SECOND EDITION

Visualization, Modeling, and Graphics for ENGINEERING DESIGN

LIEU & SORBY

Visualization, Modeling, and Graphics for

ENGINEERING DESIGN

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Visualization, Modeling, and Graphics for ENGINEERING DESIGN

Second Edition

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SECTION **FOUR:** DRAWING ANNOTATION AND DESIGN IMPLEMENTATION

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THE FOLLOWING CHAPTERS WILL BE AVAILABLE IN OUR MINDTAP PRODUCT

Chapter 15 Working in a Team Environment

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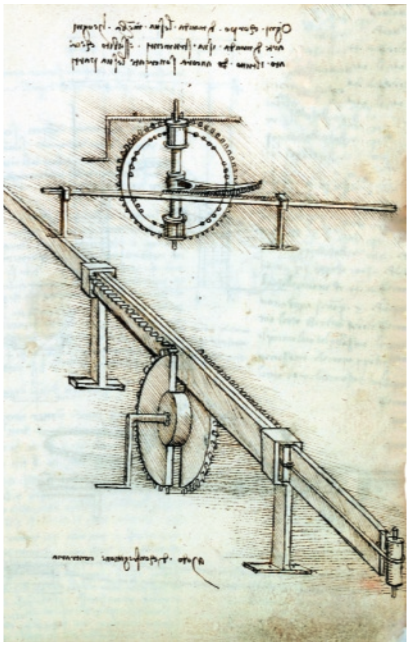
preface

Source: NASA/JPL/Cornell University

Leonardo da Vinci. You have probably learned that he was a famous Italian artist during the Renaissance. You may even subscribe to some of the conspiracy theories about him that have surfaced recently regarding secret codes and societies. What you may not know about him is that he was one of the very first engineers. (In fact, many people consider him to be *the* first engineer.) Some even say he was really an engineer who sometimes sold a painting in order to put food on the table. Artists played a prominent role at the birth of modern-day engineering, and some of the first artist-engineers included Francesco di Giorgio, Georg Agricola, and Mariano Taccola. These were the individuals who could visualize new devices that advanced the human condition. Their creativity and willingness to try seemingly "crazy" ideas propelled technology forward at a much faster pace than had occurred in the previous thousand years.



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This marriage between art and engineering has diminished somewhat since the early beginnings of the profession; however, creativity in engineering is still of paramount importance. Would the Apollo spaceship have landed on the moon without the creative thinking of hundreds of engineers who designed and tested the various systems necessary for space travel? Would we be able to instantaneously retrieve information and communicate with one another via the World Wide Web without the vision of the engineers and scientists who turned a crazy idea into reality? Would the modern-day devices that enrich and simplify our lives such as washing machines, televisions, telephones, and automobiles exist without the analytical skills of the engineers and technologists who developed and made successive improvements to these devices? The answer to all of these questions is "no." The ability to think of systems that never were and to design devices to meet the changing needs of the human population is the purview of the engineering profession.

Graphical communication has always played a central role in engineering, perhaps due to engineering's genesis within the arts or perhaps because graphical forms of communication convey design ideas more effectively than do written words. Maybe a picture really *is* worth a thousand words. As you might expect, the face of engineering graphics has evolved dramatically since the time of da Vinci. Traditional engineering graphics focused on two-dimensional graphical mathematics, drawing, and design; knowledge of graphics was considered a key skill for engineers. Early engineering programs included graphics as an integral topic of instruction, and hand-drawn engineering graphics from 50 years ago are works of art in their own right.

However, in the recent past, the ability to create a 2-D engineering drawing by hand has become de-emphasized due to improvements and advances in computer hardware and software. More recently, as computer-based tools have advanced even further, the demand for skills in 3-D geometric modeling, assembly modeling, animation, and data management has defined a new

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engineering graphics curriculum. Moreover, three-dimensional geometric models have become the foundation for advanced numerical analysis methods, including kinematic analysis, kinetic analysis, and finite element methods for stress, fluid, magnetic, and thermal systems.

The engineering graphics curriculum has also evolved over time to include a focus on developing 3-D spatial visualization ability since this particular skill has been documented as important to the success of engineers in the classroom and in the field. Spatial visualization is also strongly linked to the creative process. Would da Vinci have imagined his various flying machines without well-honed visualization skills?

We have come full circle in engineering education through the inclusion of topics such as creativity, teamwork, and design in the modern-day graphics curriculum. The strong link between creativity, design, and graphics cannot be overstated. Gone is the need for engineers and technicians who robotically reproduce drawings with little thought involved. With modern-day computational tools, we can devise creative solutions to problems without concern about whether a line should be lightly penciled in or drawn thickly and displayed prominently on the page.

It is for this new, back-to-the-future graphics curriculum that *Visualization, Modeling, and Graphics for Engineering Design, Second Edition* has been designed. This text is a mixture of traditional as well as modern-day topics, a mixture of analytical and creative thinking, a mixture of exacting drawing technique and freeform sketching. Enjoy.

Development of the Text

Many of the current graphics textbooks were written several years ago with modern-day topics such as feature-based solid modeling included as a separate add-on to the existing material. In these texts, modern-day computer-based techniques are more of an afterthought: "Oh, by the way, you can also use the computer to help you accomplish some of these common tasks." In fact, some of the more popular texts were written nearly a century ago when computer workstations and CAD software were figments of some forward-looking engineer's imagination. Texts from that era focused on drawing technique and not on graphic communication within the larger context of engineering design and creativity.

Modern engineering graphics curricula—and texts—must follow what is happening in the field. Modern product development techniques allow engineers to use computer hardware and software to examine the proper fit and function of a device. Engineers can "virtually" develop and test a device before producing an actual physical model, which greatly increases the speed and efficiency of the design process. The virtual, computer-based model then facilitates the creation of the engineering drawings used in manufacturing and production—an activity that required many hours of hand drafting just a few short decades ago.

In the real world, modern CAD practices have also allowed us more time to focus on other important aspects of the engineering design cycle, including creative thinking, product ideation, and advanced analysis techniques. Some might argue that these aspects are, in fact, the *most* important aspects of the design process. The engineering graphics curricula at many colleges and universities have evolved to reflect this shift in the design process. However, most engineering graphics textbooks have simply added CAD sections to cover the new topics. Thick textbooks have gotten even thicker. As a wise person has said, "Engineering faculty are really good at addition, but are miserable at subtraction."

