useful to calculate the power used by each resistor and add them together. Their sums should add up to  $2.4\text{ W}$  (see Figure 17.13).

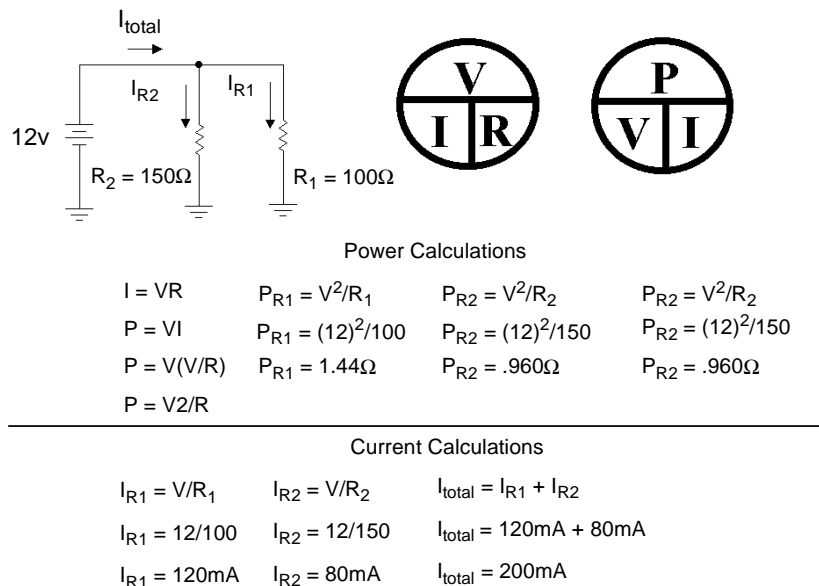


Figure 17.13. Total power and current calculations for a circuit with resistors in parallel.

The example illustrated in Figure 17.13 may be expanded by calculating the power through  $R_1$ . The value of the resistor  $R_1$  is given, and since this is a parallel circuit,  $R_1$  and  $R_2$  are connected to the same source. Therefore, they both feel a voltage of  $12\text{V}$ , and this same voltage value is used for both resistors in the calculation. Using the formula  $P=V/R^2$ ,  $P_{R1}$  is  $1.44\text{W}$  and  $P_{R2}$  is  $0.964\text{W}$ . Adding them together (resulting in a value of  $2.40\text{W}$ ) confirms the total power calculation.

To confirm the current calculations, compute the individual currents for each resistor and add them together. The example in Figure 17.13 illustrates that the sum of the currents does confirm the total current calculation from Figure 17.12 of  $200\text{mA}$ . In contrast, recall that in a series circuit, the current is the same throughout the circuit and is equal to the total current. Whereas, in a parallel cir-

cuit, the current in each component must be summed together to determine the total current drawn from the battery.

### Voltage Drop

Recall that voltage is a relative measurement taken as a difference between two points. Voltage drop is the difference in voltage, measured from one side of the resistor to the other. This is similar to a kinked water hose: on one side of the kink is higher pressure and on the other side is lower pressure. If there is just one resistor in series with the battery, the voltage drop across the resistor is equal to the voltage of the battery.

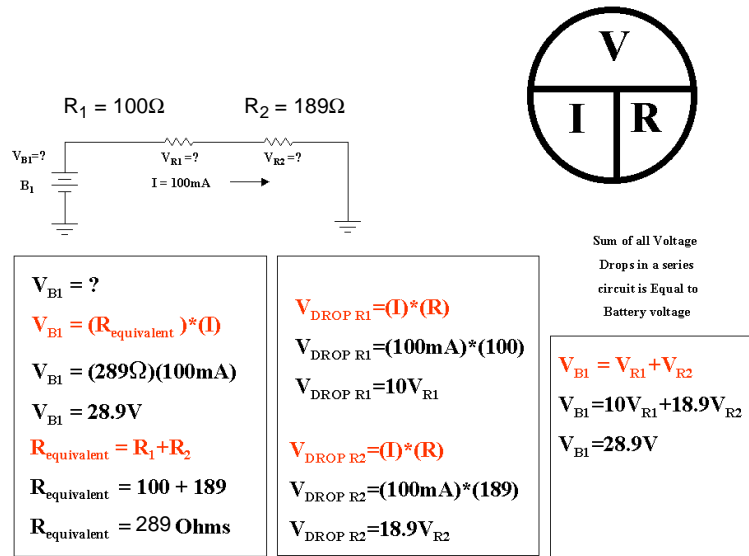


Figure 17.14. Example circuit with voltage drop calculation.

