sectionone

Laying the Foundation

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The materials presented in this section focus on the needs of today's beginning engineering students, who typically have well-developed math and computer skills but less-developed hands-on mechanical skills compared to students of earlier generations. Incoming engineering students may no longer be people who work on their cars or bikes in the garage and who took shop and drafting classes in high school. Although many engineering students enter college having spent time in a virtual computer environment, the lack of hands-on experience often results in a lack of three-dimensional visualization skills. So in addition to the classical material on standard engineering graphics practices, these students need to enhance their visualization skills. Prior to the advent of CAD, the graphics classroom featured large tables topped with mechanical drafting machines and drawers full of mechanical drawing instruments. Engineering students and engineers now have additional time to focus on aspects of the engineering design cycle that are more worthy of their talents as engineers. These aspects include creative thinking, product ideation, and advanced analysis techniques to ensure a manufacturable and robust product. Formalization of the design process allows designers to focus their energies on certain areas in the process and gain more meaningful results.

1

An Introduction to Graphical Communication in Engineering

objectives

After completing this chapter, you should be able to

- Explain and illustrate how engineering graphics is one of the special tools available to an engineer
- Define how engineering visualization, modeling, and graphics are used by engineers in their work
- Provide a short history of how engineering graphics, as a perspective on how it is used today, was used in the past

1.01 introduction

Because engineering graphics is one of the first skills formally taught to most engineering students, you are probably a new student enrolled in an engineering program. Welcome!

You may be wondering why you are studying this subject and what it will do for you as an engineering student and, soon, as a professional engineer. This chapter will explain what engineering is, how it has progressed over the years, and how graphics is a tool for engineers.

What exactly is engineering? What does an engineer do? The term *engineer* comes from the Latin *ingenerare*, which means "to create." You may be better able to appreciate what an engineer does if you consider that *ingenious* also is a derivative of *ingenerare*. The following serves well enough as a formal definition of engineering:

The profession in which knowledge of mathematical and natural sciences, gained by study, experience, and practice is applied with judgment to develop and utilize economically the materials and forces of nature for the benefit of humanity.

A modern and informal definition of engineering is "the art of making things work." An engineered part or an engineering system does not occur naturally. It is something that has required knowledge, planning, and effort to create.

So where and how does graphics fit in? Engineering graphics has played three roles through its history:

1. Communication
2. Record keeping
3. Analysis

First, engineering graphics has served as a means of communication. It has been used to convey concepts and ideas quickly and accurately from one person to another without the use of words. As more people became involved in the development of products, accurate and efficient communication became increasingly necessary. Second, engineering graphics has served as a means of recording the history of an idea and its development over time. As designs became more complex, it became necessary to record the ideas or features that worked well in a design so they could be repeated in future applications. And third, engineering graphics has served as a tool for analysis to determine critical shapes and sizes, as well as other variables needed in an engineered system.

These three roles are still vital today, more so than in the past, because of the technical complexity required to make modern products. Computers, three-dimensional modeling, and graphics software have made it increasingly effective to use engineering graphics as an aid in design, visualization, and optimization.

1.02 A Short History

The way things are done today evolved from the way things were done in the past. You can understand the way engineering graphics is used today by examining how it was used in the past. Graphical communications has supported **engineering** throughout history. The nature of engineering graphics has changed with the development of new graphics tools and techniques.

1.02.01 Ancient History

The earliest documented forms of graphical communication are cave paintings, such as the one shown in Figure 1.01, which showed human beings depicting organized social

FIGURE 1.01. Undated cave painting showing hunting and the use of tools.
Source: ACE STOCK LIMITED/ Alamy

behavior, such as living and hunting in groups. The use of tools and other fabricated items for living comfort and convenience were also communicated in cave paintings. However, these paintings typically depicted a lifestyle, rather than any instructions for the fabrication of tools, products, or structures. How the items were made is still left to conjecture.

The earliest large structures of significance were the Egyptian pyramids and Native American pyramids. Some surviving examples are shown in Figure 1.02. The Egyptian pyramids were constructed as tombs for the Pharaohs. The Native American pyramids were built for religious ceremonies or scientific use, such as observatories. Making these large structures, with precision in the fitting of their parts and with the tools that were available at the time, required much time, effort, and planning. Even with modern tools and construction techniques, these structures would be difficult to re-create today. The method of construction for the pyramids is largely unknown—records of the construction have never been found—although there have been several theories over the years.

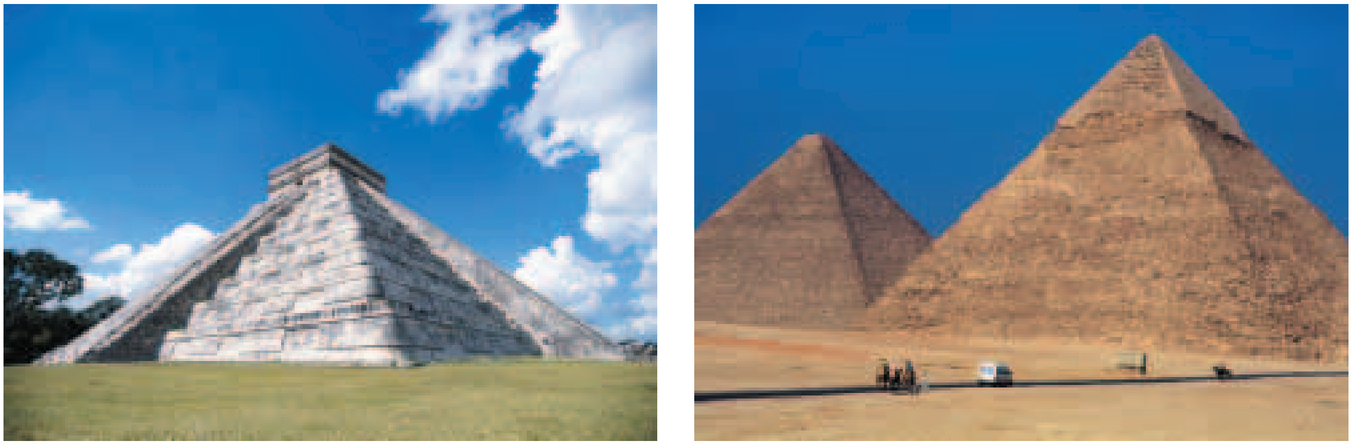


FIGURE 1.02. Mayan pyramid, Yucatan, Mexico (left), and Pharaoh Knufu and Pharaoh Khafre Pyramids, Giza, Egypt (right).
Sources: Brand X Pictures/Alamy, above; DIOMEDIA/Alamy, below.

FIGURE 1.03. Ancient Egyptian hieroglyphics describing a life story.
Source: © Bettmann/CORBIS

Egyptian hieroglyphics, which were a form of written record, included the documentation of a few occupational skills, such as papermaking and farming, although, for the most part, they documented lifestyle. An example of a surviving record is shown in Figure 1.03. As a result of those records, papermaking and farming skills could be maintained and improved over time. Even people who were not formally trained in those skills could develop them by consulting the written records.

Two engineering construction methods helped the Roman Empire expand to include much of the civilized European world. These methods were used to create the Roman arch and the Roman road.

The Roman arch, shown in Figure 1.04, was composed of stone that was precut to prescribed dimensions and assembled into an archway. The installation of the keystone at the top of the arch transferred the weight of the arch and the load it carried into the

FIGURE 1.04. Pont-du-Gard Roman aqueduct (left) built in 19 BC to carry water across the Gardon Valley to Nimes. Spans of the first- and second-level arches are 53–80 feet. The Ponte Fabricio bridge in Rome (right) built in 64 BC spans the bank of the River Tiber and Tiber Island.
Photos by William G. Godden. Reprinted with permission from EERC Library, Univ. of California, Berkeley.

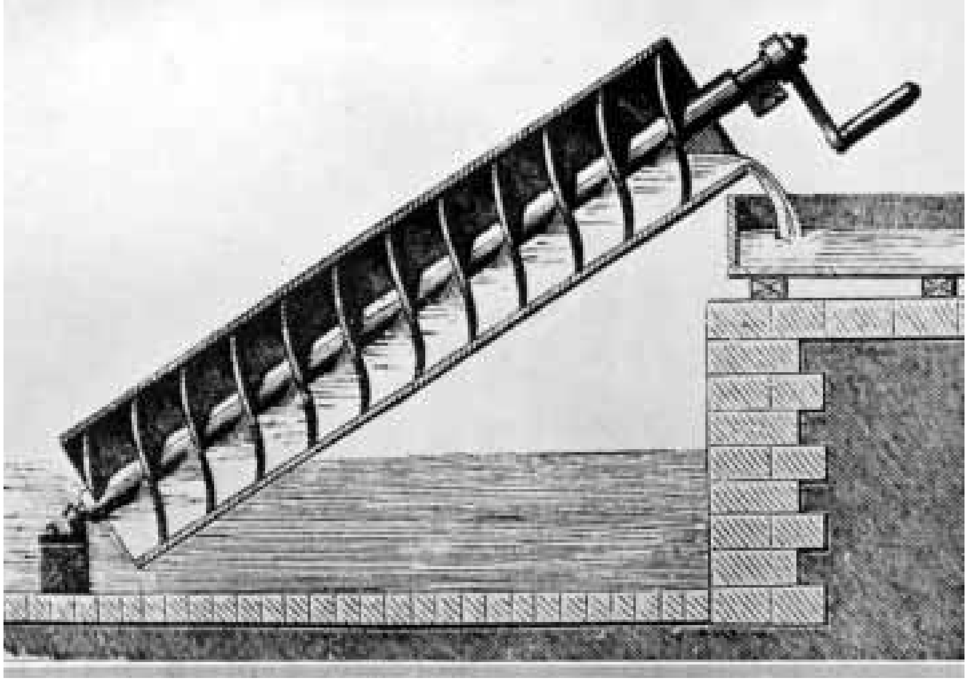


FIGURE 1.05. An engraving showing the operation of an Archimedes screw to lift water. *Courtesy of Time Life Pictures/Getty Images*

remaining stones that were locked together with friction. This structure took advantage of the compressive strength of stone, leading to the creation of large structures that used much less material. The Roman arch architecture was used to create many large buildings and bridges. Roman era aqueducts, which still exist today in Spain and other countries in Europe, are evidence of the robustness of this **design**.

The method used to construct Roman roads prescribed successive layers of sand, gravel, and stone (instead of a single layer of the native earth), forming paths wide enough for commercial and military use. In addition to the layered construction methods, these roads were also crowned to shed rain and had gutters to carry away water. This construction method increased the probability that the roads would not become overgrown with vegetation and would remain passable even in adverse weather. As a result, Roman armies had reliable access to all corners of the empire.

The Roman Empire is long gone, but the techniques used for the construction of the Roman arch and the Roman road are still in use today. The reason for the pervasiveness of those designs was probably due to Marcus Vitruvius, who, during the Roman Empire, took the trouble to carefully document how the structures were made.

The Archimedes screw, used to raise water, is an example of a mechanical invention developed during the time of the Greek Empire. Variations of the device were used for many centuries because diagrams depicting its use were (and still are) widely available. One of those diagrams is shown in Figure 1.05. These early documents were precursors to modern engineering **drawings**. Because the documents graphically communicated how to build special devices and structures, neither language nor language translation was necessary.

1.02.02 The Medieval Period

Large building construction helped define the medieval period in Europe. Its architecture was more complicated than the basic architecture used for the designs of ancient buildings. The flying buttress, a modification of the Roman arch, made it possible to construct larger and taller buildings with cavernous interiors. This type of structure was especially popular in Europe for building cathedrals, such as the one shown in Figure 1.06. The walls of fortresses and castles became higher and thicker. Towers were included as an integral part of the walls, as shown in Figure 1.07, to defend the inhabitants from many directions, even when attackers had reached the base of a wall.

FIGURE 1.06. Flying buttress construction used to support the exterior walls of Notre Dame Cathedral in Paris.
Courtesy of Getty Images

FIGURE 1.07. Warwick Castle, England, circa 1350, is an example of a medieval style fortification.
Source: © Royalty-Free/CORBIS

FIGURE 1.08. The Great Wall of China, built during the medieval period, used simple engineering principles despite the large scale of the project. *Source: Nigel Hicks/Alamy*

In Asia, large fortifications, shrines, and temples, as shown in Figure 1.08, were built to last hundreds of years. The complexity of techniques to build those structures required planning and documentation, especially when raw materials had to be transported from long distances. Building structures of such sizes required an understanding of the transmission of forces among the supporting members and the amount of force those members could withstand. That knowledge was especially important when wood was the primary building material.

Large-scale civil engineering **projects** were begun during the medieval era. Those projects were designated by a civilian government to benefit large groups or the general population, as opposed to projects constructed for private or military use. The windmills of Holland, shown in Figure 1.09, are an example of a civil engineering project. The windmills harvested natural wind energy to pump large amounts of water out of vast swampland, making the land suitable for farming and habitation.

Windmills and waterwheels were used for a variety of tasks, such as milling grain and pumping water for irrigation. Both inventions were popular throughout Europe and Asia; a fact that is known because diagrams showing their construction and use have been widely available.