When we sat down to plan this text, we wanted to produce the engineering graphics benchmark of the future—an engineering graphics approach that teaches design and design communication rather than a vocational text focused on drafting techniques and standards. We wanted to integrate modern-day design techniques throughout the text, not treat these topics as an afterthought.

A strength of this textbook is its focus not only on "what" to do, but also on "why" you do it (or do not do it) that way—concepts as well as details. This text is intended to be a learning aid as well as a reference book. Step-by-step software-specific tutorials, which are too focused on techniques, are very poor training for students who need to understand the modeling strategies rather than just which buttons to push for a particular task. In fact, we believe that mere *training* should be abandoned in favor of an *education* in the fundamentals. Students need to learn CAD strategy as well as technique. Students need to develop their creative skills and not have these skills stifled through a focus on the minutiae. In order to prepare for a lifelong career in this fast-changing technological world, students will need to understand fundamental concepts. For example, in the current methods-based approach to graphics training, students learn about geometric dimensioning and tolerancing. Many texts describe what the symbols mean, but do not explain how, why, and when they should be used. Yet, these questions of how, why, and when are the questions with which most young engineers struggle and the questions that are directly addressed in this text. They are also the *important* questions—if a student knows the answer to these questions, she or he will understand the fundamental concepts in geometric dimensioning and tolerancing. This fundamental understanding will serve

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far into the future where techniques, and possibly the symbols themselves, are likely to change.

Organization of the Text

The textbook is organized into 14 main chapters; a number of supplementary chapters are available in our MindTap product to create custom versions for specific course needs. In organizing the chapters of this text, we were careful to group topics in a way that reflects the modern engineering design process. We purposely did not mimic the decades-old graphics classical texts, which were written in an era when the design process was based on drawings and not computer models, an era when physical and not virtual models were analyzed for structural integrity. For this reason, the order of topics in this text will not match that of the traditional graphics texts where Lettering was often the first topic of instruction.

In this text, we start with foundational topics such as sketching and visualization since these are useful in the initial or "brainstorming" step in the design process and since these are fundamental topics on which many other topics hinge. Also included is a chapter on creativity and design. From there, we move to 3-D modeling because, in the real world, design typically begins with the production of a computer model. In the next stage of the modern design process, a computer model is analyzed either virtually or sometimes physically, and these topics are covered next. Once your model is complete and thoroughly analyzed, engineers move into the design documentation stage where drawings are created and annotated. The text is organized into four major sections as described subsequently. Supplemental chapters cover topics in traditional graphics instruction as well as some modern-day, "not quite ready for primetime" topics such as HTML and web utilization.

Section One—Laying the Foundation

The materials presented here focus on the needs of today's first-year engineering students who might have well-developed math and computer skills and less-developed hands-on mechanical skills. Incoming engineering students likely no longer work on their cars or bikes in the garage or may not have taken shop and drafting classes in high school. Hands-on tinkering is probably an activity of the past replaced by hands-on web page design and text messaging. (Engineering students of today in all probability have much greater dexterity in their thumbs from "texting" than do the authors of this text!) Although many engineering students enter college having spent time in a virtual computer environment, the lack of hands-on experiences that involve more than just the thumbs and that also involve real-life physical objects, often results in poorly developed three-dimensional visualization skills. In this section, these skills are explored and developed. This section also includes a project-oriented approach with inclusion of topics in design and creativity to prepare students for a lifetime of professional engineering practice.

Section Two—Modern Design Practice and Tools

The modern topics found in this section reflect the current state of design in industry. Solid modeling has revolutionized engineering graphics. The widespread availability of computers has made three-dimensional modeling the preferred tool for engineering design in nearly all disciplines. Solid modeling allows engineers to easily create mathematical models, parts, and assemblies, visualize and manipulate these models in real time, calculate physical properties, and inspect how they mate with other parts. The modern-day design process is characterized by computer methods that take advantage of the efficiency and advantages offered by workstations and feature-based modeling software. These new technologies have revolutionized the design process and have enabled around-the-clock engineering. By this model, engineers in Europe hand off (via the Internet) a design project when they leave work to American engineers. The Americans, in turn, hand off the design as they leave the office at the end of the day to Asian engineers. The Asian engineers complete the cycle by passing the design back to the Europeans at the end of their day. The sun never sets on an engineering design. Over your lifelong engineering career, the details of the design process may change again in ways that are unimagined today, but the fundamentals, as described in this section, will migrate from system to system with each advance in technology.

Section Three—Setting Up an Engineering Drawing

This section contains material found in most conventional textbooks on engineering graphics; however, the content is presented in novel ways and with a fresh approach to problem solving. The topics and techniques in this section are in wide use in engineering graphics classrooms today and are likely to continue to be invaluable into the foreseeable future. These traditional graphics topics continue to be important for several reasons. First, many legacy designs out there were produced prior to the feature-based solid modeling revolution. You may be asked to examine these designs, so it is important that you thoroughly understand drawings. Second, not every company has the capability to go directly from a computer model to a manufactured part, and drawings are still important in these environments. Finally, while the computer can usually automatically generate a drawing for you, certain conventions and dimensioning practices do not translate well. You will need to be

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able to verify the integrity of drawings that the computer generates for you and make changes where needed. For all of these reasons, no matter how sophisticated the computer design, hardware and software, or the manufacturing system, engineers must still be able to visualize a three-dimensional object from a set of two-dimensional drawings and vice versa.

Section Four—Drawing Annotation and Design Implementation

The ultimate goal of the engineering design process is to develop devices where everything fits together and functions properly. The sizes of the features that define an object are crucial to the overall functionality of the system. The chapters in this section describe how sizes and geometries of entities are specified. Since no part can be made to an "exact" size even with the best in computer technologies, the allowable errors for part sizes are also described in this section. The final drawings produced in preparation for fabrication must meet exacting criteria to ensure that they are properly cataloged and interpreted for clear communication among all parties. If your drawing includes nonstandard annotations, the machinist or contractor who uses those drawings to produce an engineered system may unknowingly misinterpret the drawing, resulting in higher project costs or even failure. The chapters in this section detail standard practice in drawing annotation to help you avoid making blunders. The ability to make proper, 100 percent correct drawing annotations will likely take you several years to develop. Be patient and keep learning.