In a series circuit, the *sum* of the voltage change across each resistor is equal to the battery voltage. In Figure 17.14, the voltage across each resistor is calculated and added together. Note that the sum of these is equal to the battery voltage. In addition, the sum of the power used by each resistor is equal to the power the battery puts out. In contrast, for a parallel circuit configuration, no voltage drop calculation is necessary. Recall that the battery provides the same voltage to each parallel resistor; i.e., the voltage drop across one resistor equals the voltage drop across the second resistor, etc., which all equal the battery voltage.

## ADDITIONAL CIRCUIT COMPONENTS

### Diodes

Diodes are like one-way check valves that allow current to flow in only one direction. They can be used to protect circuits and convert alternating current (AC) into direct current (DC). Since many components can only function in one direction, diodes are also used to protect the circuit from a battery connected backwards.

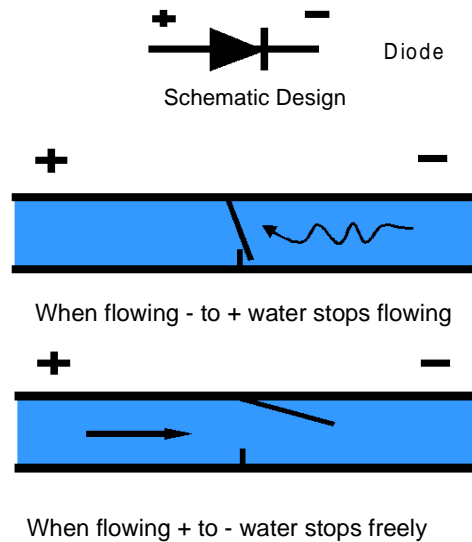


Figure 17.15. The top diagram is the electronic schematic symbol for a diode. The lower two diagrams illustrate a diode's function using the water analogy.

The lower two diagrams in Figure 17.15 illustrate a diode's function using the water analogy. As water flows in a pipe from the plus side to the negative side, the gate ("diode") opens, allowing water to flow through. When water flow is reversed, the gate closes, preventing water from flowing through. The top diagram in Figure 17.15 is the schematic symbol for a diode as used in circuit diagrams. Note that unlike resistors, it is critical to place the diode in the right location in relation to the direction of the electron flow.

### **Standard Diodes**

Looking at the two regular diodes illustrated in Figure 17.16, notice that each diode has a bar at one end. This bar represents the negative side of the diode, or the part that points towards the ground side. The numbers represent the model type, which can be referenced in a data book.

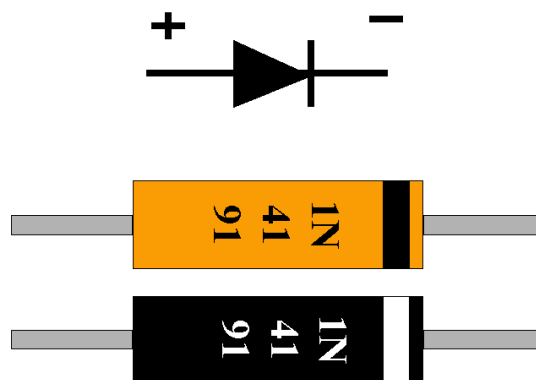


Figure 17.16. The top diagram is an electronic schematic symbol for a regular diode. The lower two diagrams show two regular diodes with model numbers printed on them and bars on the negative side.

Diodes have many values that characterize their performance. The two main values of concern in this discussion are the maximum current that can flow through it and the peak inverse voltage (PIV):

- ◆ The maximum current value represents the limit of forward current flow. When a diode is used in a circuit, it is important that the amount of current that flows through the circuit is less than the maximum that the diode can handle.
- ◆ The PIV is the maximum reverse voltage the diode can hold. Referring back to the diagram in Figure 17.15 in which the water pipe has a one-way gate, if the pressure in the reverse direction is higher than the gate can hold, it would break. In electronics lingo, the diode would “burn up.”