1.02.03 The Renaissance

The beginning of the Renaissance in the 1400s saw the rise of physical scientific thinking, which was used to predict the behavior physical **systems** based on empirical observation and mathematical relationships. The most prominent person among the scientific physical thinkers at that time was Leonardo da Vinci, who documented his ideas in drawings. Some of those drawings, which are well known today, are shown in Figure 1.10. Many of his proposed devices would not have worked in their original form, but his drawings conveyed new ideas and proposals as well as known facts.

Prior to the Renaissance, nearly all art and diagrams of structures and devices were records of something already in existence or were easily extrapolated from something already tried and known to work. When inventors applied physical science to

FIGURE 1.09. The network of windmills in Holland, used to drain water from flooded land, is an example of an early large-scale civil engineering project.
Source: © PaulAlmasy/CORBIS

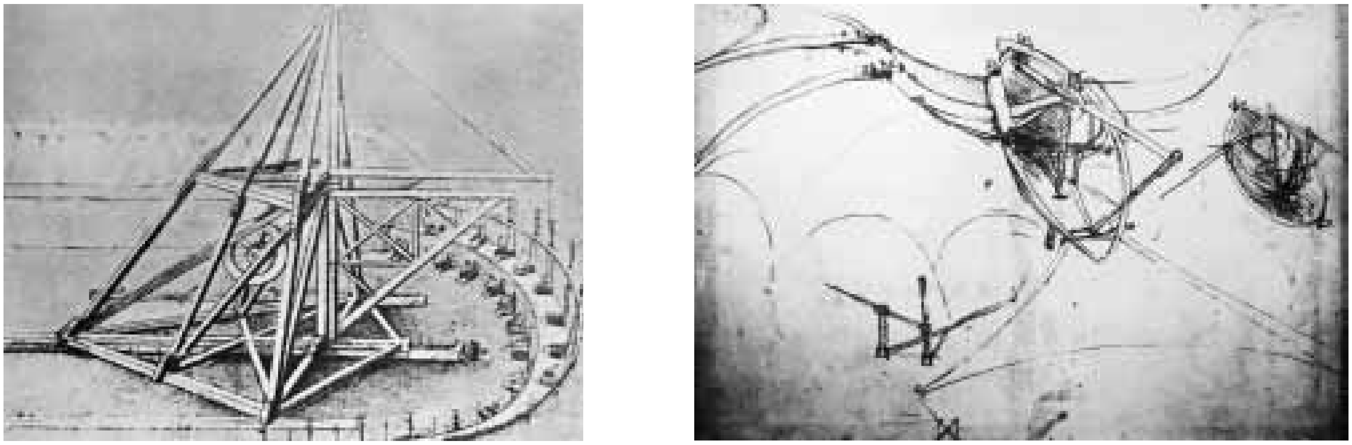


FIGURE 1.10. Images of original da Vinci drawings: a machine used for canal excavation (left) and a flying ship (right). Codex Atlanticus, folio 860; drawing from Il Codice Atlantico di Leonardo da Vinci nella biblioteca Ambrosiana di Milano, Editore Milano Hoepli 1894–1904; the original drawing is kept in the Biblioteca Ambrosiana in Milan.
Sources: © Bettmann/CORBIS

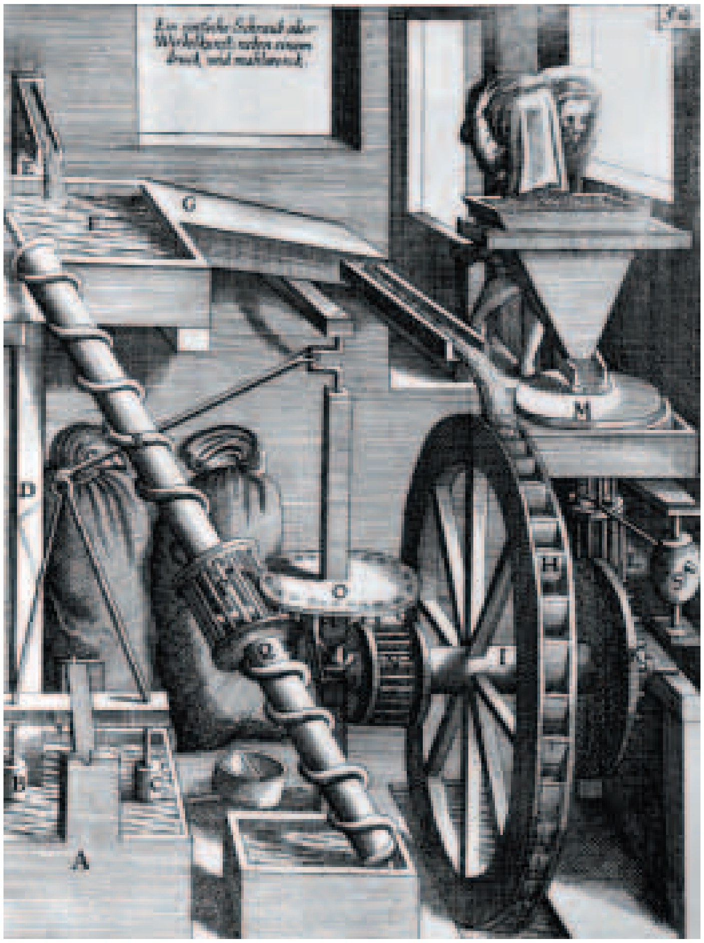


FIGURE 1.11. A perpetual motion machine by medieval inventors: an Archimedes screw driven by a waterwheel is used to mill grain.
Source: Timewatch Images/Alamy

engineering, they could conceive things that theoretically should have worked without having been previously built. When inventors did not understand the science behind the proposed devices, the devices usually did not work. The many perpetual motion machines proposed at that time, as shown in Figure 1.11, are evidence of inventors' lack of understanding of the physical science and their resultant failed attempts to build the machines.

Engineers began to realize that accurate sizing was an element of the function of a structure or device. Diagrams made during the Renaissance paid more attention to accurate depth and perspective than in earlier times. As a result, drawings of proposed and existing devices looked more realistic than earlier drawings.

Gunpowder was introduced during the Renaissance, as was the cannon. The cannon made obsolete most of the fortresses built during the medieval era. The walls could not withstand impact from cannon projectiles. Consequently, fortresses needed to be redesigned to survive cannon fire. In France, a new, stronger style of fortification was designed. The fortification was constructed with angled walls that helped to deflect cannon fire and did not crumble as flat vertical walls did when struck head on. The new fortresses were geometrically more complicated to build than their predecessors with vertical walls. Further, the perimeter of the fortress had evolved from a simple rectangular shape to a pentagonal shape with a prominent extension at each apex. That perimeter shape, coupled with the angled walls, resulted in walls that intersected at odd angles that could not be seen and measured easily or directly. Following is a list of questions that builders of earlier fortresses could easily answer but that builders of the angled wall fortresses could not:

- What is the surface area of a wall?
- What is the fill volume?

- What are the specific lengths of timbers and beams needed to construct and brace the walls?
- What are the true angles of intersection between certain surfaces?
- What are the distances between lines and other lines, between points and lines, and between points and surfaces?

Fortunately, the French had Gaspard Monge, who developed a graphical analysis technique called **descriptive geometry**. Analytical techniques using mathematics were not very sophisticated at that time, nor were machines available to do mathematical calculations. But mechanical **instruments**, such as compasses, protractors, and rulers, together with the graphical method, were used to analyze problems without the need to do burdensome math. Descriptive geometry techniques enabled engineers to create any view of a geometric object from two existing views. By creating the proper view, engineers could see and measure an object's attributes, such as the true length of its lines, the true shape of planes, and true angles of intersection. Such skills were necessary, especially for the construction of fortifications, as shown in Figure 1.12. The complex geometry, odd angles of intersection, and height of walls were intended to maximize the cross fire on an approaching enemy, while not revealing the interior of the fortress. Another objective was to construct the ramparts and walls by moving the minimum amount of material for maximum economy.

The astuteness of the French at building fortifications kept France the prime military power in Europe until the 1700s. At that time, descriptive geometry was considered a French state secret; divulging it was a crime punishable by death. As a result of the alliance between France and the newly constituted United States, many U.S. fortifications used French designs. An example is Fort McHenry (shown in Figure 1.13), which was built in 1806 and is exquisitely preserved in Baltimore, Maryland. Fort McHenry survived bombardment by the British during the War of 1812 and is significant because it inspired Francis Scott Key to write "The Star Spangled Banner."

By the 1800s, most engineering was either civil engineering or military engineering. Civil engineering specialized in the construction of buildings, bridges, roads, commerce ships, and other structures, primarily for civilian and trade use. Military engineering specialized in the construction of fortifications, warships, cannons, and other items for military use. In both fields of engineering, as projects became more complicated, more people skilled in various subspecialties were needed. Clear, simple,

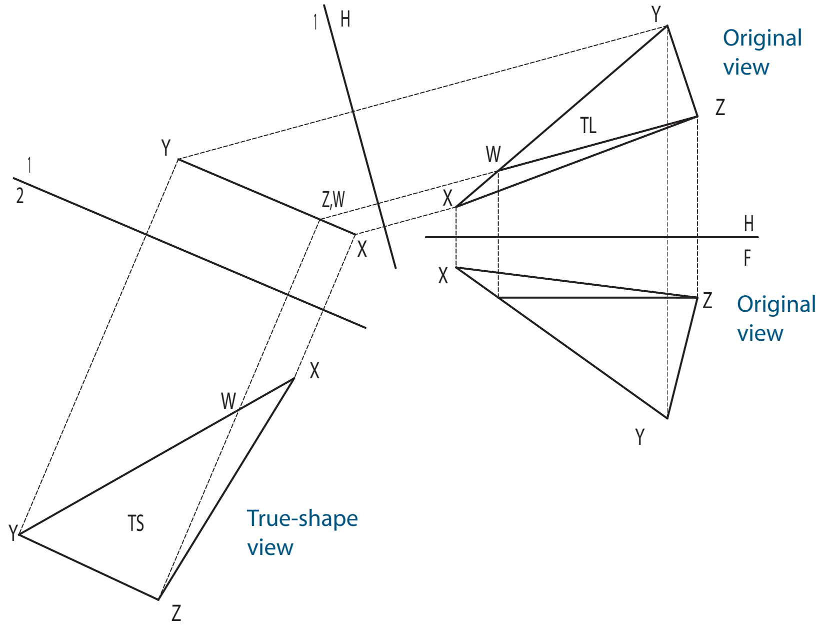


FIGURE 1.12. Using descriptive geometry to find the area of a plane.
Courtesy of D. K. Lieu

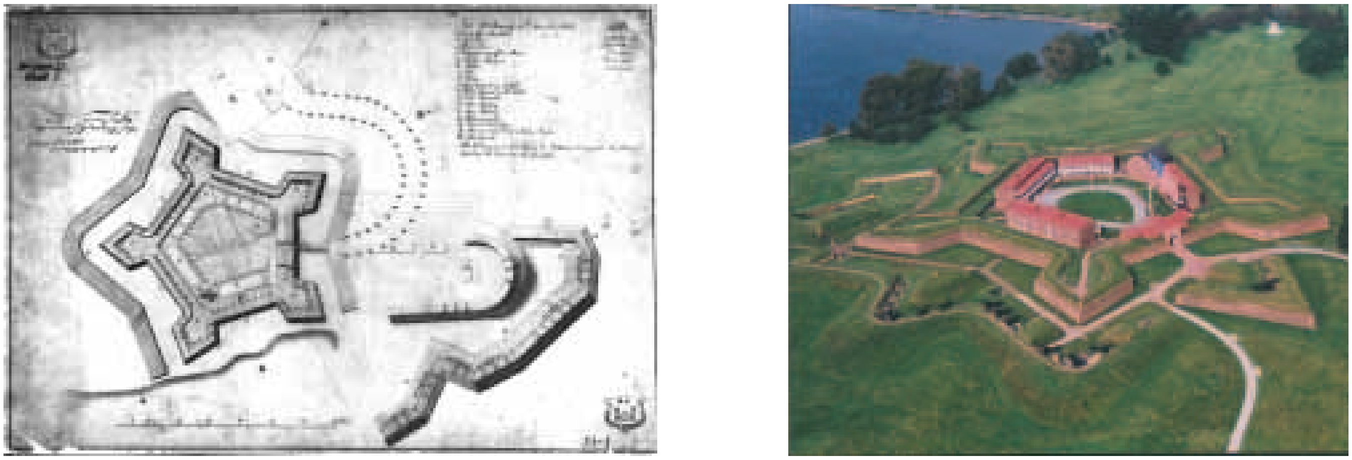


FIGURE 1.13. French fortification design principles (left) and Fort McHenry (right) in Baltimore, Maryland, whose design was based on those principles.
Courtesy of The National Archives, College Park, Maryland, left; Courtesy of The National Park Service, Fort McHenry NMHS, right.

and universal communication was necessary to coordinate and control the efforts of specialists interacting on the same project. Different people needed to know what other people were doing in order for various **parts** and **assemblies** to fit together and function properly. To fill that need, early forms of scaled drawings began to be used as the medium for communications in constructing a building or device.