Advanced Topics in Engineering Graphics

Additional chapters on topics in graphic communication are available in our MindTap product. A chapter is included to assist you with communicating your thoughts, ideas, analyses, and conclusions through animation, graphs, and charts. You may think that this type of communication is a "no brainer" with modern tools such as a spreadsheet. However, many times the automatically generated graph from a spreadsheet does not follow standard engineering practice for graphic communication and must be edited in order to meet these standards. For example, spreadsheets typically leave axis labels and titles off a graph resulting in a pretty, but meaningless, picture. A picture may be worth a thousand words, but sometimes it takes a few words to describe what a picture is illustrating. For communication with nontechnical (or sometimes even technical) audiences, tremendous amounts of information can be conveyed through the use of animation. If a picture is worth a thousand words, then an animation is surely worth a million.

Chapter Structure

With a few exceptions, each chapter is organized along similar lines. The material is presented with the following outline:

1. Objectives
   Chapter-opening objectives alert students to the chapter's fundamental concepts.

2. Introduction
   This section provides an overview of the material that will be presented in the chapter, and discusses why it is important.

3. The Problem
   Each chapter directly addresses a certain need or problem in graphical communication. That problem is presented here as if the student had to face such a problem in the field. The presence of a real problem that needs to be solved gives a student added incentive to learn the material in the chapter to solve that problem.

4. Explanation and Justification of Methods
   Engineering graphics has evolved and continues to evolve at an increasingly fast pace due to advances in computer hardware and software. Although new methods associated with new technologies exist, these modern methods must remain compatible with conventional graphics practices. This consistency is required to eliminate possible confusion in the interpretation of drawings, maintain sufficient flexibility to create designs unencumbered by the tools available to document them, and reduce the time and effort required to create the drawings.

5. Summary
   This section distills the most important information contained in the chapter.

6. Glossary of Key Terms
   Formal definitions of the most important terms or phrases for the chapter are provided. Each term or phrase is highlighted the first time it is used in the chapter.

7. Questions for Review
   These questions test the student's understanding of the chapter's main concepts.

8. Problems
   A variety of problems and exercises help to develop skill and proficiency of the material covered in the chapter.

Key Features of the Presentation

We believe that this text will have a broad appeal to engineering graphics students across a wide spectrum of institutions. The following are key features of the text:

- *A focus on learning and fundamental skill development, not only on definitions, tools, and techniques.* This approach prepares students to apply the material to unfamiliar

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problems and situations rather than simply to regurgitate previously memorized material. In the fast-changing world we live in, an understanding of the fundamentals is a key to further learning and the ability to keep pace with new technologies.

- *Formal development of visualization skills as a key element at an early stage of the curriculum.* Development of these skills is important for students who have not had the opportunity to be exposed to a large number of engineering models and physical devices. Further, the link between visualization and creativity is strong—tools for success over a lifelong career.
- *Use of a problem-based approach.* This approach presents the student with real problems at the beginning of each chapter, shows the graphics solutions, and then generalizes the solutions.
- *A casual tone and student-friendly approach.* It is a proven fact that students learn the material better if they are not fast asleep!
- *Several common example threads and a common project that are presented in most chapters.* The text shows how the material contained in each chapter was actually applied in the context of product development.

One of the case studies to be presented, for example, is the Hoyt Aerotec^{TM} Olympic style recurve target bow. The unique geometry of this bow was brought to prominence after it was part of the equipment package used to win the Gold Medal in target archery at the summer Olympic Games in Sydney, Australia. The design history of the development of this product is traced starting from its ideation as an improvement to all other target bows on the market at that time. As a student moves through the chapters of this book, the progress of the development of this product will be documented. This product was selected as an example for these reasons:

1. It was a very successful design that accomplished all of the goals set forth by its engineers.
2. It was also a product that is relatively unencumbered by the complexity of mechanisms or electronics, which are not the focus of this book.
3. The design is mature, having made it to the consumer market; this means it offers an opportunity to study some of the nontechnical issues that play an important role in engineering design.

Final Remarks

This textbook contains a "core" of material covered in a traditional engineering graphics course and also a number of other chapters on modern graphics techniques. The collected material represents over 50 combined years of personal experience in the learning, application, and teaching of engineering graphics. The result is a text that should appeal to both traditional and contemporary graphics curricula. We, the authors, would like to thank you for considering this text.

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New to This Edition

Chapter 1
- The People and Their Skills (Section 1.03) has been removed from the print edition. It can be found in the MindTap course.

Chapter 2
- Strategies for Simple Pictorial Sketches (Section 2.11) has been removed from the print edition. It can be found in the MindTap course. Caution (pp. 2-27 through 2-29) has been removed from the print edition. It can be found in the MindTap course.

Chapter 3
- New section added discussing the importance of spatial skills.
- Strategies for Developing 3-D Visualization Skills (Section 3.12) has been removed from the print edition. It can be found in the MindTap course.
- Caution (pp. 3-48 through 3-50) has been removed from the print edition. It can be found in the MindTap course.

Chapter 4
- Formerly Chapter 5.
- Patents (Section 5.06) has been removed from the print edition. It can be found in the MindTap course.

Chapter 5
- Formerly Chapter 6.
- Strategies for Making a Model (Section 6.11) has been removed from the print edition. It can be found in the MindTap course.
- Caution (pp. 6-71 through 6-78) has been removed from the print edition. It can be found in the MindTap course.
- Problems 5.1 and 5.4 are new.

Chapter 6
- Formerly Chapter 7.
- The vise assembly example has been removed from the book and is located in the MindTap course.
- Caution (pp. 7-30 through 7-31) has been removed from the print edition. It can be found in the MindTap course.
- Problems 6.2 and 6.5 thru 6.14 are new.

Chapter 7
- Formerly Chapter 8.
- The Finite Element Analysis

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Process (Section 8.07) has been removed from the print edition. It can be found in the MindTap course.
- All problems are new.

Chapter 8
- Formerly Chapter 10.
- Strategies for Creating Multiviews from Pictorials (Section 10.06) has been removed from the print edition. It can be found in the MindTap course.
- Caution (pp. 10-51 through 10-62) has been removed from the print edition. It can be found in the MindTap course.
- Problems 8.3 and 8.5 through 8.7 are new.

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- Problems 10.5 through 10.9 are new.

Chapter 11
- Formerly Chapter 14.
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- Problems 12.2 and 12.3 are new.

Chapter 13
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- Caution (pp. 16-44 through 16-48) has been removed from the print edition. It can be found in the MindTap course.
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Chapter 14
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- Caution (pp. 18-57 through 18-70) has been removed from the print edition. It can be found in the MindTap course.
- All new problems.