For safety concerns, when determining the type of diode required for a circuit, the general rule of thumb guideline is to select a diode with a PIV and maximum current value that is about 20% higher than the current flow required. For example, in a circuit that uses a 12V battery and a current flow of 1.5A, a diode is needed to protect the circuit from someone connecting a battery backwards. Realizing that the battery in reverse produces a PIV of 12V, the chosen diode must have a PIV of more than 12V. Using the general rule of thumb of selecting a value that is about 20% higher allows a 20% margin of error for safety. Using this 20% margin results in a selected diode rated at 14.4PIV and 1.8A max current flow. Remember these are only safe minimums; higher values may be used. In addition, there are many other types of diodes that do the same thing but with slightly different characteristics.

### ***Light-Emitting Diodes (LED)***

Another type of diode is a light-emitting diode (LED). An LED acts just like a standard diode except it lights up only when current flows through in the forward direction, unlike a resistor or light bulb that lights up or works in either direction. Also unlike a regular light bulb, an LED uses less power to produce light (thus using less energy and lasting longer). An LED also serves as a protection device for the circuit since it prevents current from flowing in the opposite direction. But, note that running about 30mA through an LED is a general rule of thumb.

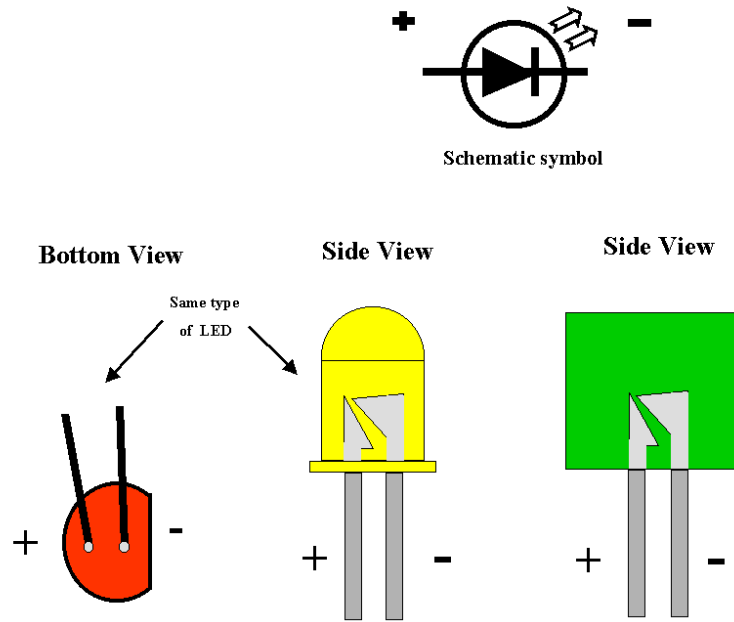


Figure 17.17. The top diagram is an electronic schematic symbol for a light-emitting diode (LED). The lower row of diagrams illustrate commonly used circular and square LEDs.

In the lower row of diagrams in Figure 17.17, there are two basic LED types: circular and square. The left and middle of these diagrams show the same circular LED from a bottom view and a side view. The right diagram shows a square LED.

There are two ways to determine which are the plus and the minus side of an LED. The best way, which works for both shapes of LEDs, is to look at the two elements inside. The biggest element is the negative lead; it is connected to the side going to ground. The smaller lead indicates the side where the electrons enter the LED. The second method of determining the polarity works only for the circular shaped LEDs. By looking at the bottom view of the circular LED, it is clear that the LED has a flat side that resembles a capital "D." The lead closest to the flat side is the negative side and is connected to the ground side of the circuit. The other lead is the positive side and is connected towards a power source (such as a battery).



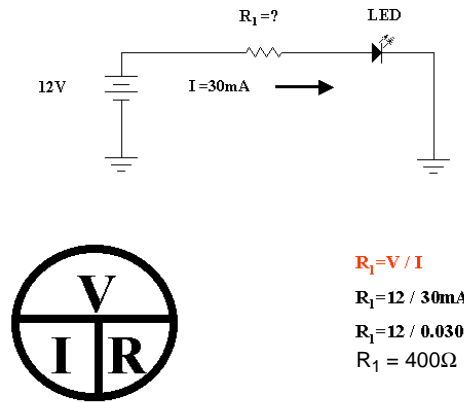


Figure 17.18. Example of the calculation to determine the resistor value required in a circuit with a light-emitting diode (LED).