1.02.04 The Industrial Revolution

The industrial revolution began in the early 1800s with the new field of mechanical engineering. This revolution was, in part, a result of the need for new military weapons. Before the 1800s, ships and guns were fabricated one at a time by skilled craftsmen. No original plans of any ships from the Age of Discovery exist, because shipwrights did not use plans drawn on paper or parchment. The only plans were in the master shipwright's mind, and ships were built by eye. As the demand for ships grew, production methods changed. It was far more economical to build many ships using a single design of common parts than to use a custom design for each ship. Constructing from a common design required accurate specifications of the parts that went into the design.

The hardware products that general and military consumers needed then were no longer produced by skilled craftsmen but were mass-produced according the techniques and machines specified by engineers. Mass production meant that each product had to be identical to all other products, had to be fabricated within predictable and short production times, had to be made from parts that were interchangeable, and had to be produced economically in volumes much larger than in the past. The consistent and repetitive motions of machines required efficient, large-scale production which replaced manufacturing operations that had needed the skilled motions of craftsmen. Also, engines, boilers, and pressure vessels were required to provide power to machines. An early manufacturing facility with machine tools and an early steam engine are shown in Figure 1.14 and Figure 1.15, respectively.

Creating not only a product but also the machines to produce it was beyond the abilities of individual craftsmen—each likely to have a different set of skills needed for the production of a single product. The high demand for creating machines as well as products meant that the existing master-apprentice relationship could no longer supply the demand for these skills. To meet the growing demand, engineering schools had to teach courses in basic physics, machine-tool design, physical motion, and energy transfer.

FIGURE 1.14. A photo showing early factory conditions during the industrial revolution.
Courtesy of Time Life Pictures/Getty Images

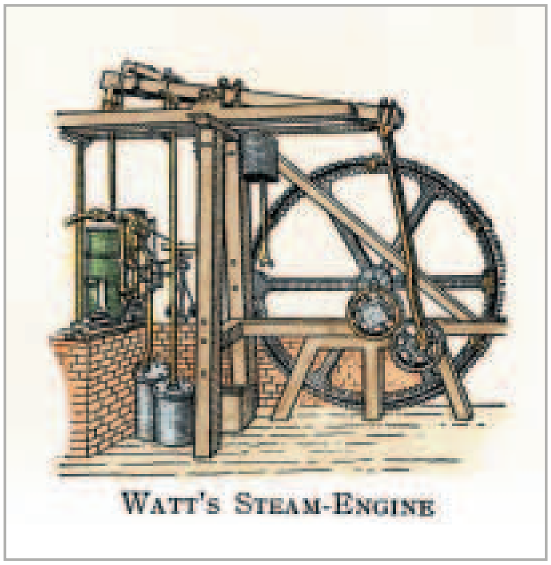


FIGURE 1.15. A schematic drawing of a James Watt steam engine; the type commonly used to power production machinery during the early years of the industrial revolution.
Source: North Wind Picture Archives/Alamy

Communication was necessary to coordinate and control the efforts of different people with different skills. Each craftsman, as well as each worker, on a project needed to know what others were doing so the various pieces, devices, structures, and/or systems would fit together and function properly. The ideas of the master designer had to be transferred without misinterpretation to those who worked at all levels of supporting roles. In the design stage, before things were actually built, the pictorial diagrams once used were soon found to be insufficient and inaccurate when new structures with new techniques were being built. More accurate representations, which would provide exact sizes, were needed. That need eventually led to the modern engineering drawing, with its multiple-view presentation, identification of sizes, and specification of allowable errors.

Around the time of the industrial revolution, patents started to become important. As a method of stimulating innovation in an industrialized society, many governments offered patents to inventors. The owners of patents were guaranteed exclusive manufacturing rights for the device represented in the patent for a prescribed number of years in exchange for full disclosure of how the device operated. Since a single successful patented invention could make its owner rich, many people were inspired to create new products. From the start, the difference between patent drawings and engineering has been that engineering drawings are made to be viewed by those formally trained in engineering skills and to show precise sizes and locations. Patent drawings, on the other hand, are made to teach others how and why a device operates. Consequently, patent drawings often do not show the actual or scaled sizes of the parts. In fact, sizes are commonly distorted to make the device more difficult for potential competitors to copy. An example of a patent drawing is shown in Figure 1.16.

1.02.05 More Recent History

As technology advanced over time, additional engineering specialties were born. In the late 1800s, as electric power became more popular and more available, electrical engineering was born. Electrical engineering at that time was concerned with the production, distribution, and use of electrical energy. The information derived from the study of

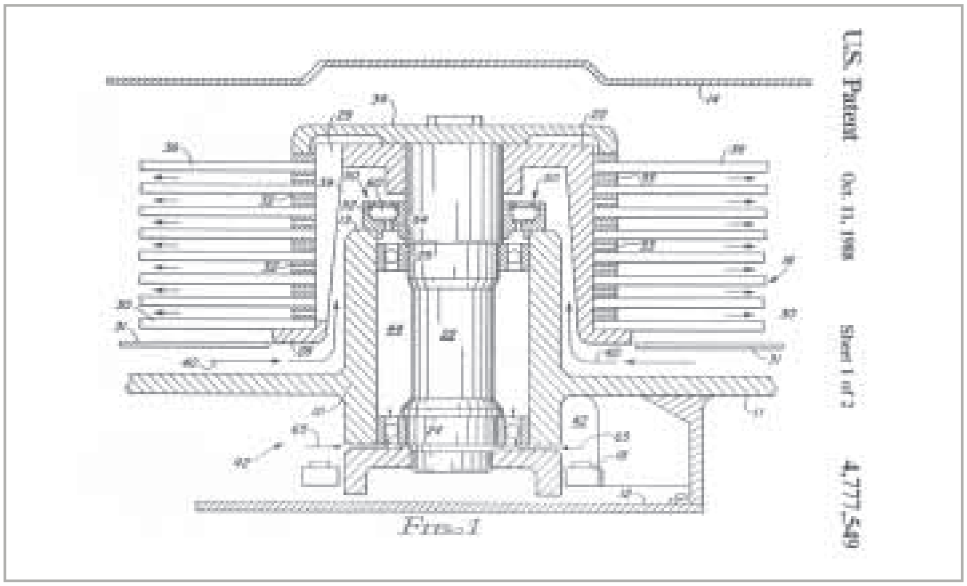


FIGURE 1.16. A U.S. patent drawing showing function but not necessarily the true sizes of the parts.
Courtesy of D. K. Lieu

electric motors, generators (shown in Figure 1.17), power conversion, and transmission lines needed for their design was more than other engineers—not specifically electrical engineers—could be expected to know and use. Chemical engineering, as a special engineering discipline, emerged at the beginning of the twentieth century with the need for large-scale production of petroleum products in refineries, as shown in Figure 1.18, and the production of synthetic chemicals.

During the 1950s, industrial engineering and manufacturing engineering emerged from the necessity to improve production quality, control, and efficiency. Nuclear engineering emerged as a result of the nuclear energy and nuclear weapons programs.

Some of the more recent engineering disciplines include bioengineering, information and computational sciences, micro-electro-mechanical systems (MEMS), and nano-engineering. The design of a MEMS device (for example, the valve shown in

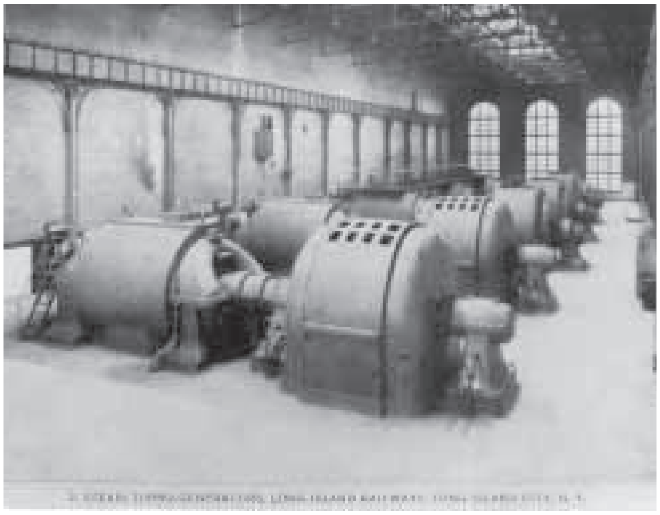


FIGURE 1.17. Later during the industrial revolution, steam engines were replaced by electric power supplied, for example, by these generators at the Long Island Railway shown (circa 1907). Electrical engineering was born.
Courtesy of SMITHSONIAN INSTITUTION Neg.#44191D

FIGURE 1.18. The demand for chemical and petroleum products led to the construction of sophisticated plants and refineries and the disciplines of chemical and petroleum engineering.
Courtesy of DOE/NREL, photo by David Parsons.

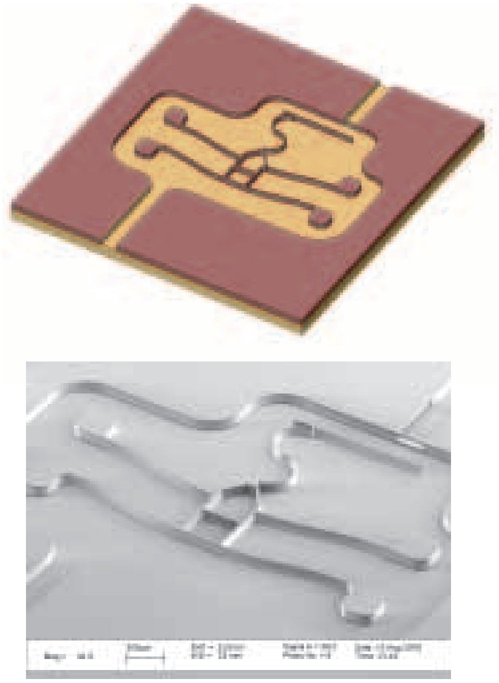


FIGURE 1.19. This MEMS valve was designed with a solid modeler and was fabricated using semiconductor processing techniques.
Courtesy of the Berkeley Sensor and Actuator Center, University of California.

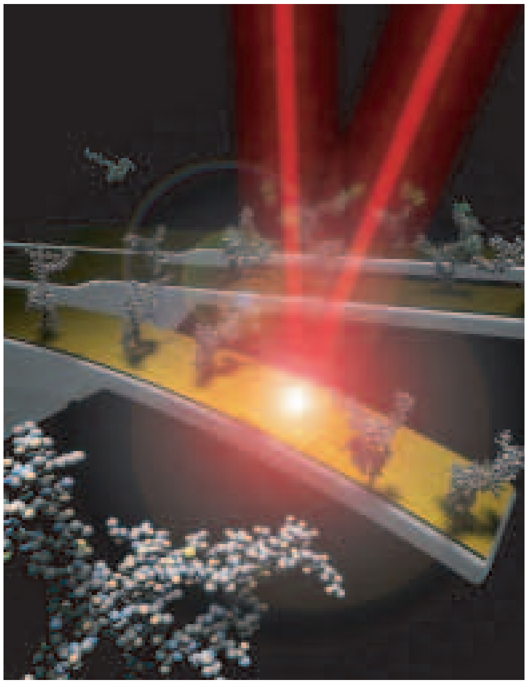
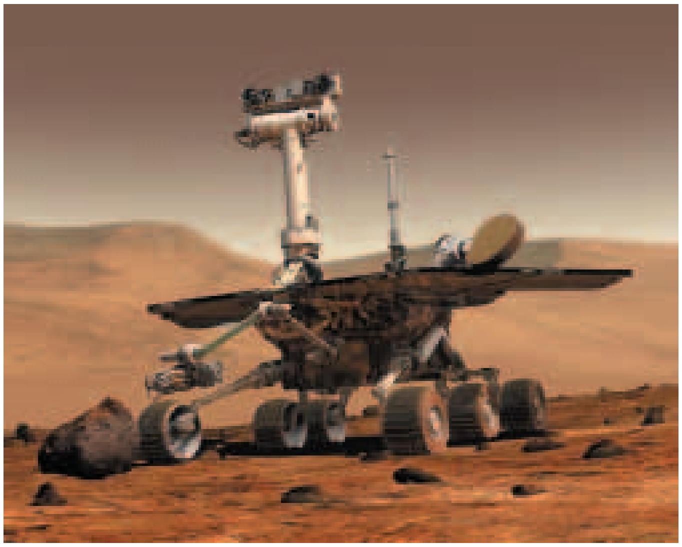


FIGURE 1.20. This nano-device for sorting molecules does not actually appear as shown, but the use of graphics aids in understanding its operating principles.
Courtesy of Kenneth Hsu.

Figure 1.19) requires skills from both electrical and mechanical engineering. A nano-engineered device cannot be seen with conventional optics. Its presumed appearance, such as that shown in Figure 1.20, and function are based on conjecture using engineering graphics tools.

With the emergence of a new discipline comes formal intensive training, specifically in the specific discipline, as opposed to subspecialty training within an existing discipline. Most complex engineering projects today require the combined skills of engineers from a variety of disciplines. Engineers from any single discipline cannot accomplish landing an astronaut on the moon or putting a robotic rover, shown in Figure 1.21, on Mars.