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- Former Chapter 4: Working in a Team Environment has been removed from the print edition. It can be found in the MindTap course.
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SECTION ONE

LAYING THE FOUNDATION

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.

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CHAPTER 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

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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 in making 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.

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FIGURE 1.01. Undated cave painting showing hunting and the use of tools.

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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 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 using 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

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FIGURE 1.02. Mayan pyramid, Yucatan, Mexico (left), and Pharaoh Knufu and Pharaoh Khafre Pyramids, Giza, Egypt (right).

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FIGURE 1.03. Ancient Egyptian hieroglyphics describing a life story.

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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.

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 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.

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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.

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.

FIGURE 1.05. An engraving showing the operation of an Archimedes screw to lift water.

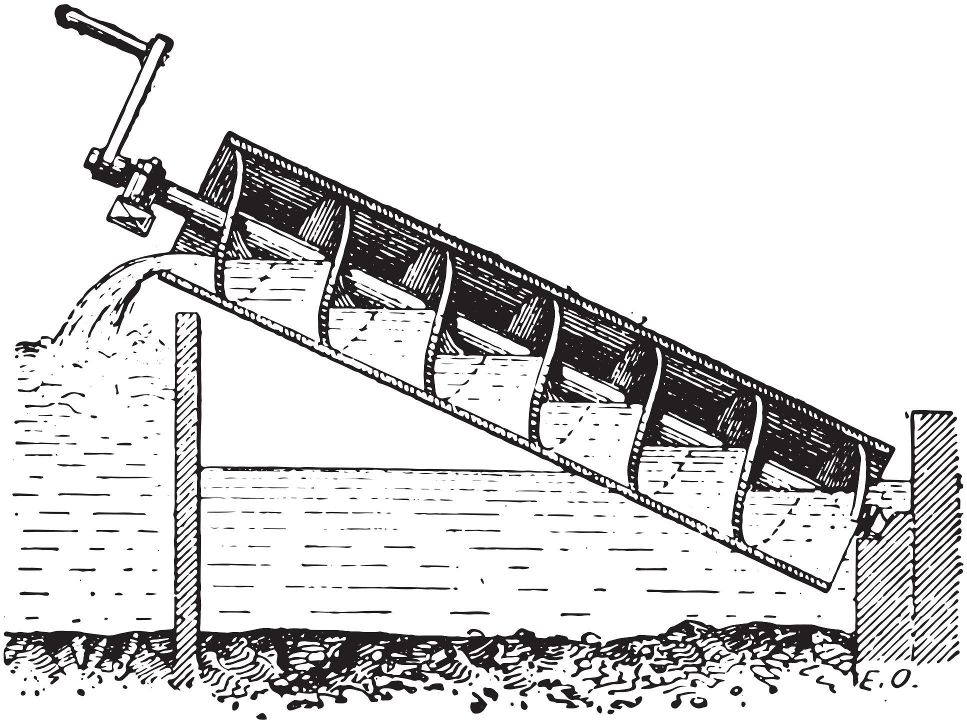

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FIGURE 1.06. Flying buttress construction used to support the exterior walls of Notre Dame Cathedral in Paris.

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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 1.07. Warwick Castle, England, circa 1350, is an example of a medieval style fortification.

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FIGURE 1.08. The Great Wall of China, built during the medieval period, used simple engineering principles despite the large scale of the project.

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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 of 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 engineering, they could conceive things that theoretically should have worked without having been previously built. When inventors did not understand the science

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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.

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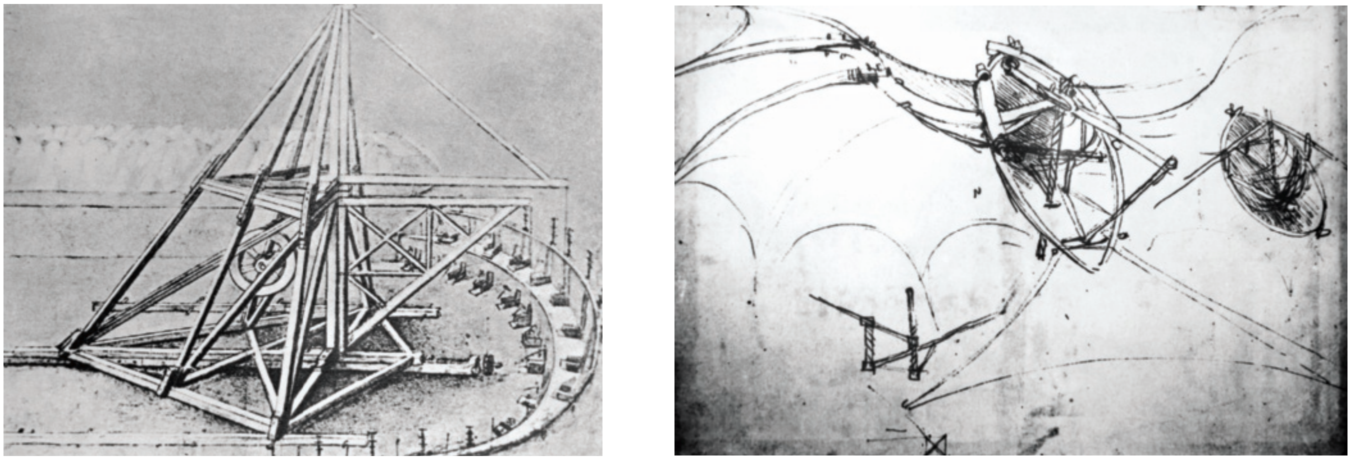

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FIGURE 1.10. Images of original da Vinci drawings: a machine used for canal excavation (left) and a flying ship (right). Codex Atlanticus, folio 860; drawing from Il Codice Atlantico di Leonardo da Vinci nella biblioteca Ambrosiana di Milano, Editore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

