CHAPTER 1

ENGINEERING DESIGN

What does it mean to design something? How does engineering design differ from other kinds of design?

PEOPLE HAVE been designing things for as long as we can "remember" or archaeologically uncover. Our earliest ancestors designed flint knives and other basic tools to help meet their most basic needs. Their wall paintings were designed to tell stories and to make their primitive caves visually more attractive. Given the long history of people designing things, it is useful to wonder what an engineer who designs a building's structure does differently than a decorator who designs the building's interior decor. We will use this chapter to set some contexts for engineering design and to start developing both a vocabulary and a shared understanding of what we mean by engineering design.

1.1 WHERE AND WHEN DO ENGINEERS DESIGN?

There are a lot of questions we could ask about engineers doing design, and there are probably more answers than there are questions: What does it mean for an *engineer* to design something? When do engineers design things? Where? Why? For whom?

An engineer might work for a large company that processes and distributes various food products, where she could be asked to design a new container for a new juice product. He could work for a design-and-construction company, for which he is designing part of a highway bridge embedded in a larger transportation project. An engineer might work for an automobile company that wants to develop a new concept for the instrumentation cluster in its cars, perhaps to enable drivers to check various parameters without taking their eyes off the road. Or an engineer could work for a school system that wants to design specialized facilities to better serve students with orthopedic disabilities.

Clearly, this list could easily be lengthened, so it is worth asking: Are there common elements in the engineers' situations, or in the ways that they do their designs? In fact, there are common features both in their situations and their design work, and these commonalities make it possible to describe a design process and the context in which it occurs.

We can start by identifying three "roles" being played as the design of a product unfolds. Obviously there is the *designer*. Then there will be a *client*, the person or group or company that wants a design conceived, and there is the *user*, the person (or the set of people) who will actually use whatever is being designed. For the working engineer, the client could be internal (e.g., the person who decides the food company should start selling a new juice product) or external (e.g., the government agency that contracts for the new highway system). And while the designer may relate differently to internal and external clients, in either case it is the client who presents a *problem* or *project statement* from which all else flows. Design project statements may be oral, and often they are quite short. These two qualities suggest that the designer's first task is to clarify what the client really wants and translate it into a form that is useful to her as an engineering designer. We'll say more about this in Chapter 3 and beyond, but we want to emphasize that *a design is motivated by a client* who wants some sort of device, system, or process.

Design is motivated by a client.

The user is the third player or stakeholder in the design effort. In the contexts mentioned above, the users are, respectively, consumers who buy the new juice drink, drivers on the interstate highway system, drivers of the new line of autos, and students with orthopedic disabilities (and their teachers). The users hold a stake in the design process because a product won't sell if its design doesn't meet their needs. Thus, the designer, the client, and the user form a triangle, as shown in Figure 1.1. The designer has to understand what the client wants, but the client also has to understand what his users need or what the markets want and communicate that to the designer. In Chapter 2 we will describe design processes that model how the designer can interact and communicate with both the client and potential users to help inform her own design thinking, and we will identify some tools (discussed in detail in Chapters 3–5) that she can use to organize and refine her thinking.

In addition, there is a stakeholder we've not yet named, that is, the *public*. That's in part because the public is implicitly embodied in the notion of the user. Including the notion of a public that is affected by a design as much as (or more than) the users we've already identified is interesting because it suggests that we may well confront ethical issues in such design projects. We will explore this further in Chapter 12. It's also worth noting that often the client speaks on behalf of the intended users, although anyone who has sat in cramped coach seating on a commercial flight would have to ask both airlines and airplane manufacturers who their customers really are!

The designer and the client have to understand what the users want in a design.

As described above, engineering designers work in many different kinds of environments, including: small and large companies, start-up ventures, government, not-for-profit organizations, and engineering services firms (one breed of which is the industrial design consultancy). Apart from the salaries and perks of working in these various places to do design, designers will most likely see differences in the size of a project, the number of colleagues on

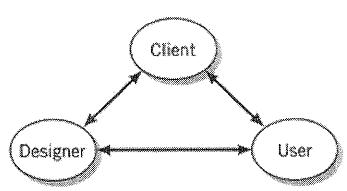

FIGURE 1.1 The designer–client–user triangle. There are three parties involved in a design effort: the client, who has objectives that the designer must clarify; the user of the designed device, who has his own requirements; and the designer, who must develop specifications such that something can be built to satisfy everybody!

the design team, and their access to relevant information about what users want. On large projects, many of the designers will be working on pieces of a project that are so detailed and so confined that much of what we describe in this book may not seem immediately useful. Thus, the designers of a bridge abutment, an airplane's fuel tank, or components on a computer motherboard are not likely to be as concerned with the larger picture of what clients and users want because the system-level design context has already been established when this level of design is reached. Indeed, as we will explain in Chapter 2, these kinds of design problems are the part of the process called *detailed design*, in which the choices and procedures are well understood because more general design issues have already been resolved. However, even for such large projects, the response to a client's project statement is initiated with *conceptual design*. Some thinking about the size and mission of the airplane will have been done to identify constraints surrounding fuel tank design, while the performance parameters that the computer motherboard must display will be determined by some assessment of the market for and the price of the computer in question.