FIGURE 1.21. Complex engineering projects, such as interplanetary space missions, require interdisciplinary engineering skills.
Source: NASA/JPL/Cornell University



1.03 The People and Their Skills

Today few engineering projects exist where a single person or a small group of people is responsible for all aspects of the project from beginning to end. Many people with many different types of technical and nontechnical skills participate in the development and production phases of a project. Whether that person is the engineer who conceives the overall idea or the fabricator who makes the individual pieces or the technician who assembles the parts to make the system operate, they all have common questions:

- What is this part, device, or structure supposed to do?
- What is it supposed to look like?
- What are the precise geometries and sizes of its features?
- What is it made of?
- How is it made?
- How does it fit into other parts, devices, or structures?
- How do I know if everything is made the way it was supposed to be made?

To answer these questions, a clear, unbroken, and unambiguous flow of communication must take place, as depicted in each diagram in Figure 1.22.

The object envisioned by the engineer must be the same object produced by the fabricator and the same object assembled into the working system by the technician. Graphical communication that follows universally accepted standards for representing shapes and sizes makes that happen.

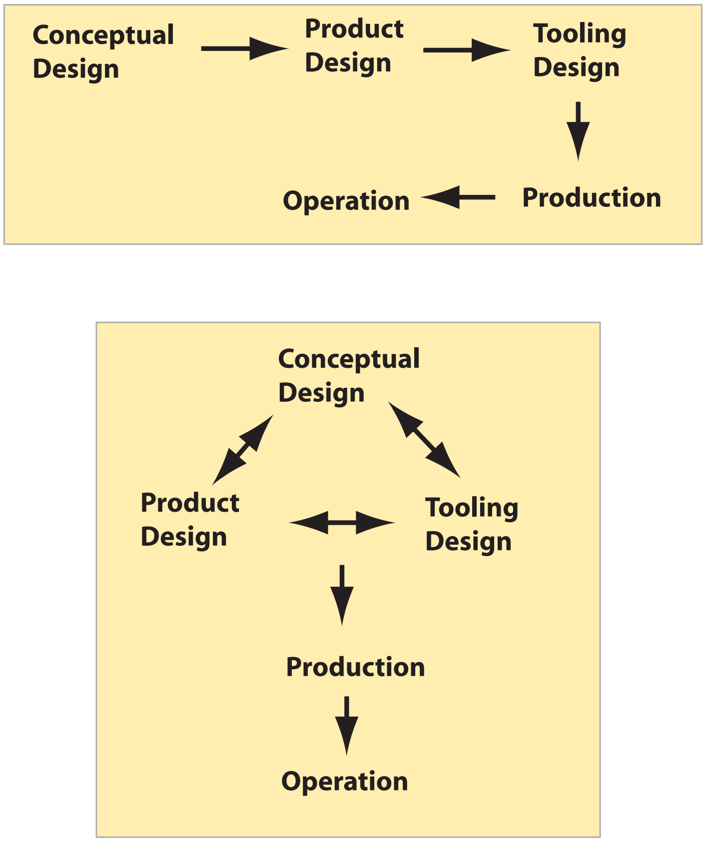


FIGURE 1.22. In conventional product design (above), phases of the development cycle occur sequentially. Concurrent engineering (below) combines two or more phases to accelerate the cycle.
Courtesy of D. K. Lieu

1.03.01 Organization of Project Life Phases

An engineering project may be as simple as a one-piece can opener or as complex as an interplanetary space mission—or anything in between. The number of people involved can be as few as one to as many as several thousand. Regardless of the complexity of the project or the number of people involved, any project can be broken into several phases over its lifetime. These life phases are as follows:

- Concept
- Design
- Fabrication
- Installation
- Operation
- Disposal

For example, consider the wind-powered electric generation facility located at California's Altamont Pass approximately 100 km east of San Francisco. This facility, composed of about 7,200 large wind turbines covering an area of several hundred square kilometers, is one of the largest wind-energy-producing facilities in the world. Many of the lessons learned in the construction and operation of the Altamont facility were incorporated into the plans to build a new wind-powered generation facility for the Solano County area, which is near the Sacramento River delta in California. A small portion of the Solano facility is shown in Figure 1.23.

FIGURE 1.23. A few of the 100-meter-high wind turbines at the Solano Wind Power Generation Facility (above) and one of the turbines on the ground before mounting (below).
Courtesy of D. K. Lieu

Before the facility could be built, it had to be decided during the Concept Phase whether the project would be economically viable and socially and environmentally acceptable. Other decisions involved the size and density of turbines.

During the Design Phase, the types of turbines were selected. The shapes and sizes of the various parts for the turbines and their supporting structures were developed, as was a scheme for collecting, controlling, and distributing the electric power that would be produced.

Parts that could not be purchased as finished units were custom-built during the Fabrication Phase. During the fabrication of custom parts for any project, the appropriate manufacturing processes are selected to reduce costs as much as possible. For large projects, it is just as common to use foreign and domestic suppliers for prefabricated as well as custom-fabricated parts.

The Installation Phase involves taking the individual parts and putting them together to create individually operating turbines. The individual turbines needed to be networked to supply power as an entire system.

The Operation Phase includes not only the control of the system but also the maintenance of the individual turbines and the networked power grid. When parts wear out or are damaged, they must be repaired or replaced.

Finally, when the entire facility has reached the end of its useful life, there must be a plan in the Disposal Phase for removal of the facility, disposal or recycling of its components, and return of the land to other uses.

1.03.02 Organization of Functional Groups

The larger the number people within each phase and between phases, the greater the need for effective communication. In a complex engineering project, the work needs to be divided into many subspecialties that are usually performed by different organizations. The personnel involved in each phase of a project generally can be organized into the following functions:

- Research and Development
- Design
- Manufacturing
- Sales and/or Buying
- Service
- Subcontractors

Depending on the complexity of the project, the same person can handle each function as a specialty, or an entire group of people may be responsible for each function. In the case of the Solano wind-powered generation facility, let's examine one of the project phases. During the Design Phase, certain people were responsible for seeking and evaluating new materials, devices, and technologies that would be of immediate use in designing and building the turbines. Those people filled the Research and Development function. Other people in the Design function were responsible for specifying the shapes and sizes of premade and custom parts so the parts would fit and function as intended. The people who actually made the parts or assembled them into operating prototypes filled the Manufacturing function. Any premade items or raw materials that had to be purchased were done by people in the Buying function. People in the Service function were responsible for operating the prototypes and, if necessary, to collect data needed to evaluate the design for improvement. Subcontractors supplied items or services that could be produced more quickly and efficiently by third parties. For the project life phases, similar responsibilities could be identified for each of the functions just mentioned.

1.03.03 Organization of Skills

Within each function of each project phase, the responsibility of the engineering personnel can be further subdivided as follows:

- Engineers
- Designers
- Drafters
- Fabricators
- Inspectors
- Technicians

Engineers are responsible for ensuring that systems and devices are specified to operate within their theoretical limits, specifying the materials and sizes of parts and assemblies so that failures do not occur, specifying the methods in which the devices are maintained and operated, and evaluating and preparing the environment in which large projects are to be placed.

Designers are responsible for the project's fit and finish, that is, specifying the geometry and sizes of components so they properly mate with each other and are ergonomically and aesthetically acceptable within the operating environment.

Drafters are responsible for documentation—the formal graphical records of parts and assemblies that are required not only for record keeping but also for unambiguous communication between people working on the project.

Fabricators are responsible for making the parts according to the specifications of the engineers and designers, using the documentation provided by the drafter as a guide.

Inspectors are responsible for checking; they take parts made by the fabricators and compare the actual sizes of the parts' features to the desired sizes. This is done to ensure that the parts are properly made and will fit and function as intended. Some projects are installed over large pieces of land. In those cases, inspectors ensure that the land has been properly prepared and that the various elements that compose the project have been made and installed according to the specifications of the engineers.

Technicians are responsible for operation and maintenance; they typically assemble various components to create working devices or structures, operate them, and maintain them.

Depending on the particular phase of the project and the particular function group within that phase, a group will have different combinations of engineering personnel. For example, the Design Phase of the wind-powered generation facility had many engineers and designers but few technicians. However, during the Operation Phase, the facility had mostly technicians, with only a few engineers. One interesting problem that engineers faced during the Operation Phase of the Altamont Pass wind power facility was how to reduce the number of birds, including large raptors, that were killed every year by the spinning turbine blades. No one foresaw this problem during the earlier phases of the project. Special avian experts had to be consulted during the Operation Phase to assist the engineers with possible solutions. Those same avian experts were consulted during the Design Phase of the Solano wind power facility. The new turbines at Solano were designed to have slower blade rotation speeds, and their towers were designed to make bird nesting difficult.

Regardless of the makeup of the engineering group, whenever a number of people participate in any aspect of a project, such as designing and constructing a part, everyone must know what that part is supposed to look like, what the part is made of, and what the part is supposed to do.

1.03.04 Concurrent Engineering

You should not finish the preceding section thinking that the only way engineering projects are done, or even the preferred way to get them done, is through formally

FIGURE 1.24. Entering the maintenance hatch in one of the Solano wind turbine towers. *Courtesy of D. K. Lieu*

organizing functional groups and separating skills. Separate functions and skills may be the classic way to do things, but many modern products use concurrent engineering to reduce the time needed for the product design and production cycles. Concurrent engineering is a process where the design and certain aspects of the fabrication phases are combined. The engineers responsible for the design of a product and the engineers responsible for manufacturing or construction work together closely. Thus, as a part is being conceived, its method of fabrication and assembly into other parts is being given careful consideration. The design of the part is then altered to facilitate its fabrication and, when economically feasible, its assembly into a larger system. Concurrent engineering also considers the method of disposal once the part has reached the end of its useful life.

As an example of concurrent engineering, consider the support tower for one of the wind turbines at the Solano facility. This structure supports the turbine, transmission gearbox, and generator; it also provides access (via a very long stairway) to these devices for maintenance, shown in Figure 1.24. Assume you are the designer of this structure and you want it made from steel.

Since several thousands of these structures may be needed for the many wind power installations around the world, you need to consider the economics of fabricating them. Using a conventional engineering timeline approach, you need to determine the required material and geometry, then make the drawings for the structure. You would have a prototype fabricated, installed on a prototype wind turbine, and tested to prove that it will do what you designed it to do and, especially, that it will not fail. Then you would turn the part and its drawings over to a manufacturing engineer to figure out the best and most economical way to **fabricate** large numbers of the structures to satisfy the worldwide needs of wind-power generation installations. For example, one way of fabricating the tower would be to make it from many small curved plates of steel, with all of the plates welded together. But it may be more economical to produce large sections of complete tubes that are the diameter of the tower and then connect those sections. However, the cost of any special tooling required to make and transport the large tubes would need to be included in the final cost of the structure. Different fabrication processes are possible for making the sections. Each process has different advantages and disadvantages in terms of cost and efficiency.

With concurrent engineering, engineers from all phases of the project work together. Engineers who ordinarily become involved later in the process get together with the designer at the early stages of the design. For example, the manufacturing engineer would advise the part designer on how to change a part so it would be easier to fabricate or handle. At nearly the same time, the manufacturing engineer would begin to design any specialized tools that would be needed to fabricate, handle, and assemble the part in large numbers. As the part prototype is being fabricated, these special tools also would be built. The advantage of concurrent engineering is that product development is reduced. The disadvantage is that large errors in design are expensive because any changes in design also require changes to the production tooling.

1.04 Engineering Graphics Technology

Mechanical drawing instruments have been a tremendous aid for the creation of engineering graphics. These instruments greatly improve the precision with which graphics can be produced and reproduced, reducing any distortion and making analyses easier and more accurate. The improvement of engineering graphics technology over the years has been a major factor in the improvement of engineering design and communication.

1.04.01 Early Years

Up until the time of the Renaissance, most drawing was done by hand without mechanical devices, because none were available. As a result, many of the drawings that were made to depict some sort of engineering device were distorted. The amount of distortion depended on the skill of the person making the drawing. **Two-dimensional (2-D) drawings** were common because they were easy to make. Attempts at drawing objects showing depth had mixed results. Leonardo da Vinci was one of few people who was good at it, but he was also a skillful artist. In general, though, handmade drawings were good for conveying ideas and some rough sizing. They were poor when precision was necessary, mostly because it was not possible to determine exact sizes from them. In fact, the inch and foot as units of measurement in Europe were not standardized until the twelfth century, and the meter was not defined until the eighteenth century. As a result, when different craftsmen built the same item, the sizes of the parts would be slightly different. Those differences made part interchangeability, and thus mass production, extremely difficult.

1.04.02 Instrument Drawing

Early instruments used to make drawings included straightedges with graduated scales, compasses and dividers, and protractors. They were generally custom-made items for the convenience of those who could afford them. Mechanical instruments for drawing did not become widely available until the industrial revolution, when, for a reasonable cost, machines could produce accurate instruments for both drawing and measuring. Both standardized units and accurate drawings made it possible for different fabricators to make the same part. With careful specifications, those parts would be interchangeable between the devices in which they functioned. Now that engineering drawing made it possible to fabricate the same part at different manufacturers, engineering drawing became a valuable means of communication.