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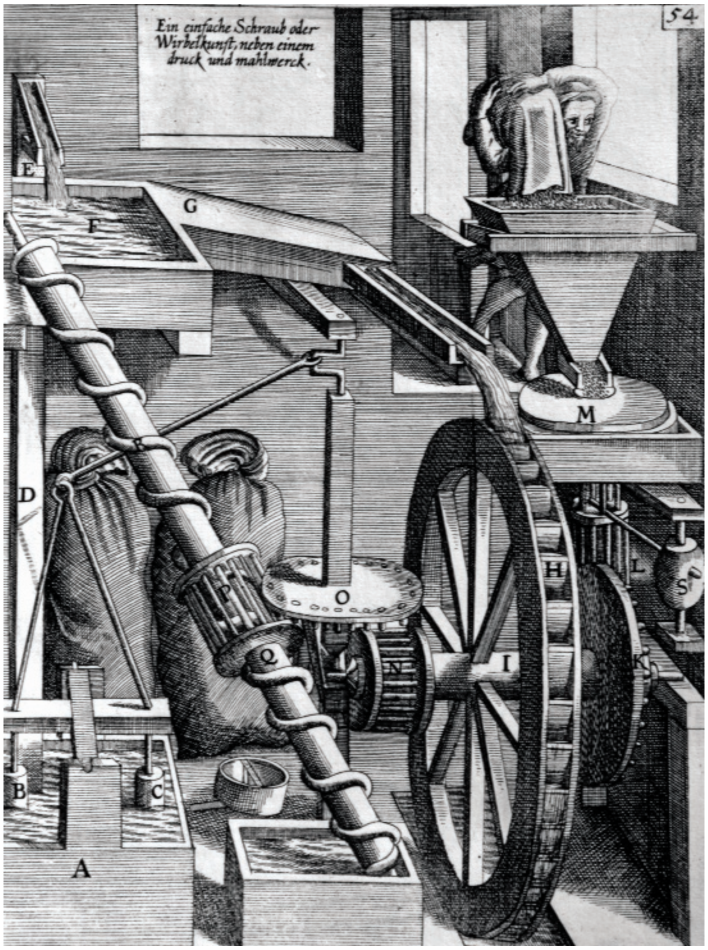

FIGURE 1.11. A perpetual motion machine by medieval inventors: an Archimedes screw driven by a waterwheel is used to mill grain.

Timewatch Images/Alamy

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 both 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 the 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?

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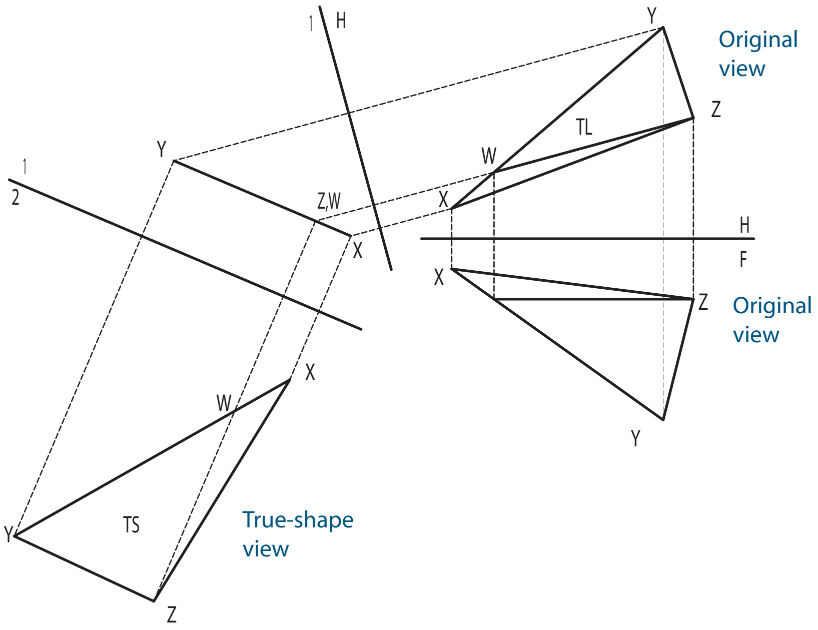
- What are the specific lengths of timbers and beams needed to construct and brace the walls?
- What are the true angles of intersection between certain surfaces?
- What are the distances between lines and other lines, between points and lines, and between points and surfaces?

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

FIGURE 1.12. Using descriptive geometry to find the area of a plane.



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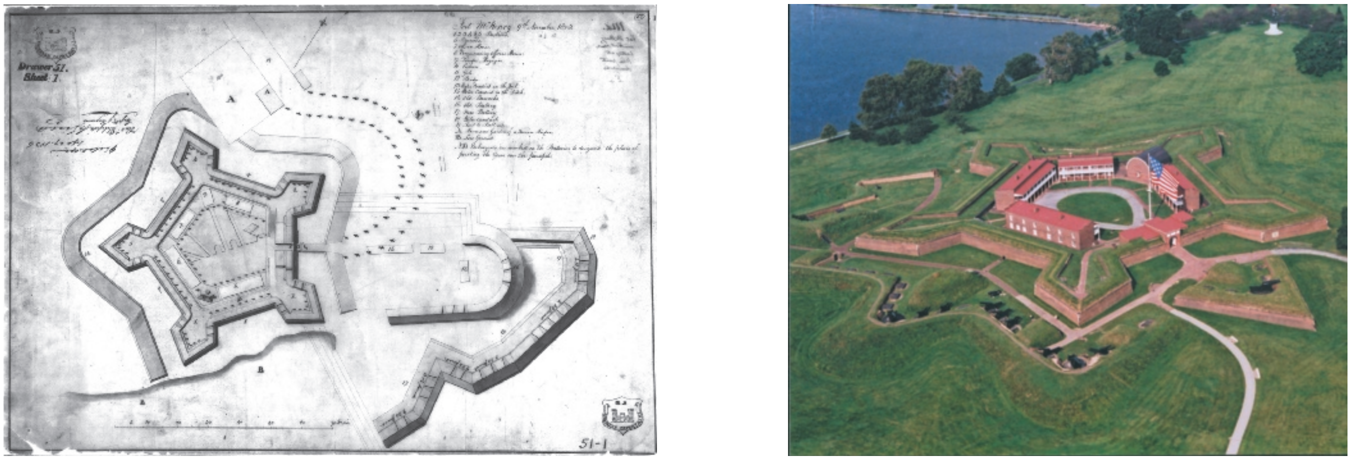

Courtesy of The National Archives, College Park, Maryland

Courtesy of The National Park Service, Fort McHenry NMHS

FIGURE 1.13. French fortification design principles (left) and Fort McHenry (right) in Baltimore, Maryland, whose design was based on those principles.

complicated, more people skilled in various subspecialties were needed. Clear, simple, 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 Figures 1-14 and 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.