Large, complex projects often lead to very different interpretations of client project statements and of user needs. One has only to look at the many different kinds of skyscrapers that decorate our major cities to see how architects and structural engineers envisage different ways of housing people in offices and apartments. Visible differences also emerge in airplane design (Figure 1.2) and wheelchair design (Figure 1.3). Each of these sets of devices could result from a simple, common design statement: The airplanes

FIGURE 1.2 A few "devices that safely transport people and goods through the air," i.e., airplanes. No surprises here, right? We've all seen a lot of airplanes (or, at least, in pictures or movies). But even these planes, albeit of different eras and origins, show that they clearly were designed to achieve very different missions.

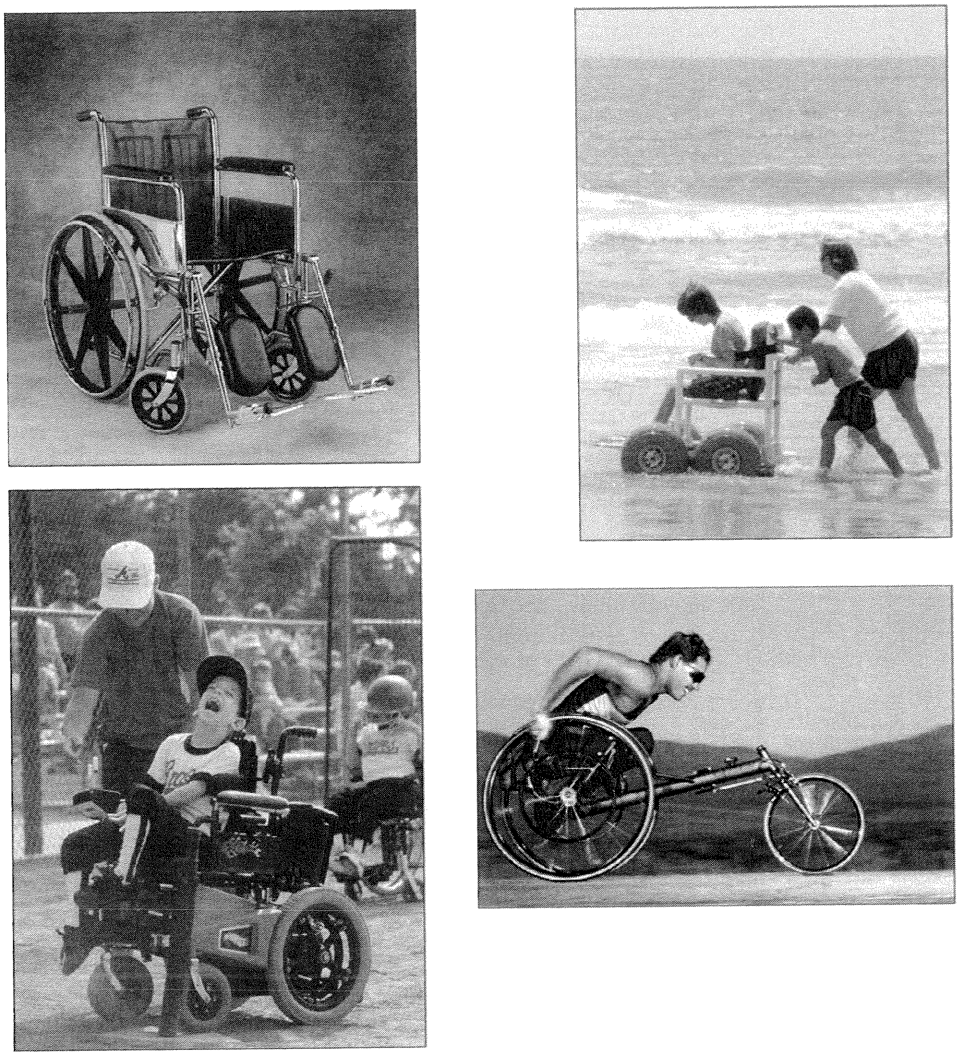

FIGURE 1.3 A collection of "personal mobile devices that transport people who are unable to use their legs," i.e., wheelchairs. Here too, as with the airplane, we see some sharp differences in the configurations and components of these wheelchairs. Why are the wheels so different? Why are the wheelchairs so different?

are "devices to transport people and goods through the air," and the wheelchairs are "personal mobile devices to transport people who are unable to use their legs." However, the different products that have emerged represent different concepts of what clients and users wanted (and what designers perceived they wanted!) from these devices. Designers have to clarify what a client wants and translate those wants into an engineered product.