From the industrial revolution to the late twentieth century, drawing instruments slowly improved in quality and became less expensive. Drawing instrument technology reached its most effective and highest level of use during the 1970s. Some companies and individuals today still retain, and even prefer, to use mechanical instruments for making engineering drawings. Classic drawing instruments, some of which are shown

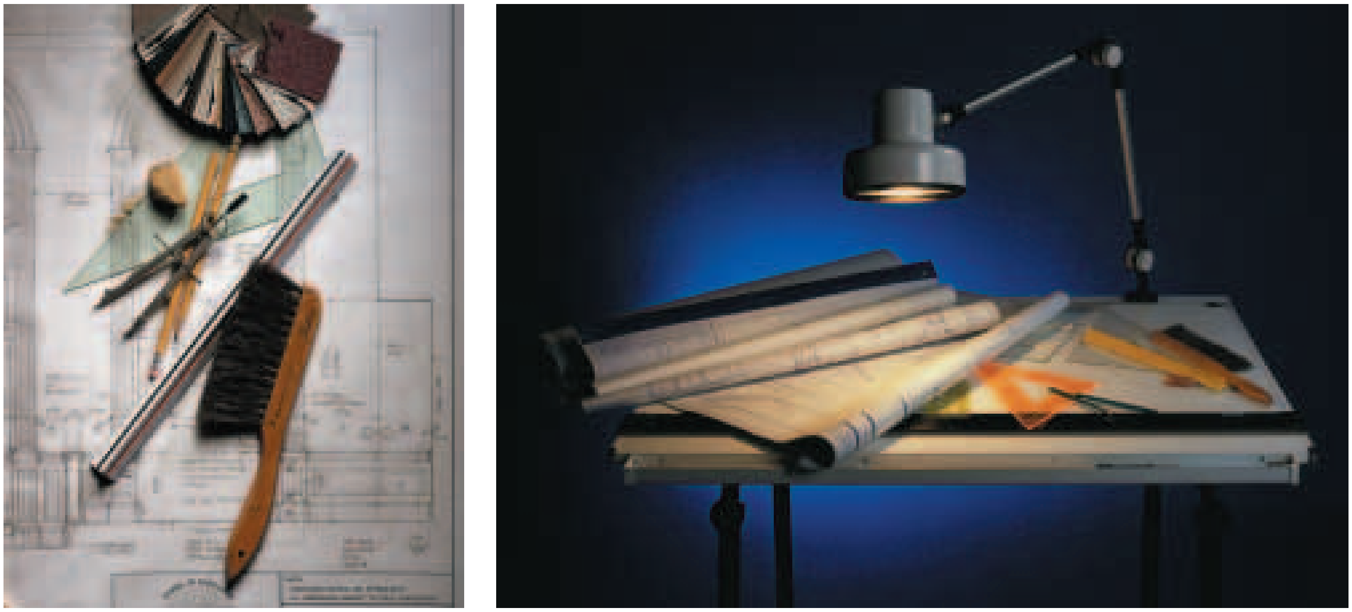


FIGURE 1.25. Tools for instrument drawing (left) and a drafting machine (right).
Sources: © Peter Harholdt/SuperStock, left; © Françoise Gervais/CORBIS, right.

in Figure 1.25, are available from architecture, art, and engineering supply shops; these instruments include the following:

- Drafting board—a large, flat table with straight, square edges for alignment of drawing instruments
- Drawing vellum—a tough, dimensionally stable, and age-resistant paper on which drawings are made when placed on the drafting board
- T square—an instrument used to make horizontal and vertical lines by using the edges of the drafting board for reference
- Triangle—an instrument used to make lines at common angles
- Protractor—an instrument used to measure angles or make lines at arbitrary angles
- Scale—an instrument used to measure linear distances
- Drafting machine—a special machine used to hold scales at arbitrary angles while the scales are allowed to translate across the drawing, thus replacing many of the previously listed instruments
- Compass—an instrument used to make circles and arcs
- French curve—an instrument used to make curves
- Template—an instrument used to make common shapes

Using pencil or ink, engineers use instruments to draw directly on the desired sized vellum sheet. Large drawings are reproduced on special copy machines. Up until the 1980s, engineering students often were burdened with having to learn how to use the drawing instruments.

1.04.03 The Computer Revolution

During the 1970s, many large companies, particularly those in the automotive and aerospace industries, recognized the advantages of computer-based drawing and graphics: ease of storage and transmission of data, precise drawing data, and ease of data manipulation when drawings needed to be changed. Several large companies began developing computer-aided drawing (**CAD**) tools for their own use. Mainframe computers were just reaching the point where their cost, computation power, and storage capability would support computer-based drawing. The CAD systems consisted of computer terminals connected to a mainframe computer. However, the conversion to computer-based drawing was slow. Mainframe computers were expensive, the user had to have some computer skills, computer hardware and software were not very reliable, and special input and output devices were necessary. Thus, the average engineer or drafter still had a difficult time making the transition from mechanical tools to computer-based tools.

In the late 1970s and early 1980s, several companies specializing in CAD developed freestanding computer-drawing stations based on small independent computers called workstations. Those companies marketed the computer hardware and software as a complete, ready-to-operate unit known as a turnkey system. The workstation approach to CAD made the software more affordable for smaller companies. Also, CAD software became more sophisticated and easier to use. It began to grow in popularity. As personal computers (PCs) began to proliferate in the 1980s, CAD software made specifically to run on PCs became popular. One company that became a leader in this application was Autodesk, with its AutoCAD software. Companies that formerly supplied mainframe computer-based or turnkey CAD systems either quickly adapted their products for PC use or went out of business. As PCs became more powerful, cheaper, easier to use, and more prolific, CAD software did the same. Drafting boards were quickly replaced by PCs. An example of a PC-based CAD system is shown in Figure 1.26.

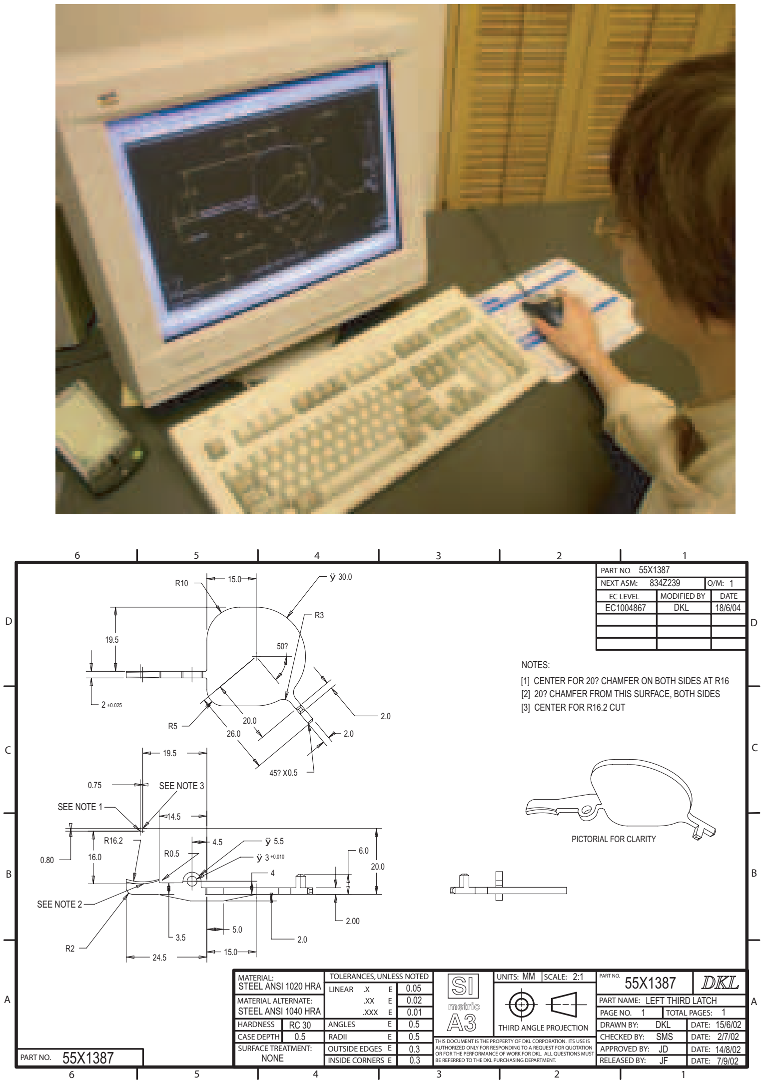


FIGURE 1.26. Computer graphics stations have replaced mechanical drawing instruments in most applications. A CAD drawing can be created by itself or extracted from a solid model.
Courtesy of D. K. Lieu

1.04.04 Graphics as a Design Tool

Computer-based **three-dimensional (3-D) modeling** as an engineering design tool began in the 1980s. CAD was a great convenience, but it produced only drawings. In this sense, CAD was just a very accurate instrument for making drawings. A drawing's representation of an object in three dimensions had to be visualized by the person reading the drawing. It was the same for any fit or function of an assembly—the person reading the drawing had to visualize it. One problem was that not all readers visualized a drawing the same way. Three-dimensional modeling addressed those problems directly. Unlike a 2-D CAD drawing, which was a collection of 2-D objects used to represent specified views of an object, computer-based solid models had 3-D properties.

The field of mechanical engineering quickly adopted 3-D modeling, calling it **solid modeling**, for the design and analysis of mechanical parts and assemblies. Extrusion or revolution of 2-D shapes created simple 3-D geometries. More complex geometries were created by Boolean operation with simple geometries. The computer calculated a 3-D pictorial **image** of the part, which the engineer could see on a computer monitor. The biggest advantage of solid modeling over CAD was that it permitted viewing a 3-D object from different perspectives, greatly easing the **visualization** of a proposed object. Multiple parts could be viewed together as an assembly and examined for proper fitting. With solid modeling, graphics became more of an engineering design tool, rather than merely a drawing tool. An example of a solid **model** for a single part is shown in Figure 1.27. An assembly model is shown in Figure 1.28.

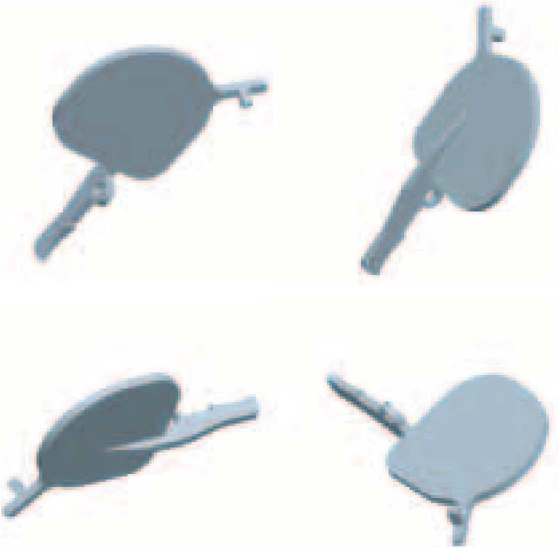


FIGURE 1.27. Solid modeling allows a proposed part to be easily visualized in a variety of orientations.
Courtesy of D. K. Lieu

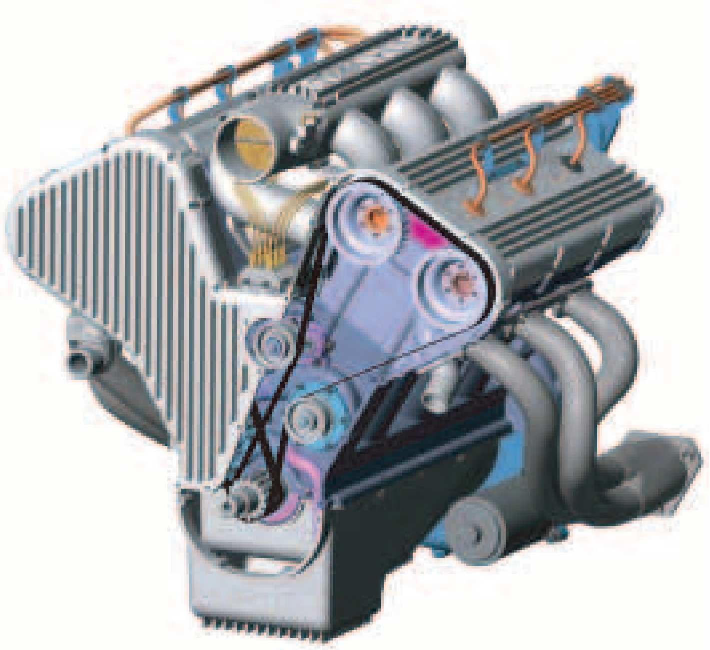


FIGURE 1.28. An assembly model of an Omnica 3.2-liter V-6 engine made from a collection of solid model parts.
Courtesy of SolidWorks Corporation