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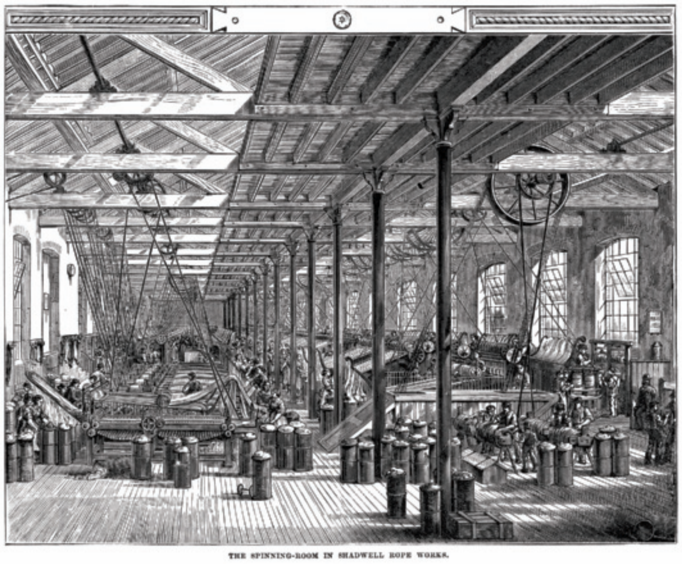

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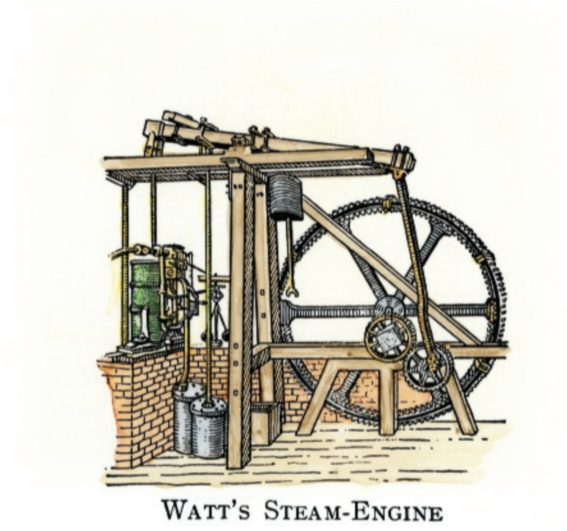
FIGURE 1.14. A photo showing early factory conditions during the industrial revolution.



North Wind Picture Archives/Alamy

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.

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 electric motors, generators (shown in Figure 1.17), power conversion,

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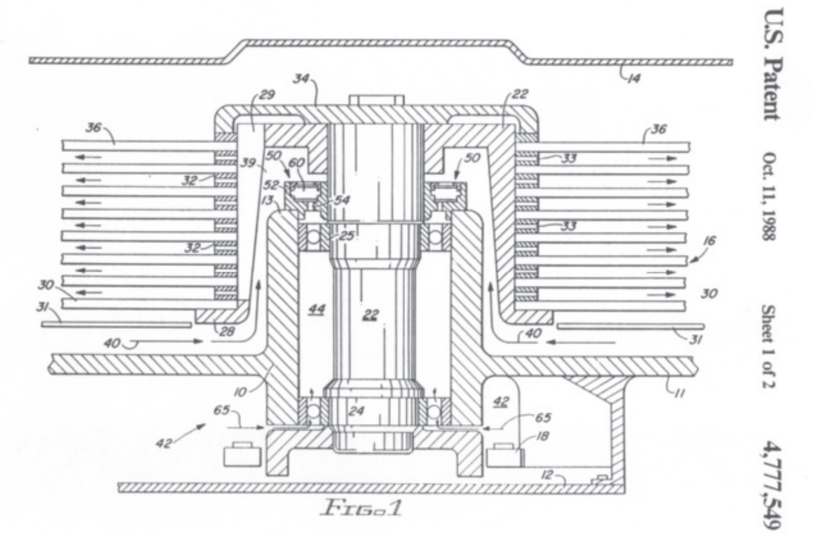
FIGURE 1.16. A U.S. patent drawing showing function but not necessarily the true sizes of the parts.



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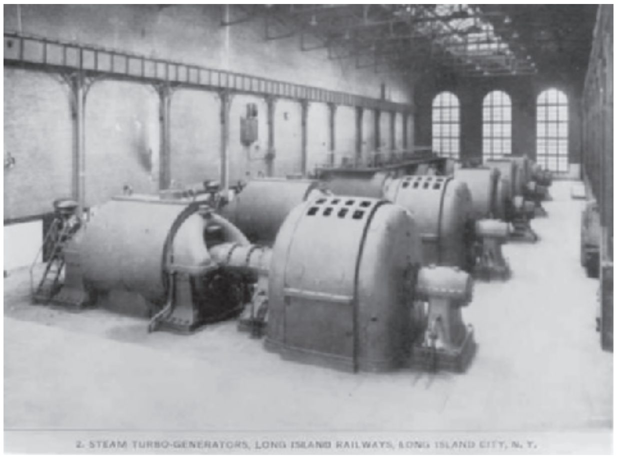
and transmission lines needed for their design was more than other engineers—not specifically electrical engineers—could be expected to know and use. Chemical engineering, as a special engineering discipline, emerged at the beginning of the twentieth century with the need for large-scale production of 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 1.19) 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.



Courtesy of SMITHSONIAN INSTITUTION Neg. #44191D

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 (circa 1907). Electrical engineering was born.

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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.