The designer-client-user triangle also prompts us to (a) recognize that the interests of the three players might diverge, and (b) consider that the consequences of such divergence could mean more than financial problems resulting from a failure to meet users' needs. This is because the interaction of multiple interests creates an interaction of multiple obligations, and these obligations may well conflict. For example, the designer of a juice container might consider metal cans, but easily "squashed" cans are a hazard if sharp edges emerge during the squashing. There could be tradeoffs among design variables, including the material of which a container is to be made and the container's thickness. The choices made in the final design could easily reflect different assessments of the possible safety hazards, which in turn could lay a foundation for potential ethics problems. Ethics problems, which we discuss in Chapter 12, occur because designers have obligations not only to clients and users, but also to their profession and, as detailed in the codes of ethics of engineering societies, to the public at large. Thus, ethics issues are always part of the design process.

Designers have obligations to the profession and to the public.

Another aspect of engineering design practice that is increasingly common in projects and firms of all sizes is the use of *teams* to do design. Many engineering problems are inherently multidisciplinary (e.g., the design of medical instrumentation), so there is a need to understand the requirements of clients, users, and technologies in very different environments. This, in turn, requires that teams be assembled to address such different sets of environmental needs. The widespread use of teams clearly affects how design projects are managed, another recurring theme of this book.

Engineering design is a multifaceted subject, and in no way do we think that the reader will truly understand this wonderfully complex activity by reading this one short book (or by doing a single design project). However, we do think that we can provide some frameworks within which the reader can think productively about some of the conceptual issues and the resulting choices that are made very early in the design of many different kinds of engineered products.

1.2 A VOCABULARY PRIMER FOR ENGINEERING DESIGN

It is already clear that the word *design* is used both as a noun (*n*) and a verb (*vb*). *Webster's New Collegiate Dictionary* defines the two usages as:

- **design** *n*: a mental project or scheme in which means to an end are laid down; the arrangement of elements that go into human productions (as of art or machinery).
- **design** *vb*: to conceive and plan out in the mind; to devise for a specific function or end.

The points behind these two definitions are clear: Designing is about people planning and creating ways to produce things that achieve some known goals.

There are many, many definitions of *engineering design* in the literature, and there is a fair bit of variation in the ways in which design actions and attributes are described by engineers. So we will now define what we mean by engineering design and then will go on to define some of the related terms that are commonly used by engineers and designers.

1.2.1 Our definition of engineering design

Engineering design is a thoughtful process for generating designs for devices, systems, or processes that attain given objectives while adhering to specified constraints.

The following formal definition of engineering design is the most useful one for our purposes:

- **Engineering design** is a systematic, intelligent process in which designers generate, evaluate and specify designs for devices, systems or processes whose form(s) and function(s) achieve clients' objectives and users' needs while satisfying a specified set of constraints.

It is important to recognize that when we are designing devices, systems and processes we are designing artifacts: artificial, human-made objects, the "things" or devices that are being designed. They are most often physical objects like airplanes, wheelchairs, ladders, cell phones and carburetors. But "paper" products such as drawings, plans, computer software, articles, and books are also artifacts in this sense, as are the "soft" electronic files that become "real" when displayed on a computer screen. In this text we will use device or system rather interchangeably as the objects of our design.

With further recourse to our dictionary, we note (and then comment on) the following definitions:

- **form** *n*: the shape and structure of something as distinguished from its material

  So what we mean by *form* is pretty straightforward, and its meaning in the engineering context is consistent with its more common use.

- **function** *n*: the action for which a person or thing is specially fitted or used or for which a thing exists; one of a group of related actions contributing to a larger action

  Simply put, *functions* are those things the designed device or system is supposed to do. As we describe in Sections 2.3 and 4.1, *engineering functions* involve the transfer or flow of energy, information and materials. Note, too, that we view energy transfer quite broadly: It includes supporting and transmitting forces, the flow of current, the flow of charge, and so on.

- **means** *n*: an agency, instrument, or method used to attain an end

  Although not explicitly recognized in our definition of engineering design, *means* is nonetheless important as in this context it refers to a way of making a function happen.

- **objective** *n*: something toward which effort is directed; an aim or end of action

  An *objective* in our context is consistent with its common usage.

- **constraint** *n*: the state of being checked, restricted, or compelled to avoid or perform some action

  This definition, too, is what we would expect from standard use. It is worth stressing that *constraints* are extremely important in engineering design because they impose absolute limits which, if violated, mean that a proposed design is simply not acceptable.