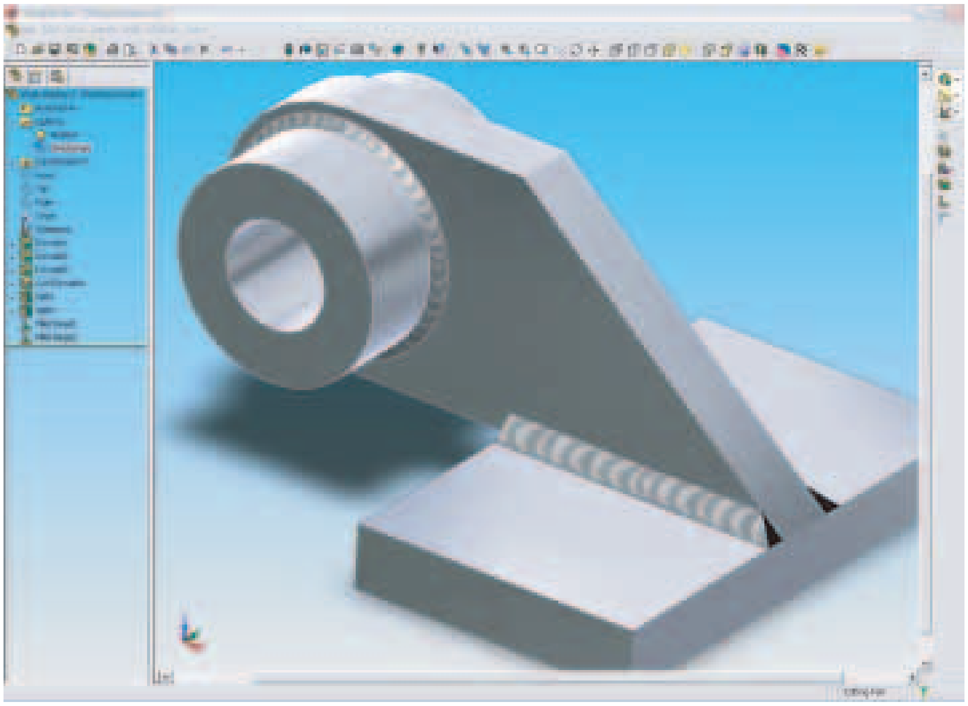


FIGURE 1.29. The graphical user interface of a solid modeling software program.
Courtesy of SolidWorks Corporation

As you may have realized, solid modeling required more computation power and memory to process files than CAD did. That is why solid modeling was originally introduced on computer workstations using UNIX operating systems, which were relatively costly at the time. In the late 1980s, a new software algorithm increased the utility of solid modeling by making it possible to link the sizes and locations of features on an object to variables that could be input and changed easily. The process was known as parametric design. Those products made it easy for an engineer to add, delete, or change the geometry and sizes of features on a part and see the results almost immediately. Dynamic viewing, which enabled the engineer to twist and turn the part image in real time, was also a powerful software feature. A particular facility of that software—the quick and easy extraction of engineering drawings from the 3-D model—made the total software package a valuable drawing tool as well as a modeling tool.

As PCs continued to become more powerful, in the 1990s solid modeling was introduced as a PC software product. The migration of solid modeling from expensive workstations to less expensive PCs made the software popular among small companies and individuals. The later development of new graphical user interfaces, such as the one shown in Figure 1.29, as opposed to the text menus prevalent at the time, made solid modeling easy to use, even for casual users. PC-based solid modeling with graphical user interfaces soon became a standard.

1.04.05 Graphics as an Analysis Tool

Prior to the 1970s, before the days of inexpensive digital computers and handheld calculators, many types of mathematical problems were solved using graphical techniques. Those types of problems included graphical vector analysis, roots and intersections of nonlinear functions, and graphical calculus. Numerical techniques now solve these problems more quickly and easily than graphical techniques, so graphical techniques are not used much anymore. Although solid modeling has decreased the usefulness of descriptive geometry as an analytical tool in many mechanical engineering applications, descriptive geometry still has useful applications in some large-scale civil, architectural, and mining projects. For the most part, drafting boards have been replaced with computers and CAD software, considerably improving accuracy as

FIGURE 1.30. Design of many large structures, such as the Forth Road Bridge, Scotland, shown here, still requires the use of classical two-dimensional drawing and analysis techniques.
Sources: Photo by William G. Godden. Reprinted with permission from EERC Library, Univ. of California, Berkeley, above. Photo by Fredrick T. Godden. Reprinted with permission from EERC Library, Univ. of California, Berkeley, below.

well as ease of use. However, the classical methods of finding distances, areas, inclines, and intersections used for land characterization and modifications are still used. Many recent large-scale construction and landscaping projects, such as the one shown in Figure 1.30, used classical 2-D graphical analysis and presentation methods.

Using solid modeling, the calculation of important mechanical properties of parts and assemblies can be done easily. The volume that a part or assembly occupies usually can be calculated with a single command after the computer model has been built. Properties of volume, such as mass, center of mass, moments of inertia, products of inertia, and principal axes, can also be calculated. Without a solid modeler, the calculation of these properties would be laborious, especially for complex geometries.

The analysis capability of 3-D modeling also has made it popular for certain types of analyses in civil engineering applications. Two-dimensional topographic maps, such

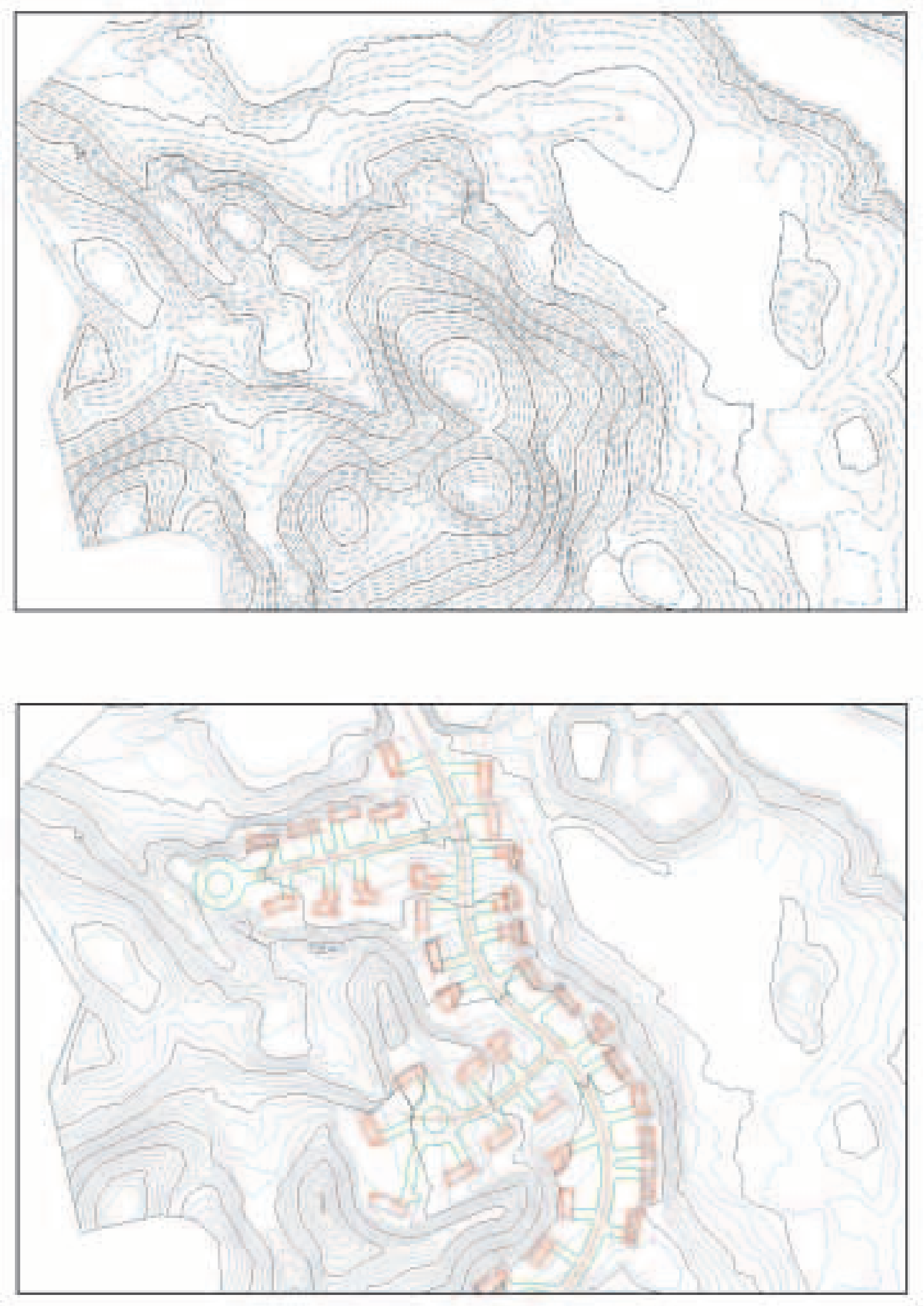


FIGURE 1.31. Classical two-dimensional presentation of land-height contours, natural landscape (top) and development for roads and housing (bottom). *Images courtesy of Autodesk Corporation.*

as the one shown in Figure 1.31, shows land elevations at development sites for proposed residential areas before and after the addition of roads and building pads. The elevation contours of the land change, because certain locations are excavated while other locations are filled with earth to accommodate the roads and pads.

The use of 3-D land models, shown in Figure 1.32, generated from surveying data has made it easier for both engineers and nonengineers to visualize the appearance of a landscape before and after a proposed development. Further, the analytical capability of 3-D modeling in civil engineering applications has made it possible to quickly calculate the volumes of earth that must be removed or added to accommodate the development. It is even possible to match the total addition to the total removal of earth to minimize the volume changed from the site.

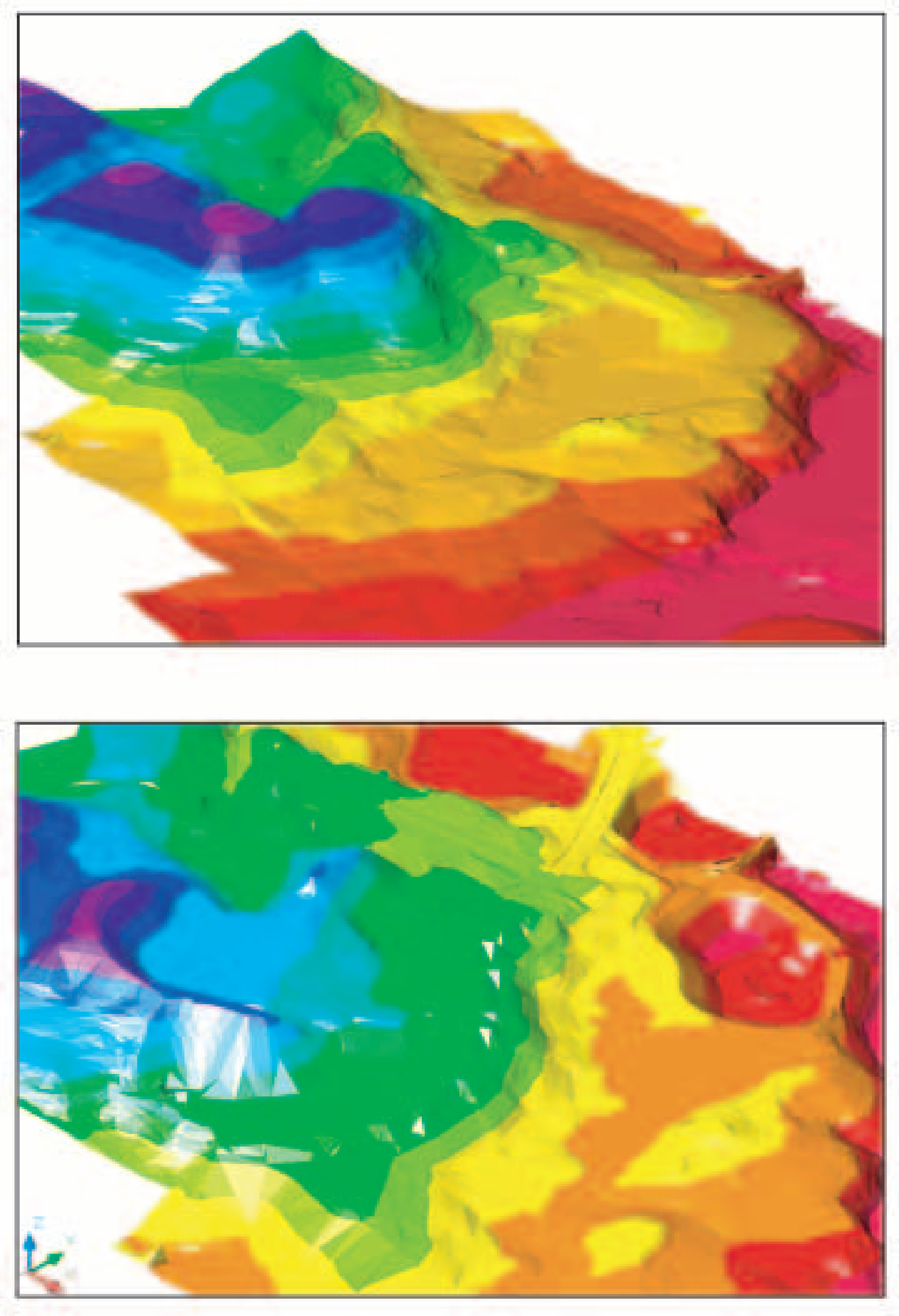


FIGURE 1.32. Three-dimensional images of the contours shown in the previous figure, original land (top) and modifications to accommodate roads and buildings (bottom). *Courtesy of Autodesk ® Civil 3D © 2005 software.*

1.04.06 Graphics as a Presentation Tool

An engineer must be able to communicate not only ideas and designs but also precise engineering data. Whether this data is empirical, as collected from experiments, or analytical, as calculated from mathematical models, they must be presented so other people can understand them quickly and easily. Traditional methods of data presentation are in the form of charts and graphs. Charts include familiar items such as pie charts and bar charts commonly used for presenting data to the general public. Graphs, which are usually more technical, show data trends when the relationship between two or more variables is plotted on orthogonal axes. Examples of these types of data presentation are shown in Figure 1.33.