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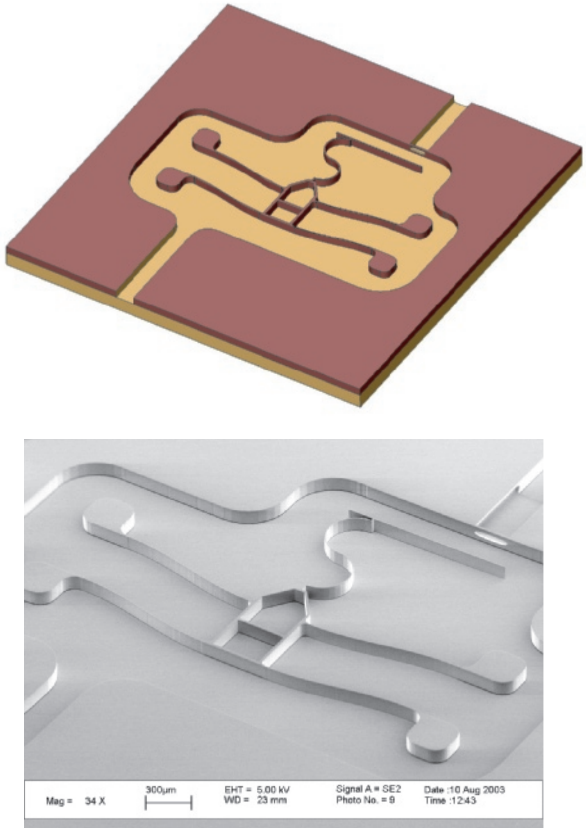
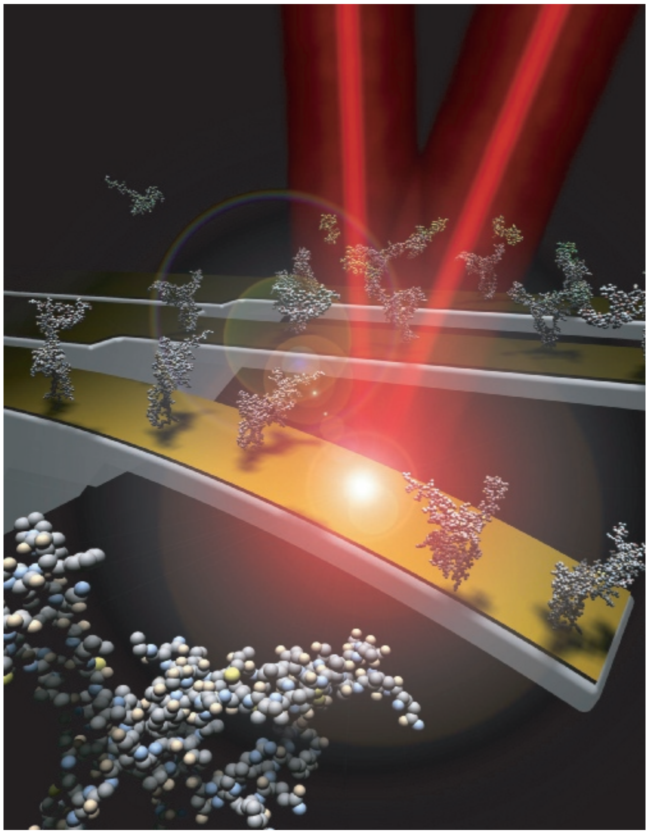


Courtesy of the Berkeley Sensor and Actuator Center, University of California

FIGURE 1.19. This MEMS valve was designed with a solid modeler and was fabricated using semiconductor processing techniques.

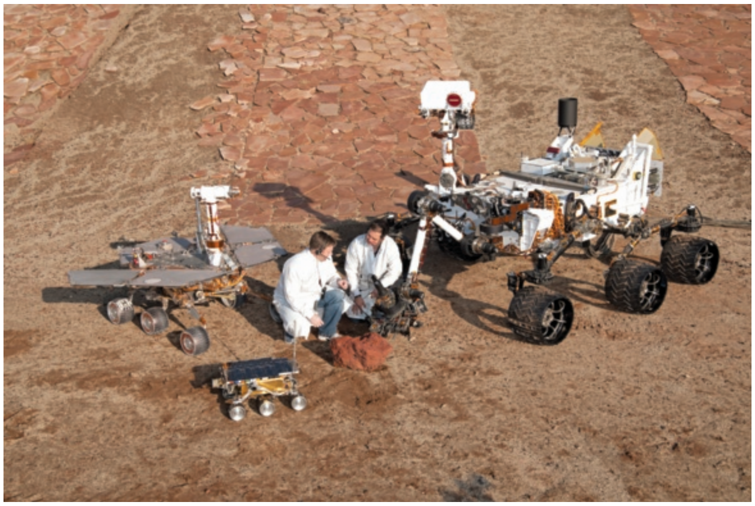


Courtesy of Kenneth Hsu

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

With the emergence of a new discipline comes formal intensive training, particularly 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/Caltech

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1.03 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.

1.03.01 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.

1.03.02 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 in Figure 1.22, 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

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FIGURE 1.22. Tools for instrument drawing (left) and a drafting machine (right).

- 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.

1.03.03 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.

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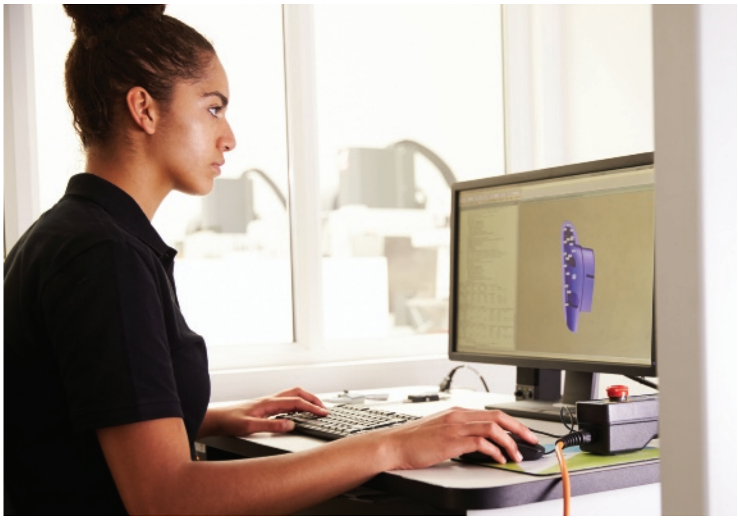
FIGURE 1.23. Computer graphics stations have replaced mechanical drawing instruments in most applications. A CAD drawing can be created by itself or extracted from a solid model.