Anticipating another point we will stress again (in Chapter 3), note that objectives for a design are entirely separate from the constraints placed on a design. Objectives may be completely achieved, may be achieved in some measure, or may not be achieved at all. Constraints, on the other hand, are binary: They are satisfied or they are not satisfied; they are black or white, and there are no intermediate states. Thus, if we were designing a corn

Desi thou proc be u

Form dedu funct

degrainer for Nicaraguan farmers to be cheaply built of indigenous (local) materials, an objective might be that it should be as cheap as possible, while a constraint might be that it could not cost more than $20.00 (US). Making the degrainer of indigenous materials could either be an objective, if it is a *desired* feature, or a constraint, if it's absolutely required.

Our definition of engineering design states that designs emerge from a *systematic, intelligent process*. This is not to deny that design is a creative process. However, at the same time, there are techniques and tools we can use to support our creativity, to help us think more clearly, and to make better decisions along the way. These tools and techniques, which form much of the subject of this book, are not formulas or algorithms. Rather, they are ways of asking questions, and presenting and reviewing the answers to those questions as the design process unfolds. We will also present some tools and techniques for managing a design project. Thus, while demonstrating ways of thinking about a design as it unfolds in our heads, we will also talk about ways to deploy the resources needed to complete a design project on time and within budget.

1.2.2 The assumptions behind our definition of engineering design

Design is a thoughtful process that can be understood.

There are some implicit assumptions behind our definition of engineering design and the terms in which it is expressed. It is useful to make them explicit.

First, design is a *thoughtful* process that can be *understood*. Without meaning to spoil the magic of creativity or the importance of innovation in design, people do *think* while designing. So it is important to have tools to support that thinking, to support design decision making and design project management. (One piece of supporting evidence for this obvious hypothesis is that computer programs have been written to emulate design processes. We couldn't write such programs if we couldn't articulate and describe what goes on in our heads when we design things.)

The idea that there are *formal methods* to use when generating design alternatives is strongly related to our inclination to think about design. This might seem pretty obvious because there's not much point in considering new ways of looking at design problems or talking about them — unless we can exploit them to do design more effectively.

Form cannot be deduced from function.

Form and *function* are two related yet independent entities. This is important. We often think of the design process as beginning when we sit down to draw or sketch something, which suggests that form is a typical starting point. However, we should keep in mind that function is an altogether different aspect of a design that may not have an obvious relationship to shape or form. In particular, while we can often infer the purpose of an object or device from its form or structure, we can't do the reverse, that is, we cannot automatically deduce what form a device must have *from the function alone*. For example, we can look at a pair of connected boards and deduce that the devices that connect them (e.g., nails, nuts and bolts, rivets, screws, etc.) are fastening devices whose function is to attach the individual members of each pair. However, if we were to start with a statement of purpose that we wish to attach one board to another, there is no obvious link or inference that we can use to create a form or shape for a fastening device. That is, knowing that we want to achieve the *function* of attaching two boards does not lead us to (or even suggest) any of the *forms* of welds, screws, rivets, or glues.

The relationship of form and function is important in understanding the creative aspects of design. If we can systematically articulate all of the functions that a device is expected to perform, then we can be creative in developing forms within which these functions can be realized. In this sense, the use of organized, thoughtful processes *adds* to the creative side of design.

There are benchmarks available to assess how we expect a design to perform and to implicitly measure the progress made toward a successful design. These benchmarks derive from a questioning process (see Chapter 2) that begins with the designer:

- translating the client's desires into *objectives* for the device or system being designed;
- establishing a set of *metrics* that can be used to ascertain or measure the extent to which a proposed design will meet the client's objectives;
- establishing the *functions* that a successful design will perform; and
- establishing the *requirements* that express in engineering terms both the design's attributes and its behavior, that is, the design's functions.

Let us formally define the two new terms we have just introduced, that is, metrics and requirements. Our definitions, while presented in standard dictionary format, represent a blend of actual dictionary definitions with our understanding of the "best practices" of engineering design as it is currently done in industry. Thus:

- **metric** *n*: a standard of measurement; in the context of engineering design, a scale on which the achievement of a design's objectives can be measured and assessed

  Metrics provide scales or rulers on which we can measure the degree to which objectives are achieved. To offer a truly simple example, let us suppose an objective of being able to jump 10 meters. A metric for a jump would award 1 point for each meter jumped, so that a jump of 2 meters earns 2 points, while a jump of 8 meters earns 8 points, and so on. As we discuss at length in Chapter 3, not all objectives are so easily quantified, and not all measurements are so easily made. Thus, there are interesting issues that must be addressed when we talk about metrics in depth.