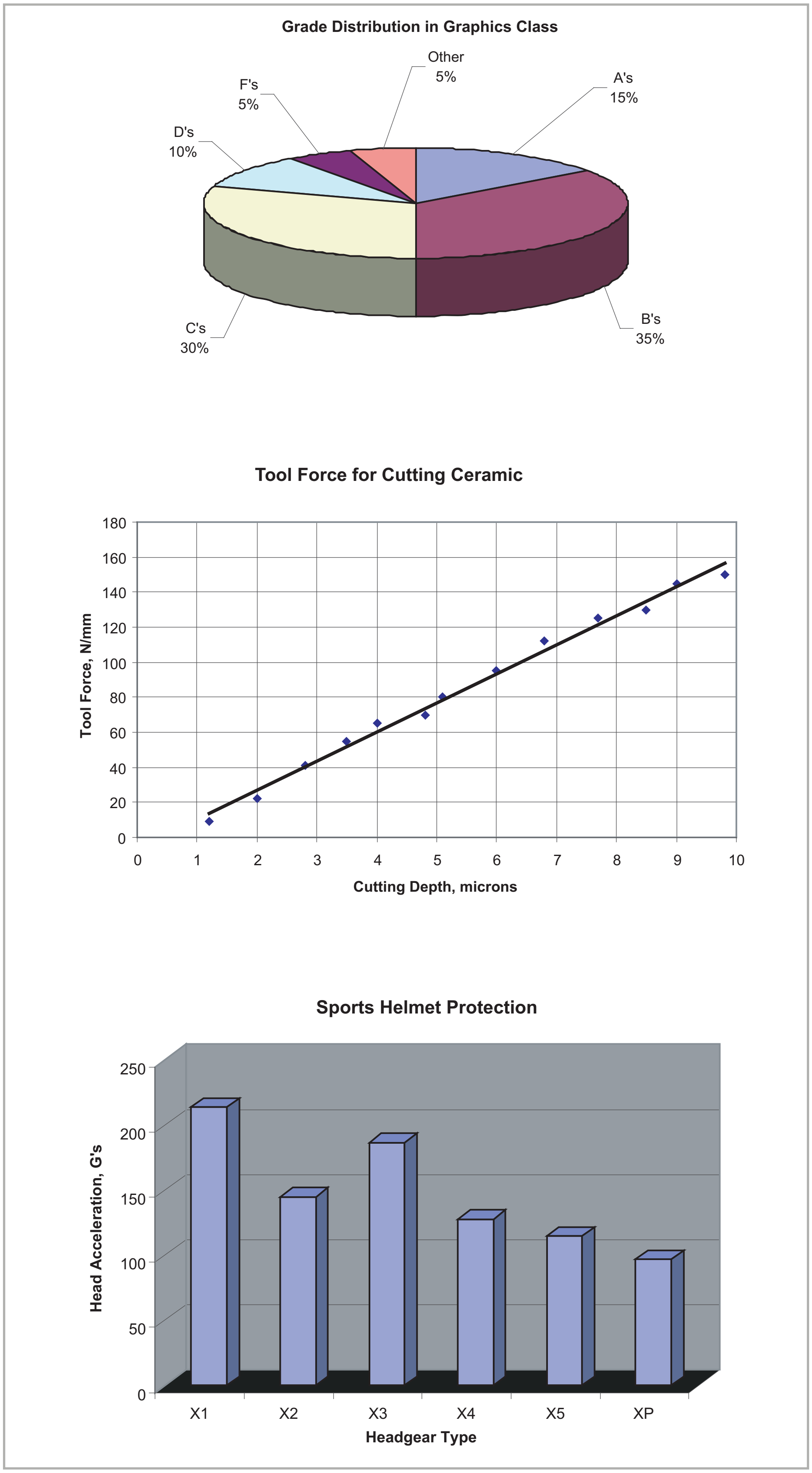


FIGURE 1.33. Data presentation and analysis is a vital part of engineering.
Courtesy of D. K. Lieu

Three-dimensional modeling software is also used to build geometric models that can be exported for finite element analysis (FEA). FEA is a numerical analysis method used to calculate results such as stress distribution, temperature distribution, or deformation in a part. Although FEA usually is not considered a formal part of engineering graphics, one of the most efficient and effective methods of presenting FEA results is to show the predicted contours of variables such as stress, deflection, or temperature atop a pictorial of the object. Different colors are used to represent different magnitudes of a variable. For example, Figure 1.34 shows how a solid model of the teeth, steel, and magnets of a small electric motor are created for geometry analysis. The same model is then used to generate a FEA mesh in preparation for an analysis of the magnetic-flux density distribution in the structure. The flux densities are calculated and their contours are plotted directly atop the original solid model image to show the location and magnitude of the flux densities in the motor.

A popular and effective data presentation method is to show the stress distribution in a part by plotting stress contours directly on the part image, as shown in Figure 1.35. In this way, the location and level of the highest stress in the part can be located easily. The same technique can be used for plotting the temperature distribution and magnetic flux densities in a part.

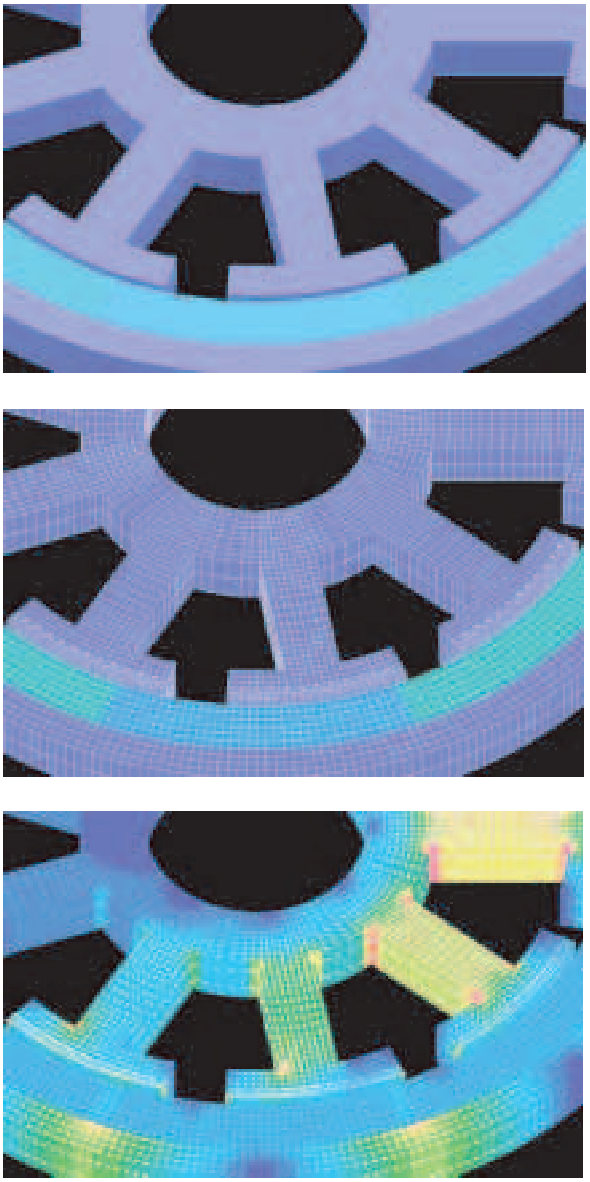


FIGURE 1.34. A three-dimensional model (top) of an electric motor is used to create a FEM mesh (center) from which magnetic flux densities can be calculated and presented (bottom).
Courtesy of D. K. Lieu

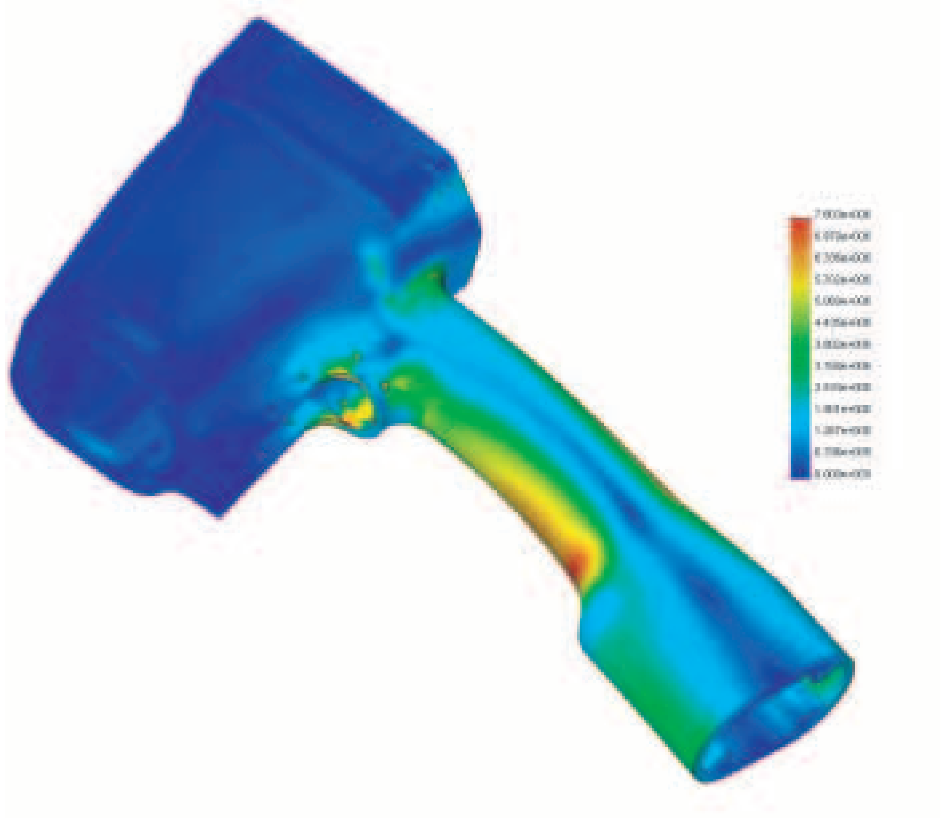


FIGURE 1.35. Graphical representation of stress, such as that produced by forces applied to the part shown, is an important part of presenting the results of a finite element analysis. *Courtesy of SolidWorks Corporation*

1.05 The Modern Role of Engineering Graphics

Although the role of engineering graphics has evolved over the years, many aspects remain the same. Graphics remains the medium for communicating ideas and technical information. The best way to communicate an idea for a part or device is to show a picture of it. In the past, the pictures were crude handmade drawings, which required time and skill to create. Now pictures are computer-generated images of 3-D models that can be turned and rotated so they are viewable from any direction, providing more accurate depictions. Because the models are easy to create, many variations can be created and viewed in a short time. This advantage makes 3-D modeling useful not only as a means of communication but also as a means of design.

Recording the history of a design also remains an important role of engineering graphics. In the past, recording the history of designs usually meant saving master hard-copy drawings in cabinets in some sort of vault. The smallest change in a design meant changing the master copy and then sending updated copies of the master to whoever needed them. Copies commonly suffered distortion or reduced resolution due to the machines that made the copies. While hard-copy drawings are still necessary, most drawing data are now stored as electronic files. There are enormous advantages in the cataloging, retrieval, and transmission of data stored in this manner. Today model and drawing data and their updates can be sent across the world in a fraction of a second with no loss in resolution.

Engineering graphics remains an analysis tool, but the type of analysis has changed. Graphical means are no longer used to solve vector algebra, mathematics, or calculus problems. Instead, graphical models are now used to do things like examine the proper fit and function of parts within assemblies. Using 3-D models, engineers can examine parts in their final assembled state for proper motion and location. Engineers can extract the volumetric and inertial properties of the parts and assemblies, to ensure that they fit as specified. Based on externally applied forces, the stresses and deflections in the material also can be examined to ensure that failure of the device does not occur.

Formal engineering drawing remains a part of the overall design process. The traditional role of formal engineering drawings was to ensure that parts would be fabricated to specified sizes, that they would appear as specified, and that various parts would fit together properly. Prior to the 1990s, most engineering graphics classes concentrated on drawing technique and accuracy and on proper use of mechanical drawing instruments. Since engineering drawings can now be created easily and accurately with computers and software tools, the effort required by the formal drawing process is greatly reduced from what it was in the past. Since most computer graphics tools are easy to master, modern graphics classes concentrate mainly on visualization, analysis, function, and **optimization** of designs.

The development of visualization skills is a particular goal of modern engineering graphics courses. Developing visualization skill is necessary for envisioning, specifying, and creating complex designs with functional features in the three-spatial dimensions. Traditionally, these skills are developed through hand-eye coordination involving physical parts. Hands-on experience, such as repairing an automobile or a bicycle, constructing models, or playing with building toys, is helpful for developing visualization skills. In an engineering graphics curriculum, these skills can be developed by doing special visualization exercises and by building and working with solid models. Another method of developing visualization skills is to disassemble and reassemble engineered devices in a process known as mechanical dissection. During this process, students examine the operating concepts and their practical implementation, as shown in Figure 1.36.

