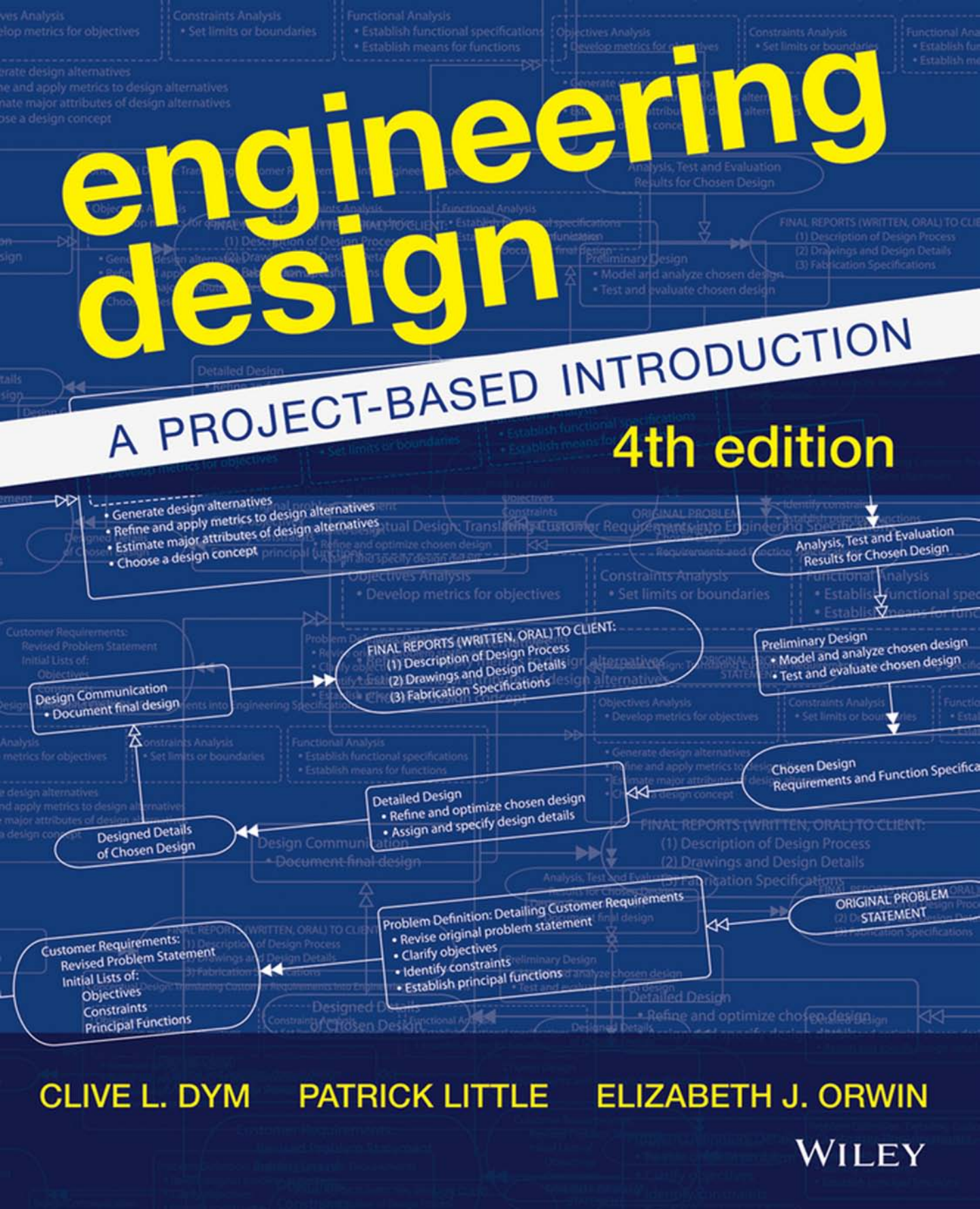


# engineering design

A PROJECT-BASED INTRODUCTION

4th edition



CLIVE L. DYM

PATRICK LITTLE

ELIZABETH J. ORWIN

WILEY



FOURTH EDITION

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*ENGINEERING DESIGN:  
A PROJECT-BASED INTRODUCTION*

**CLIVE L. DYM, PATRICK LITTLE, and ELIZABETH J. ORWIN**

*Harvey Mudd College*

**WILEY**

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To  
Joan Dym  
*whose love and support are distinctly nonquantifiable*

cld

Charlie Hatch  
*a teacher's teacher*

pl

Carl Baumgaertner  
*who inspired me to teach*

ejo

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## FOREWORD\*

To design is to imagine and specify things that don't exist, usually with the aim of bringing them into the world. The "things" may be tangible—machines and buildings and bridges; they may be procedures—the plans for a marketing scheme or an organization or a manufacturing process, or for solving a scientific research problem by experiment; they may be works of art—paintings or music or sculpture. Virtually every professional activity has a large component of design, although usually combined with the tasks of bringing the designed things into the real world.