- **requirement(s)** *n*: thing(s) wanted or needed; thing(s) essential to the existence or occurrence of something else; in the context of engineering design, engineering statements of the functions that must be exhibited and the attributes that must be displayed by a design

  The design requirements, which are often called *design specifications*, are stated in a number of ways, depending on the nature of the requirements the designer chooses to articulate. As we explain in Chapter 5, design requirements may specify: *values* for particular design attributes; the *procedures* used to calculate attributes or behavior of the design; or *performance levels* of the functional behavior that must be attained by the design. We shall explore the nature of design requirements (or specifications) extensively in Chapter 4.

Fabrication specifications enable implementation independent of the designer's involvement.

The endpoint of a successful design is a set of plans for making the designed device. This set of plans, often called *fabrication specifications*, may include drawings, assembly instructions, and lists of parts and materials, as well as a host of text, graphs, and tables that explain: what the artifact is; why it is what it is; and how it can be realized or brought to life. This will be the case whether the artifact is a physical object, a process description, or some soft representation.

Further, fabrication specifications must be clear, unambiguous, complete, and transparent. This is because fabrication specifications must, *by themselves*, enable someone other than the designer (or others involved in the design process) to make what the designer intended so that it performs as the designer intended. This is a facet of modern engineering practice that represents a departure from a (long-ago) time when designers were often craftsmen who made what they designed. These designer-fabricators could allow themselves latitude or shorthand in their design plans because as fabricators they knew exactly what they intended as designers. Nowadays engineers rarely make what they design. Sometimes designs are "thrown over the wall" to a manufacturing department or to a fabricator who acts entirely on "what's in the specs." But increasingly manufacturing issues are addressed during the design process, which means that manufacturing engineers and even suppliers become part of the design team, which also means there are further needs for designers to be good communicators!

It often happens that the manufacture or use of a device highlights deficiencies that were not anticipated in the original design. Designs often produce *unanticipated consequences* that may become *ex post facto* evaluation criteria. For example, the automobile does provide the intended personal transportation. On the other hand, some regard the automobile as a failure because of its contribution to air pollution and traffic congestion. In addition, changing societal expectations have dictated serious redesign of many of the automobile's attributes and behaviors.

Communication is a key issue in design.

Finally, our definition of engineering design and the related assumptions we have identified clearly rely heavily on the fact that communication is central to the design process. Some set of languages or representations is inherently and unavoidably involved in every part of the design process. From the original communication of a design problem through the specification of requirements and of fabrication specifications, the device or system being designed must be described and "talked about" in many, many ways. Thus, *communication is a key issue*. It is not that problem solving and evaluation are less important; they are extremely important. But problem solving and evaluation are done at levels and in styles — whether spoken or written languages, numbers, equations, rules, charts, or pictures — that are appropriate to the immediate task at hand. Successful work in design is inextricably bound up with the ability to communicate.

1.3 LEARNING AND DOING ENGINEERING DESIGN

Design is rewarding, exciting, fun, even exhilarating. But good design doesn't come easily. In fact, achieving excellence in design is hard. That is why learning and doing (and teaching!) design is hard.

1.3.1 Engineering design addresses hard problems

Engineering design is an ill structured, open-ended activity.

Engineering design problems are generally difficult because they are usually *ill structured* and *open-ended*:

- Design problems are *ill structured* because their solutions cannot normally be found by applying mathematical formulas or algorithms in a routine or structured way. Mathematics is both useful and essential in engineering design, but much less so in the early stages when "formulas" are both unavailable and inapplicable. In fact, some engineers find design difficult simply because they can't fall back on structured, formulaic knowledge — but that's also what makes design a fascinating experience.
- Design problems are *open-ended* because they typically have several acceptable solutions. Uniqueness, so important in many mathematics and analysis problems, simply does not apply to design solutions. In fact, more often than not designers work to reduce or bound the number of design options they consider lest they be overwhelmed by the possibilities.

Evidence for these two characterizations can be seen in the familiar ladder. Several ladders are shown in Figure 1.4, including a stepladder, a portable stepladder, and a rope ladder. If we want to design a ladder, we can't identify a particular ladder type to target unless and until we determine a specific set of uses for that ladder. Even if we decide that a particular form is appropriate, say a stepladder for the household handyman, other questions arise: Should the ladder be made of wood, aluminum, plastic, or a composite material? How much should it cost? And, which ladder design would be the *best*? Can we identify the *best* ladder design, or the *optimal design*? The answer is, "No," we can't stipulate a ladder design that would be universally regarded as the best or that would be mathematically optimal in every dimension.

How do we talk about some of the design issues, for example, purpose, intended use, materials, cost, and possibly other concerns? In other words, how do we articulate the choices and the constraints for the ladder's form and function? There are different ways of representing these differing characteristics by using various "languages" or representations. But even the simple ladder design problem becomes a complex study that shows how the two characteristics of poorly defined endpoints (e.g., what kind of ladder?) and ill defined structure (e.g., is there a formula for ladders?) make design a tantalizing yet difficult subject. How much more complicated and interesting are projects to design a new automobile, a skyscraper, or a way to land a person on the moon?