In the example illustrated in Figure 17.18, the circuit includes an LED being used as a light. There is a 12V battery, an LED and a resistor used to limit the amount of current that will go through the LED. As mentioned earlier, the general rule is to allow no more than 30mA through an LED. Based on this information, the required resistance of  $400\Omega$  is calculated using 12V and 30 mA and Ohm's Law. This example is typical of the calculation to determine an appropriate resistor value in order to safely limit the amount of current going into the LED.

## Capacitors

Capacitors may be considered like “storage tanks” for electrons. They are mainly used for timing, filtering and smoothing out the flow of electrons. Using the water analogy, capacitors could be compared to a water tank. Imagine a bucket of water with a hole at the bottom and a hose at the top filling the bucket. Even if the hose was turned on and off erratically filling the bucket, the flow of water coming out at the bottom would flow consistently. This is a form of smoothing out the flow; even as the input flow of water surges the output still remains fairly constant.

Continuing with the water analogy, imagine a water tank that takes 5 seconds to fill and the same time to drain. If the water flowing into the bucket was turned on for 3 seconds and then turned off for 3 seconds (in circuits, this is called a “duty cycle”), the water flow coming out of the bucket would still be consistent. If the input duty cycle was increased to 6 seconds on / 6 seconds off, the output flow would surge. This is because the bucket would drain completely before the input flow would turn on again (a 6 second delay is greater than a 5 second drain time), causing a surge of flow in the output. In this case, to compensate for the input duty cycle, a bigger bucket would be needed to provide a slower drain time. This same idea applies when selecting capacitors in electronic circuits.

The occurrence of voltage spikes or surge can be detrimental to many circuit components. A good way to protect circuits from surge damage is to use capacitors, in the same way the right-sized water tank was used to even out the flow of water.

Capacitors are also used to regulate current in timer circuits. (An example timer circuit using an IC chip is shown in the next section; in which, the size of the capacitor determines the timing of a

blinking LED.) In a timer circuit, the rate at which the capacitor fills and discharges determines the flow of electrons. If the input flow to the capacitor remains constant, then so does the time it takes the capacitor to fill and discharge. The size of the capacitor determines the fill and discharge time, which can vary from a fill time of only a few millionths of a second to several seconds.

### Capacitor Types

There are several different types of capacitors, polarized and non-polarized. Polarized capacitors have a positive and a negative side. The plus side of the capacitor should be connected towards the positive side of the circuit, and the negative side should be connected towards the negative side. Notice that on the schematic symbol for a polarized capacitor (Figure 17.19) the side with an arc is the negative side, while the other side is the positive side. Figure 17.19 also illustrates two common types of polarized capacitors: radial and axial.

When looking at the radial type, the way to tell which side of the capacitor is negative is to search for the side of the can with several oval marks. The lead that is closest to these marks is the negative side of the capacitor, and logically the other side is the positive.

The positive end of an axial capacitor, however, is the side with the black insulation material surrounding the lead. The negative side of the lead is surrounded by the same conductive material as the lead itself.

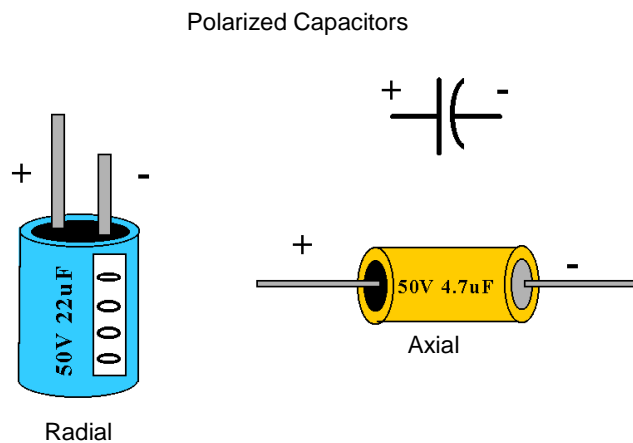


Figure 17.19. The top right diagram is the electronic symbol for a capacitor. The lower two diagrams illustrate the two types of polarized capacitors: radial and axial.