Design has been regarded as an art, rather than a science. A science proceeds by laws, which can sometimes even be written in mathematical form. It tells you how things must be, what constraints they must satisfy. An art proceeds by heuristic, rules of thumb, and "intuition" to search for new things that meet certain goals, and at the same time meet the constraints of reality, the laws of the relevant underlying sciences. No gravity shields; no perpetual motion machines.

For many years after World War II, science was steadily replacing design in the engineering college curricula, for we knew how to teach science in an academically respectable, that is, rigorous and formal, way. We did not think we knew how to teach an art. Consequently, the drawing board disappeared from the engineering laboratory—if, indeed, a laboratory remained. Now we have the beginnings—more than the beginnings, a solid core—of a science of design.

One of the great gifts of the modern computer has been to illuminate for us the nature of design, to strip away the mystery from heuristics and intuition. The computer is a machine that is capable of doing design work, but in order to learn how to use it for design, an undertaking still under way, we have to understand what the design process is.

We know a good deal, in a quite systematic way, about the rules of thumb that enable very selective searches through enormous spaces. We know that "intuition" is our old friend "recognition," enabled by training and experience through which we acquire a great collection of familiar patterns that can be recognized when they appear in our problem situations. Once recognized, these patterns lead us to the knowledge stored in our memories. With this understanding of the design process in hand, we have been able to reintroduce design into the curriculum in a way that satisfies our need for rigor, for understanding what we are doing and why.

One of the authors of this book is among the leaders in creating this science of design and showing both how it can be taught to students of engineering and how it can be implemented in computers that can share with human designers the tasks of carrying out the design process. The other is leading the charge to integrate the management sciences into both engineering education and the successful conduct of engineering design projects. This book thus represents a marriage of the sciences of design and of management. The science of design continues to move rapidly forward, deepening our understanding and enlarging our opportunities for human-machine collaboration. The study of design has joined the study of the other sciences as one of the exciting intellectual adventures of the present and coming decades.

*Herbert A. Simon*  
Carnegie Mellon University  
Pittsburgh, Pennsylvania  
August 6, 1998

\* Herb Simon graciously contributed the foreword for our first edition. Unfortunately, the passage of time since was marked by the loss of one of our great heroes and a true renaissance mind: Herb passed away on March 4, 2002. We still feel the loss.

---

# PREFACE

When we started on the first edition of this book in the late 1990s, we could not have predicted that we would someday be asked to prepare a fourth edition of a text for a then-controversial course. At that time, a cornerstone introduction to engineering design was indeed considered improbable, if not impossible or meaningless. Now such courses are a staple of many engineering programs, and we are proud to have helped bring that curricular adaptation to life. We have also been part of a similar adaptation of engineering's capstone courses, which were then often undertaken more in response to accreditation needs than a desire for real-world projects. Today externally focused capstone courses, some modeled on Harvey Mudd College's Engineering Clinic, not only give students an authentic design experience, but also often introduce them to working with peers scattered around the world. The students in the classroom or design studio have also changed: Many more women and underrepresented minority students now major in engineering.

These transitions have been accompanied by an evolution in the discipline of design and in the perception of engineering design by the faculties of engineering schools. In particular, design is now a recognized intellectual discipline, with a vocabulary, structure, and methods that reflect our increasing ability to articulate what we are doing when we design something. And as with many other disciplines, design ranges from the narrow and mathematical (e.g., kinematics, optimization) to the broad and transdisciplinary (e.g., the life of a product from its inception to use to disposal, the communication and teamwork skills that are the "soft" skills of engineering design).

We have also changed, certainly getting older, perhaps also becoming wiser. We have had opportunities to see how the design ideas we taught worked, which needed refinement, and which didn't work at all. We have tried to adapt this fourth edition both to the changing circumstances and to our increased knowledge of the world, the engineering profession, and our educational mission.

Of course, some things have not changed at all. Engineering design has always required attention to the wishes of the client, users, and the larger public. It is still true that engineers must organize their design processes to communicate their design thinking to their design partners. And it also remains true that effective design teams are those whose members respect one another. Perhaps most of all, a commitment to ethical design by and on behalf of a diverse community must remain at the forefront of what it is we do as engineers.