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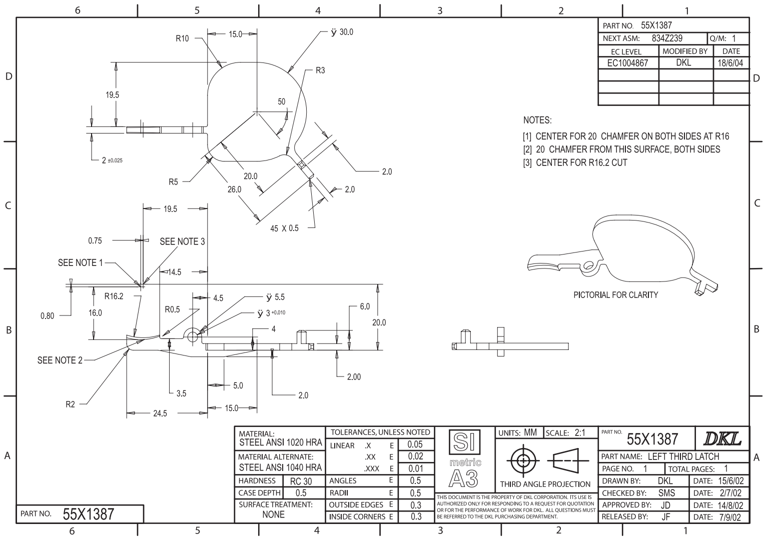

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One company that became a leader in this application was Autodesk, with its AutoCAD software. Companies that formerly supplied mainframe computer-based or turnkey CAD systems either quickly adapted their products for PC use or went out of business. 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 1.23.

1.03.04 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.

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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 operations 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 1.24. An assembly model is shown in Figure 1.25.

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 1.26, 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.

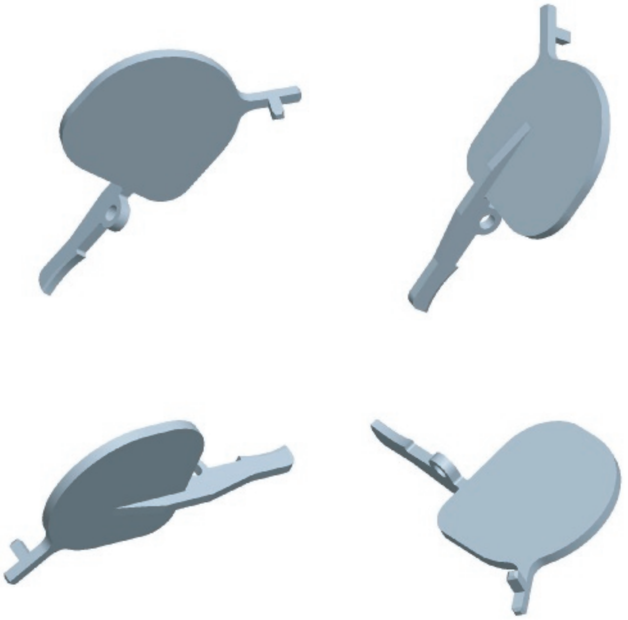

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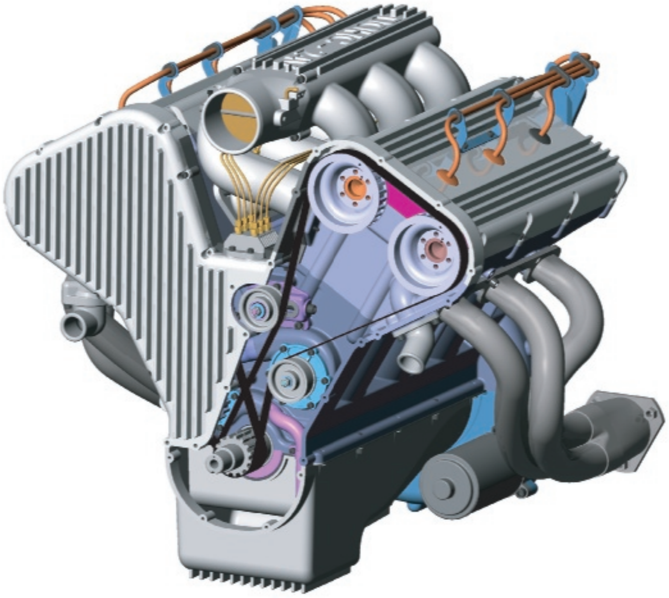
FIGURE 1.24. Solid modeling allows a proposed part to be easily visualized in a variety of orientations.



Courtesy of SolidWorks Corporation

FIGURE 1.25. An assembly model of an Omnica 3.2-liter V-6 engine made from a collection of solid model parts.

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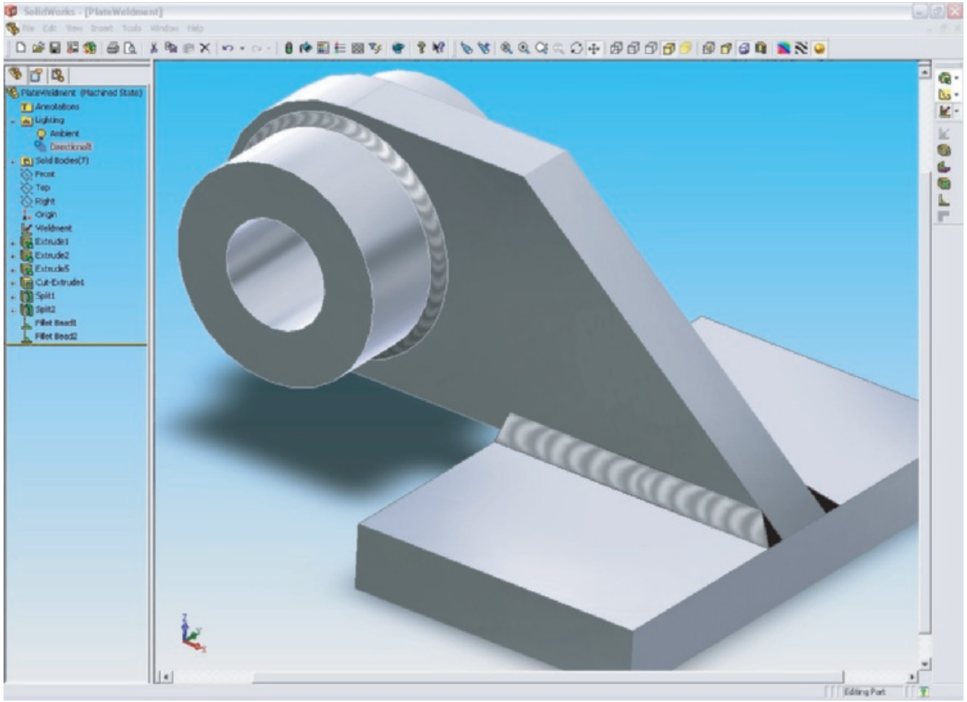

FIGURE 1.26. The graphical user interface of a solid modeling software program.

Courtesy of SolidWorks Corporation

1.03.05 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 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 1.27, 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. A two-dimensional topographic map, such as the one shown in Figure 1.28, 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.

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