1.3.2 Learning design by doing design

For someone who wants to learn *how to do it*, design is not all that easy to grasp. Like riding a bicycle or throwing a ball, like drawing and painting and dancing, it often seems easier to say to a student, "Watch what I'm doing and then try to do the same thing yourself." There is a *studio* aspect to trying to teach any of these activities, an element of *learning by doing*.

One of the reasons that it is hard to teach someone how to do design — or to ride a bike or throw a ball or draw or dance — is that people are often better at *demonstrating* a

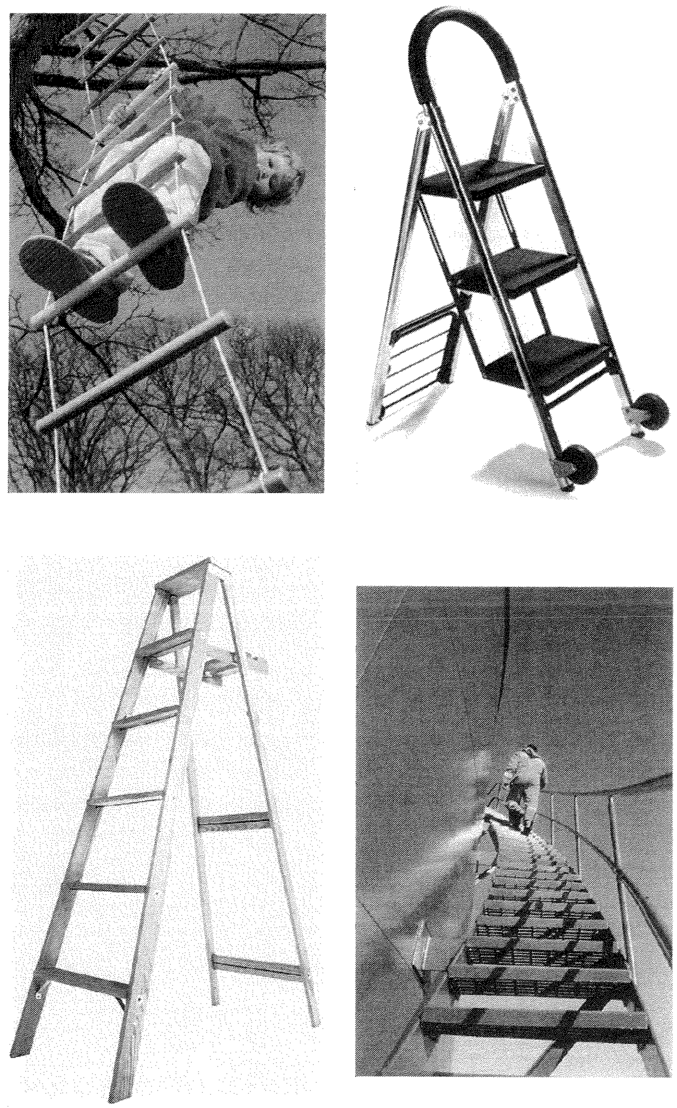

FIGURE 1.4 A collection of "devices that enable people to reach heights they would be otherwise unable to reach," i.e., ladders. Note the variety of ladders, from which we can infer that the design objectives involved a lot more than the simple idea of getting people up to some height. Why are these ladders so different?

skill than they are at *articulating* what they know about applying their individual skills. Some of the skill sets just mentioned clearly involve some physical capabilities, but the difference of most interest to us is not simply that some people are more gifted physically than others. What is really interesting is that a softball pitcher cannot tell you just how much pressure she exerts when holding the ball, nor exactly how fast her hand ought to be going, or in what direction, when she releases it. Yet, somehow, almost by magic, the softball goes where it's supposed to go and winds up in the hands of a catcher. The real point is that the thrower's nervous system has the knowledge that allows her to assess distances and choose muscle contractions to produce a desired trajectory. While we can model that trajectory, given initial position and velocity, we do not have the ability to model the knowledge in the nervous system that generates that data.

Design is best learned by both doing and studying.

Note also that designers, like dancers and athletes, *use drills and exercises* to perfect their skills, *rely on coaches* to help them improve both the mechanical and interpretive aspects of their work, and *pay close attention* to other skilled practitioners of their art. Indeed, one of the highest compliments paid to an athlete is to say that he or she is "a student of the game."

1.4 ON THE EVOLUTION OF DESIGN AND ENGINEERING DESIGN

People have been doing design from time immemorial. People have also been talking and writing about design for a long time, but for much less time than they have actually been designing things. So, let's have a brief look at the evolution of design and engineering design over time.