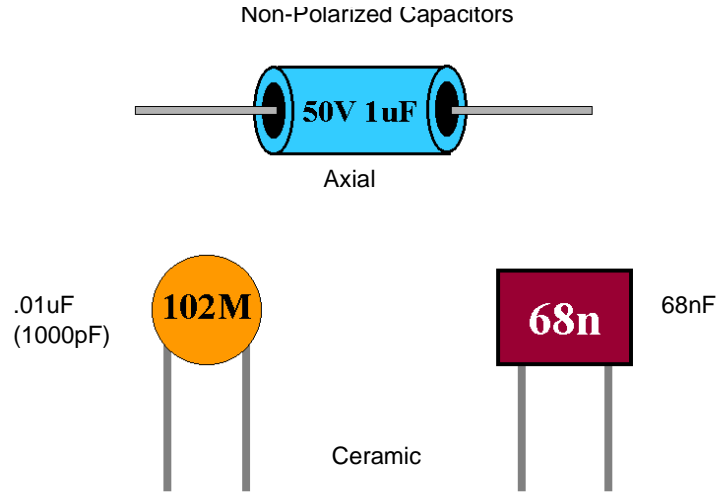


Figure 17.20. Examples of commonly-used non-polarized capacitors: axial and ceramic.

Non-polarized capacitors, as illustrated in Figure 17.20, can be connected in any direction. For the most part, it is fairly simple to distinguish between polarized and non-polarized capacitors. However, the axial non-polarized is easily confused with the axial polarized. In the axial diagram in Figure 17.20, notice that unlike the polarized type, the non-polarized type has both leads insulated from the body, shown in black.

A capacitor value is rated in two ways: the maximum voltage pressure (MVP) it can handle and how much capacity it has to store electrons. The MVP rating is in voltage; the capacity rating is in Farads (F), usually in pico Farads (pF) or microFarads ( $\mu$ F).

Examine a polarized capacitor in Figure 17.19; its values can usually be read directly off of the capacitor. But, since a non-polarized type (Figure 17.20) is often physically very small and difficult to read, a special numbering system has been developed to indicate its value (Figure 17.21).

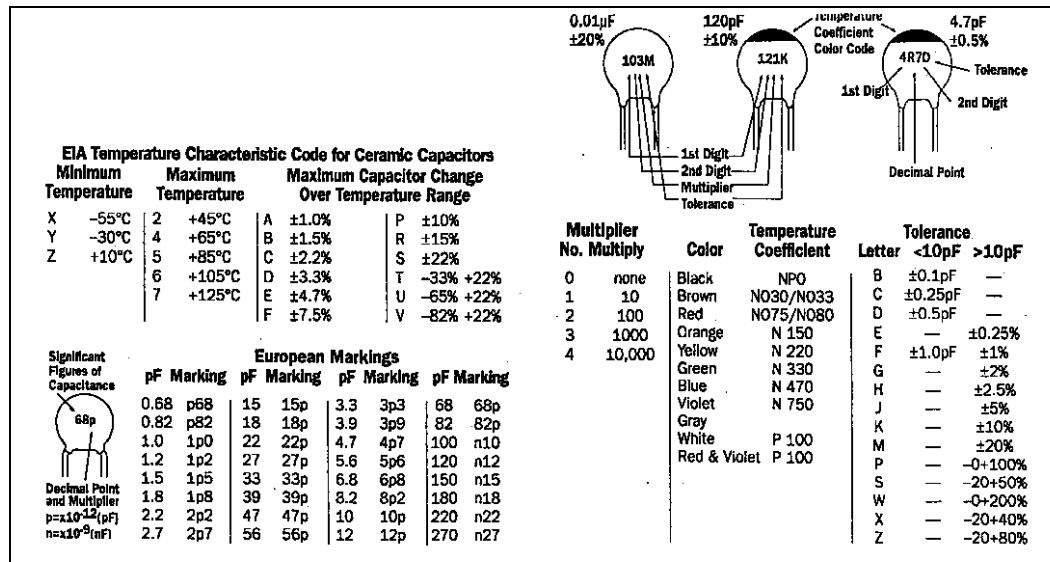


Figure 17.21. This capacitor reference guide provides the information necessary to understand the special numbering system identifying the values printed on the small-sized, non-polarized capacitors. Source: Tech America catalog.