Today there are many more books on design, engineering design, project management, team dynamics, project-based learning, and the other topics we cover in this volume, than when we wrote our first edition. We wanted then—as we still do today—to combine these topics in a single, introductory work that focused particularly on conceptual design. That original desire arose from our teaching at Harvey Mudd College, where our students do team-based design projects in a first-year design course, *E4: Introduction to Engineering Design* (called "E4"), and in the Engineering Clinic. Clinic is an unusual capstone course taken by juniors (for one semester) and seniors (for both semesters) in which students work on externally sponsored design and development projects. In both E4 and Clinic, Mudd students work in multidisciplinary teams, under specified time deadlines, and within specified budget constraints. These conditions are meant to replicate to a significant degree the environments within which most practicing engineers will do much of their professional design work. In looking for books that could serve our audience, we found that there were excellent texts covering detailed design, usually targeted toward senior capstone design courses, or "introductions to engineering" that focused on describing the branches

of engineering. We could not find a book that introduced the processes and tools of conceptual design in a project or team setting that we found suitable for first- and second-year students. And while other more “skills-oriented” texts and series have come onto the market since, we are gratified that a growing market has emerged for the book that addresses our original concerns.

In designing all four editions of this book, we confronted many of the same issues that we discuss in the pages that follow. It was important for us to be very clear about our overall objectives, which we outline below, and about the particular objectives we had for each chapter. We asked about the pedagogic function served by the various examples, and whether some other example or tool might provide a better means for achieving that pedagogical function. The resulting organization and writing represent our implementation of our best design. Thus, this and all books are designed artifacts: They require the same concern with objectives, choices, constraints, functions, means, budget, and schedule, as do other engineering or design projects.

This book is directed to three audiences: students, teachers, and practitioners. The book is intended to support *students* to learn about design, the central activity of engineering, by *doing* design. We view our design course, E4, as a setting in which students *acquire design skills* as they *experience the activity of design* by working on design projects. The book is intended to help students learn formal design tools and techniques as they solve conceptual design problems. They can then apply these formal methods to other design projects they will face later in their education in Clinic-like capstone courses and later in their careers. Students will also learn about communication, team dynamics, and project management. We have included examples of work done by our students on actual projects in E4, both to show how the tools are used and to highlight some frequently made mistakes.

We wrote this book with *teachers* also very much in mind. We thought about how to deliver the material to students, and about how introductory design courses could be taught. In this fourth edition, we decomposed and modularized much of the text, in order to avoid the confusion that often results when a new vocabulary is being learned; that is, to separate objectives from constraints, objectives from functions, functions from means, and customer requirements from design specifications. The modularization also provides options for instructors to structure their classes in a variety of ways, bringing forward (or deferring) discussions of communication, team dynamics, leadership, or management, because the chapters on these (and other) topics are self-contained. We also provide a complete design case study and two continuing design examples that can be used by an instructor as ongoing examples for illustration and as in-class exercises. (We don’t assign homework problems in E4 as our students are working on their various E4 projects as “homework” when they’re not in class.) In an accompanying *Instructor’s Manual*, we outline sample syllabi and organizations for teaching the material in the book, as well as additional examples.

Finally, we hope the book will be useful to *practitioners*, either as a refresher of things learned or as an introduction to some essential elements of conceptual design that were not formally introduced in engineering curricula in years past. We do not assume that the case study or the illustrative design examples given here substitute for an engineer’s experience, but we do believe that they show the relevance of these tools to practical engineering settings. Some of our friends and colleagues in the profession like to point out that the tools we teach would be unnecessary if only we all had more common sense. Notwithstanding that, the number and scale of failed projects suggest that common sense may not, after all, be so commonly distributed. In any case, this book offers both practicing engineers (and engineering managers) a view of the design tools that even the greenest of engineers will have in their toolbox in the coming years.

## **SOME REMARKS ON VOCABULARY AND WORD USAGE**

---

There is no engineering design community that transcends all engineering disciplines or all types of engineering practice. For that very reason, words are used differently in different domains, and so differing technical jargons have developed. Since we want to provide a unified coherent understanding that would be a useful foundation for all of our students’ future design work, whether in their formal

studies or in their chosen careers, we begin our discussions of the major concepts and terms of art with formal dictionary definitions, but leavened by our understanding of today’s “best practices” in design. We do this to remind readers that word usage has its roots in a shared understanding of vocabulary, in our case the English vocabulary. Even technical jargon has—or should have—a traceable path back to common usage. Thus, in this fourth edition we have worked much harder than we have before to be as crisp and consistent as possible with the words we chose to use.