1.4.1 Remarks on the evolution of design practice and thinking

Thinking back to early elementary artifacts, it is almost certainly true that the "designing" was inextricably linked with the "making" of these primitive implements. We have no record of a separate, discernible modeling process, so we can't know that for sure. Who can say that small flint knives were not consciously used as models for larger, more elaborate cutting instruments? The inadequacy of small knives for cutting into the hides and innards of larger animals could have been a logical driver for enlarging a small flint knife. People must have *thought* about what they were making, recognized shortcomings or failures of devices already in use before they made more sophisticated versions.

But we really have no idea of *how* these early designers thought about their work, what kinds of languages or images they used to process their thoughts about design, or what mental models they used to assess function or judge form. If we can be sure of anything, it is that much of what they did was done by trial and error. (Nowadays, when trial solutions are generated by unspecified means and tested to eliminate error, we call it *generate and test.*)

We find examples of ancient works that must have been designed, such as the Great Pyramids of Egypt, the cities and temples of Mayan civilization, and the Great Wall of China. Unfortunately, the designers of these wonderfully complex structures did not leave a paper trail of recorded thoughts about their designs. However, there are some discussions of design that go pretty far back, one of the most famous being the collection of works by the Venetian architect Andrea Palladio (1508–1580). His works were apparently first translated into English in the eighteenth century. Since then, discussions of design have been developed in fields as diverse as architecture, organizational decision making, and various styles of professional consultation, including the practice of engineering. That's one reason there are a lot of definitions of engineering design.

We see that even in ancient times, designers evolved from pragmatists who likely designed artifacts as they made them, to more sophisticated practitioners who sometimes designed immense artifacts that others constructed. It has been said that the former approach to design, wherein the designer actually produces the designed object directly, is a distinguishing feature of a *craft*, and is found in such modern and sophisticated endeavors as graphics and type design.

1.4.2 A systems-oriented definition of design

We identified several key words when we defined *engineering design*, including form, function, requirements, and specifications. Could we (and how would we) define *design*? Here, too, it is as hard to define design generally as it is to define the particular endeavor of engineering design. For example, design could be defined as a goal-directed activity, performed by humans, and subject to constraints. The product of this design activity is a *plan* to realize those goals.

Herbert A. Simon, late Nobel laureate in economics and founding father of several fields, including design theory, offered a broad definition of design that is closely related to our engineering concerns:

- **Design** is an activity that intends to produce a "description of an artifice in terms of its organization and functioning — its interface between inner and outer environments."

Designers are thus expected to describe the shape and configuration of a device (its "organization"), how that device does what it was intended to do (its "function"), and how the device (its "inner environment") works ("interfaces") within its operating ("outer") environment. Simon's definition is interesting for engineers because it places designed objects in a *systems* context that recognizes that any artifact operates as part of a system that includes the world around it. In this sense, all design is systems design because devices, systems, and processes must each operate within and interact with their surrounding environments.

1.4.3 On the evolution of engineering design

We noted earlier that engineering designers do not typically produce their artifacts. Rather, they produce fabrication specifications for making the artifacts. The designer in an engineering context produces a detailed description of the designed device so that it can be assembled or manufactured, thus separating the "designing" from the "making." This specification must be both complete and quite specific; there should be no ambiguity and nothing can be left out.

Traditionally, fabrication specifications were presented in a combination of drawings (e.g., blueprints, circuit diagrams, flow charts, etc.) and text (e.g., parts lists, materials specifications, assembly instructions, etc.). We can achieve completeness and specificity with such traditional specifications, but we may not capture the designer's intent — and this can lead to catastrophe. In 1981, a suspended walkway in the Hyatt

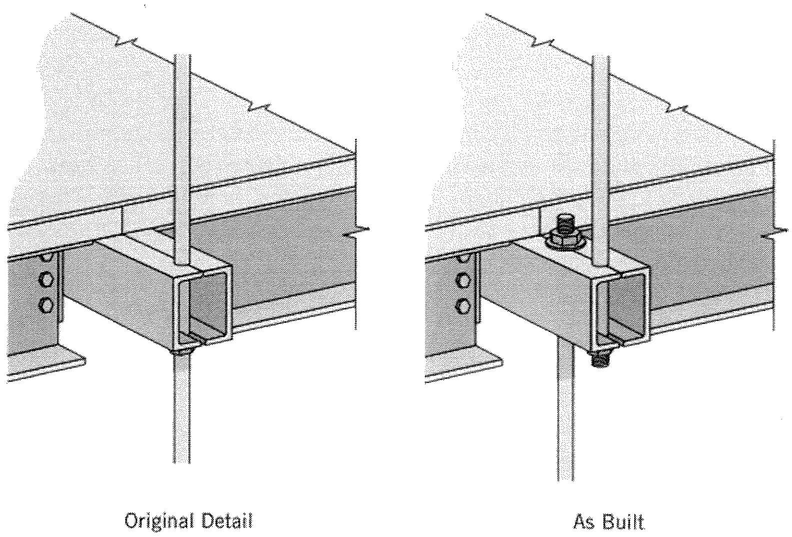

FIGURE 1.5 The walkway suspension connection—as originally designed and as built—in the Regency Hyatt House in Kansas City. We see that the change made during construction resulted in the second-floor walkway being hung from the fourth-floor walkway, rather than being connected directly to the roof truss.