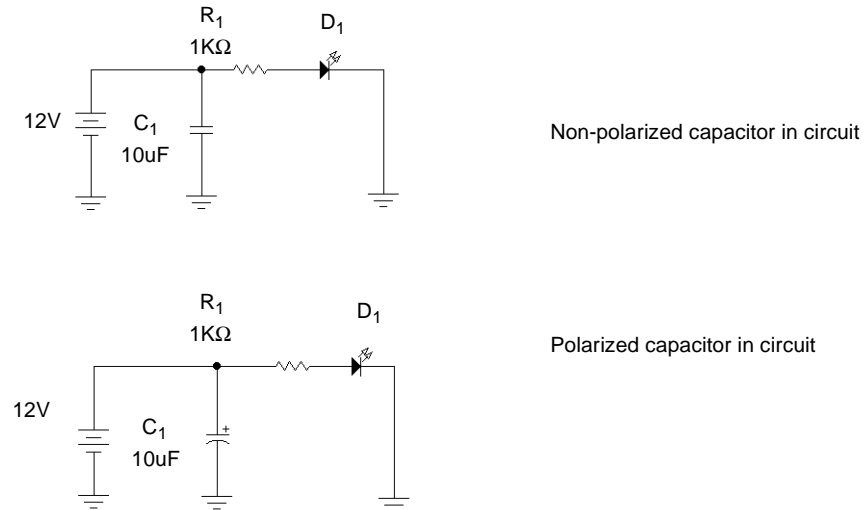


Figure 17.22. Example of a circuit diagram that demonstrates both capacitor types in use.

In Figure 17.22, the top circuit has a polar capacitor and the lower circuit has a non-polar capacitor, both providing the same function. In circuits, many things can cause voltage to fluctuate, such as heat, vibrations, magnetic fields, etc. In Figure 17.22, the use of capacitors in this very basic circuit keeps the LED at a constant level of brightness. Often, people see the lights in their homes flicker; this can be due to a surge in voltage, although in most circuits, the situation is a little more complicated.

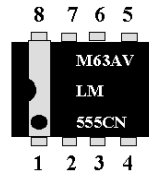
### Integrated Circuits (IC Chips)

Integrated circuits, called IC chips, are circuits that are so miniature that they can only be seen through a powerful microscope. Their small size makes it possible for devices such as laptop computers to exist and also allows for faster circuit design. Conceptually, imagine an IC chip as a “black box” that accepts an input, manipulates the signal and outputs something different. For example, a 555-timer IC chip is a timing device. This particular IC chip measures the time it takes the capacitor to fill (charge) and drain (discharge). And, by changing the value of the capacitor one can change the amount of time the IC chip outputs electrons. Once an IC chip is assigned a voltage, it will output current proportional to that voltage for a given time and then shut off. It is not required that a person know the specifics on how the IC chip works inside in order to make it work!

#### **Reading an IC Chip**

Although chips come in different sizes and shapes, reading an IC chip is quite simple. The IC chip illustrated in the top diagram of Figure 17.23 has white numbers and letters, which can be looked up in a data book to learn the chip’s specifications. To use an IC chip, think of it as a box that performs some function once the proper signal and voltage is connected to the proper pin. Notice the dot on the lower left corner of the chip illustrations; this indicates that the pin coming out of the chip in this corner is pin number one. The rest of the pins are dot numbered in a counter clockwise

direction starting from pin 1. Thus, the numbering ends with pin 8 on the opposite end of pin 1. On a 14-pin chip, the pin opposite pin 1 would be pin 14.



Schematic Symbols

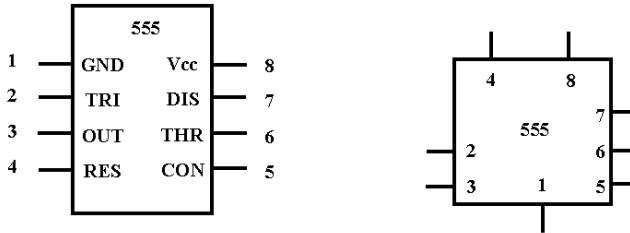


Figure 17.23. The top diagram illustrates the layout of an 8-pin integrated circuit (IC chip) type 555. The two lower diagrams are two types of electronic schematic symbols that represent and describe IC chips.