Sketching also has proven to be a valuable technique for developing visualization skills, as shown in Figure 1.37. Sketches, which can be prepared quickly, provide a simple graphical representation of an idea with a great deal of information on concepts and appearance, without the need for formal drawing tools. For this reason, even though powerful computers and software are available, sketching remains a part of engineering graphics, both as a learning tool and as a practical skill, as you will see throughout this textbook.

FIGURE 1.36. The construction and function of a device can be learned from its disassembly, examination, and reassembly in a process known as mechanical dissection.
Courtesy of D. K. Lieu

FIGURE 1.37. Sketching is not only a useful skill but also an excellent exercise for developing spatial reasoning abilities. *Courtesy of D. K. Lieu*

1.06 Chapter Summary

The history of graphical communication has shown it to be vital in nearly all aspects of engineering. The development of technology, tools, and techniques used for engineering graphics has advanced, with all of the developments supporting each other. Technological tools have made the tasks associated with classical engineering graphics much easier. The technical sophistication and simple human interface of new tools have enabled engineers to concentrate on learning and developing the techniques offered by the tools, instead of merely operating the tools. Advances in computing, modeling, and display tools have increased the speed and accuracy with which communication, visualization, and analytical problems are performed. More complex designs can be produced more quickly with better functionality and fewer errors than in the past. Engineering drawing has become quicker and simpler; making it possible for engineers to concentrate on what they do best, which is to examine the functionality of a design and to optimize it for its intended environment. Engineers have new responsibilities associated with the new tools, including following protocols for the construction of proper computer models, the electronic transmission of data, and data management.

1.07 glossary of key terms

assembly: A collection of parts that mate together to perform a specified function or functions.

CAD: Computer-aided drawing. The use of computer hardware and software for the purpose of creating, modifying, and storing engineering drawings in an electronic format.

descriptive geometry: A two-dimensional graphical construction technique used for geometric analysis of three-dimensional objects.

design (noun): An original manifestation of a device or method created for performing one or more useful functions.

design (verb): The process of creating a design (noun).

drawing: A collection of images and other detailed graphical specifications intended to represent physical objects or processes for the purpose of accurately re-creating those objects or processes.

1.07 glossary of key terms (continued)

engineer (verb): To plan and build a device that does not occur naturally within the environment.

engineer (noun): A person who engages in the art of engineering.

engineering: The profession in which knowledge of mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop and utilize economically the materials and forces of nature for the benefit of humanity.

fabricate: To make something from existing materials.

image: A collection of printed, displayed, or imagined patterns intended to represent real objects, data, or processes.

instruments: In engineering drawing, mechanical devices used to aid in creating accurate and precise images.

model: A mathematical representation of an object or a device from which information about its function, appearance, or physical properties can be extracted.

optimization: Modification of shapes, sizes, and other variables to achieve the best performance based on pre-defined criteria.

part: A single object fabricated to perform one or more functions.

project: In engineering, a collection of tasks that must be performed to create, operate, or retire a system or device.

solid modeling: Three-dimensional modeling of parts and assemblies originally developed for mechanical engineering use but presently used in all engineering disciplines.

system: A collection of parts, assemblies, structures, and processes that work together to perform one or more prescribed functions.

three-dimensional (3-D) modeling: Mathematical modeling where the appearance, volumetric, and inertial properties of parts, assemblies, or structures are created with the assistance of computers and display devices.

two-dimensional (2-D) drawing: Mathematical modeling or drawing where the appearance of parts, assemblies, or structures are represented by a collection of two-dimensional geometric shapes.

visualization: The ability to create and manipulate mental images of devices or processes.

1.08 questions for review

1. Why are most cave drawings and hieroglyphics not considered to be engineering drawings?
2. In what ways did the design of military fortifications change after the discovery of gunpowder and the invention of the cannon?
3. Why did engineering drawings need to become more precise during the industrial revolution?
4. What were the three traditional roles of engineering graphics?
5. What are some of the new roles of engineering graphics created by computer graphics?
6. What are some of the advantages and disadvantages of using mechanical drawing instruments, as opposed to mathematical tools, for problem solving?
7. What are some of the advantages and disadvantages of using mechanical drawing instruments, as opposed to computational tools, for problem solving?
8. How is solid modeling different from CAD?
9. What is visualization?
10. In what ways can visualization skills be developed?

1.09 problems

Graphical communications makes the lives of engineers easier in many ways. The following exercises are intended to give you a feeling of what communication and analysis would be like without the tools and techniques used in engineering graphics. Do not become discouraged if you find these exercises to be difficult or cumbersome or if you find that the results are not accurate, which is the point of these exercises. In the chapters that follow, you will be introduced to methods of addressing the difficulties you encounter here.

1a. Do this exercise with one of your classmates. Select one or more of the objects shown in Figure P1.1, but

1.09 problems (continued)

do not show the object(s) to your partner. Using only words, give your partner a complete description of the objects you selected. Then have your partner sketch a picture of the objects based on your verbal descriptions. Reverse roles using different objects. What errors occurred between the objects that were being described and the objects that were envisioned? What can be done to reduce these errors?

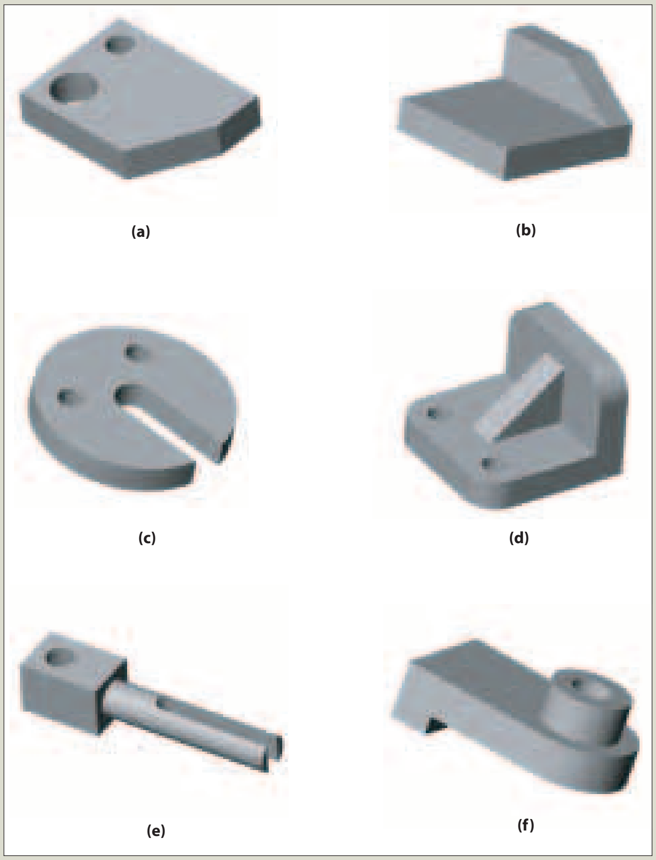


FIGURE P1.1. (a)–(f) Verbally describe these objects to your partner; then have your partner sketch a picture of the object. *Courtesy of D. K. Lieu*

1b. Give a third classmate the sketches made in Part A of this exercise. Without revealing what the original objects in the figure look like, give a complete description of the errors in the sketches and have this person make corrections to the sketches. Reverse roles using different objects. How much closer are the sketches to representing the objects shown in the figure? What additional problems occur when a third person is involved?

2. Do this exercise with a group of classmates. Select one or more of the objects shown in Figure P1.2 but do not show the figure(s) to the rest of the group. Make sketches of the object(s) you have selected, give them to the first person in the group, have that person examine them carefully, and then retrieve your sketches. Have that person use the memory of your sketches to make new sketches. Then give the new person's sketches to the second person in the group. Do not show the previous sketches to the new person. Repeat for all of the classmates in the group. When the last person is done, compare the final set of sketches to the objects selected by the first person in the original figure. What errors occurred between the final sketches and the objects that were selected? What happens to the sketches with each revision? What can be done to reduce these errors?

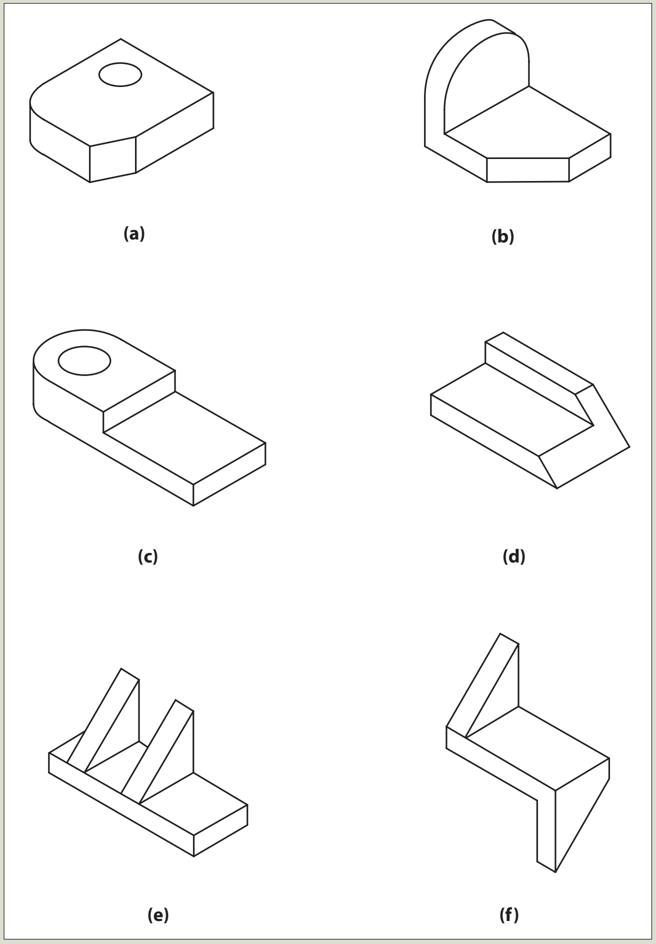
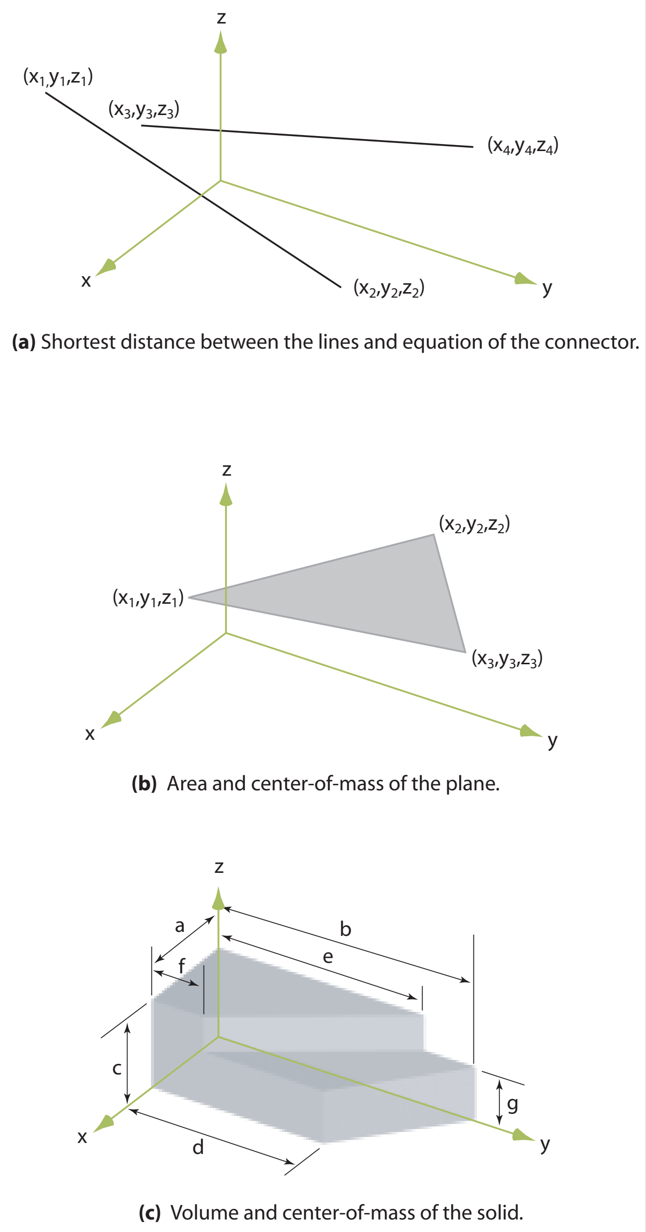


FIGURE P1.2. (a)–(f) Show one or more of these objects to your partner and have your partner sketch the object(s) from memory. Repeat the process with the newly created sketch. Compare the sketch to the original object. *Courtesy of D. K. Lieu*

1.09 problems (continued)

3. For the geometric elements shown in each of the three panels of Figure P1.3, develop formulas for finding the length, angle, area, or volume, whichever is required in each panel, using analytical methods. Generalize the solution in terms of x-, y-, and z-coordinates of the points given. What problems do you envision if the person making the calculations has no access to computers, calculators, or any other computational aids? What happens to the solution formulas as the geometries become more complicated or are rotated and translated in space?



(a) Shortest distance between the lines and equation of the connector.

(b) Area and center-of-mass of the plane.

(c) Volume and center-of-mass of the solid.

FIGURE P1.3. (a)–(c) Find the specified geometric properties of the objects.

Courtesy of D. K. Lieu