Regency Hotel in Kansas City collapsed because a contractor fabricated the connections for the walkways in a manner different than intended by the original designer.

In that design, walkways at the second and fourth floors were hung from the same set of threaded rods that would carry their weights and loads to a roof truss (see Figure 1.5). The fabricator was unable to procure threaded rods sufficiently long (i.e., 24 ft) to suspend the second-floor walkway from the roof truss, so instead, he hung it from the fourth-floor walkway with shorter rods. (It also would have been hard to screw on the bolts over such lengths and attach walkway support beams.) The fabricator's redesign was akin to requiring that the lower of two people hanging independently from the same rope change his position so that he was grasping the feet of the person above. That (upper) person would then be carrying both people's weights with respect to the rope. In the hotel, the supports of the fourth-floor walkway were not designed to carry the second-floor walkway in addition to its own dead and live loads, so a collapse occurred, 114 people died, and millions of dollars of damage was sustained. If the fabricator had understood the designer's intention to hang the second-floor walkway directly from the roof truss, this accident might never have happened. Had there been a way for the designer to explicitly communicate his intentions to the fabricator, a great tragedy might have been avoided.

The design may be the only connection between the designer and the fabricator.

There's another lesson to be learned from the separation of the "making" from the "designing." If the designer had worked with a fabricator or a supplier of threaded rods while he was still designing, he would have learned that no one made threaded rod in the lengths needed to hang the second-floor walkway directly from the roof truss. Then the designer could have sought another solution in an early design stage. In much of the manufacturing and construction business, it was the case for many years that there was a "brick wall" between the design engineers on one side and the manufacturing engineers and fabricators on the other. Only recently has this wall been penetrated. Manufacturing and assembly considerations are increasingly addressed *during* the design process, rather than afterward. One element in this new practice is *design for manufacturing*, in which the ability to make or fabricate an artifact is specifically incorporated into the design requirements, perhaps as a set of manufacturing constraints. Clearly, the designer must be aware of parts that are difficult to make or of limitations on manufacturing processes as her design unfolds.

Concurrent engineering, another recent idea, refers to the process in which designers, manufacturing specialists, and those concerned with the product's life cycle (e.g., purchase, support, use, and maintenance) work together, along with other design stakeholders, so that they can collectively and *concurrently* design the artifact together. Concurrent engineering thus works to capture the designer's intent by integrating the design and fabrication activities. Clearly, then, concurrent engineering demands teamwork of a high order. Research in this area focuses on ways to enable teams to work together on complex design tasks when team members are dispersed not only by engineering discipline, but also geographically, culturally, and by time zones.

The designer's intent must be clearly communicated to the fabricator.

The Hyatt Regency tale and the lessons drawn from it suggest that fabrication specifications are really important. Unless a design's fabrication specifications are complete and unambiguous, and unless they clearly convey a designer's intentions, the device or system won't be built in accord with the requirements set out by the designer. It is also the case that fabrication specifications provide a basis for evaluating how well a design meets its original design goals because those specifications emerge from the design's requirements, which in turn result from our ability to translate the original objectives (and constraints) of the client into those requirements.

But while worrying about design requirements and fabrication specifications, as well as all of the other issues we have raised, we should also keep in mind that design is a human activity, a social process. This means that communication among stakeholders remains a pre-eminent, consistent concern.

1.5 MANAGING ENGINEERING DESIGN

Good design doesn't just happen.

Good design doesn't just happen. Rather, it results from careful thought about what clients and users want, and about how to articulate and realize design requirements. That is why this book focuses on tools and techniques to assist the designer in this process. One particularly important element of doing good design is *managing* the design project. Just as thinking about design in a rigorous way does not imply a loss of creativity, using tools to manage the design process doesn't mean we sacrifice technical competency or inventiveness. On the contrary, there are many organizations that foster imaginative engineering design as an integral part of their management style. At 3M, for example, each of the more than 90 product divisions is expected to generate 25 percent of its annual revenues from products that didn't even exist five years earlier. We will also introduce a few tools and techniques of management that are applicable to design projects.

Just as we began by defining terms and developing a common vocabulary for design, we will do the same for management, project management, and the management of design