The two lower diagrams in Figure 17.23 are two types of common electronic symbols for IC chips. Notice that the one on the left resembles the chip and the one on the right does not, but it is more commonly used. The right schematic has all of the same pins, however, except that they are not in any particular order. Looking at the left symbol, the letters indicate what to connect to each pin. For example, connect pin 1 directly to ground, connect pin 8 ( $V_{CC}$ ) to the plus side of the battery, etc. Be careful not exceed the voltage limit found on the data sheets specifications for an IC chip.

## SIMPLE CIRCUIT EXAMPLE

As an example that summarizes all of the electronic components previously described, Figure 17.24 illustrates a blinking light circuit that turns a light on and off.

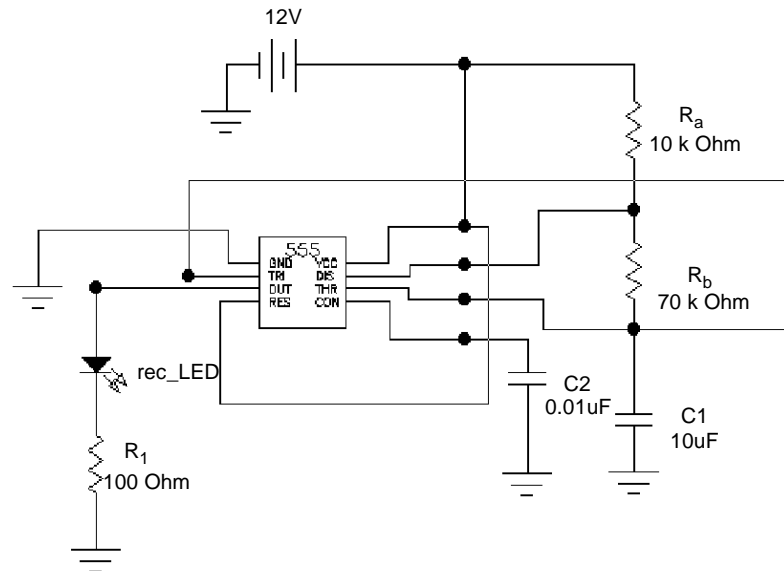


Figure 17.24. An electronic schematic diagram of a 555 blinking light circuit. The dots located where some of the wires cross indicate that all of the wires going to this point are connected. Any place where wires cross and no dot is present means that wires are *not* connected.

To obtain the desired result—a blinking light—this circuit measures how full the capacitor is. When the capacitor reaches  $2/3$  of its capacity, it turns on the LED; when it drains to  $1/3$  of its capacity, it turns off the LED. A bigger capacitor takes longer to charge and discharge; a smaller capacitor takes less time to charge and discharge, making the blink rate of the LED faster. Thus, by changing the capacitor size, the rate of the blinking light can be controlled.

## CONCLUSION

The intent of this chapter's introduction to electronics and circuits is to provide the reader with enough information to be able to recognize electronic components and their role in simple circuits, as well as introduce how to read an electronic schematic circuit design, and make basic calculations to create a safe, functioning circuit. The next step is to get a bread board and actually design and build one!

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## REFERENCES

1. Graf, Rudolf F., *Detector Circuits*, Newnes, 1997.
2. Graf, Rudolf F., *Converter and Filter Circuits*, Newnes, 1997.
3. Mims III, Forest M., Series of *Engineer's Mini-Notebooks*, Radio Shack, Siliconcepts:
  - ◆ *555 Timer IC Circuits*, 1992, Cat. No. 62-5010
  - ◆ *Op Amp IC Circuits*, 1994, Cat. No. 52-5011
  - ◆ *Optoelectronics Circuits*, 1998, Cat. No. 62-5012
  - ◆ *Digital Logic Circuits*, 1997, Cat. No. 62-5014
  - ◆ *Communications Projects*, 1993, Cat. No. 62-276-5015A
  - ◆ *Formulas, Tables and Basic Circuits*, 1994, Cat. No. 276-5016A
4. Helpful web sites:
  - ◆ [www.national.com](http://www.national.com)
  - ◆ [www.motorola.com](http://www.motorola.com)
  - ◆ [www.amasci.com](http://www.amasci.com)