Further, it is clear that words are used differently in the different domains of engineering practice. For example, different authors (in both the research literature and textbooks) define phases of the design process differently, with varying activities occurring within them. We have worked very hard to clearly articulate our model of the design process in Chapter 2. As we reviewed materials for this edition, we saw that the use of the terms *requirements* and *specifications* in engineering practice is not uniform. Thus, we choose to speak in terms of *customer requirements* to specify what the client wants and needs from her design (i.e., the client’s *objectives* and *constraints* and the *functions* as she’d like them to happen), and *design specifications* to articulate in engineering terms how a design is supposed to perform its *functions* and, as appropriate, display its *behaviors*.

## **SOME SPECIFICS ABOUT WHAT’S COVERED**

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Design is an *open-ended* and *ill-structured* process, by which we mean there is no unique solution, and that the candidate solutions cannot be generated with an algorithm. As we emphasize in the early chapters, designers have to provide an orderly process for organizing an ill-structured design activity in order to support making decisions and trade-offs among possibly competing solutions. In such cases, algorithms and mathematical formulations cannot replace the imperative to understand the often subjective needs of various stakeholders (clients, users, the public, and so on)—even if those mathematical tools are used later in the design process. Perhaps ironically, this lack of structure and the inapplicability of formal mathematical tools make the introduction of conceptual design early in the curriculum possible and, we think, desirable. It provides a framework in which engineering science and analysis can be used, while not demanding skills that most first- and second-year students have not yet acquired. We have, therefore, included in this book the following specific tools for conceptual design, for acquiring and organizing design knowledge, and for managing the team environment in which design takes place.

The following *formal conceptual design methods* are delineated:

- objectives trees
- establishment of metrics to measure the achievement of objectives
- pairwise comparison charts (PCCs) to rank objectives
- functional analysis (including black and glass boxes, enumeration, function-means trees, and so on)
- morphological (“morph”) charts to develop design alternatives
- specifications development

Since both the framing or defining of a design problem and conceptual design thinking require and produce a lot of information, we introduce a variety of means to acquire and process information, including literature reviews, brainstorming, analogies, user surveys and questionnaires, reverse engineering (or dissection), simulation and computer analysis, and formal design reviews.

The successful completion of any design project by a team requires that team members estimate a project’s scope of work, schedule, and resources early in the life of the project. To this end, we introduce several *design management tools*:

- work breakdown structures (WBSs)
- schedules
- budgets

We also discuss several other topics that we feel are increasingly important in a first exposure to design. We discuss the completion of a design project, with a strong emphasis on the *ways and means of reporting design results* in Chapters 9 and 10. These chapters allow instructors to focus on engineering communication as an integral part of the design process, including engineering drawings, reports, and presentations. We also present some more practical aspects of drawing and tolerancing in Appendix A. We did this because we wanted to bring together the basic skills needed in design, such as communicating through drawings by adhering to appropriate standards and conventions (e.g., geometric dimensioning and tolerances).

We also include a discussion about *building physical models and prototypes* in Chapter 11. We did this because we have also observed in our own students that most don't start college with much hands-on experience, even in basic woodcraft. Since we expect them to build elementary (physical) models and prototypes, it seemed only fair to include some understanding of what models and prototypes are, as well as (in Appendix B) some cautionary tips about working in a shop or laboratory, and some very basic tips on how to actually make (and fasten) some basic wooden parts.

In Chapter 12, we introduce some ideas about *mathematical modeling in design*, placed in the context of doing preliminary and detailed design. The material introduces principles of mathematical modeling to reinforce concepts behind applying mathematics and physics to engineering. Then we go on to illustrate a few of the kinds of calculations that might be done in the later phases of design. We illustrate the modeling of both battery-powered payload carts and a basic rung or step for a ladder, where we apply some results from elementary beam theory. Needless to say, in one chapter and in the kinds of course that we aimed this book toward, we could not delve into preliminary and detailed design in all engineering disciplines. What we present is representative of the “good habits of thought” needed to model and analyze designs in all disciplines.

In Chapter 13 we present a brief introduction to engineering economics and to the time value of money, the latter being quite important because we often need to balance initial or present costs against costs due, for example, to use, wear, and maintenance. In Chapter 14 we discuss “design for X” issues, including use, manufacturing and assembly, reliability and maintainability, and sustainability. This chapter provides a vehicle for faculty who want to expand on these topics and lead students into issues such as concurrent design, DFM, or emerging areas such as sustainability and carbon footprints.

In Chapter 15 we undertake a discussion of teams, exploring both the stage of team formation and the roles of individuals on both effective and ineffective teams. Then in Chapter 16 we talk about the fundamentals of managing a design project, including monitoring its progress and controlling its expenditures and costs. We finish our exploration of engineering design with our own capstone, Chapter 17, in which we discuss important ethics issues in design. This chapter reflects a wider notion of engineering ethics than in the past, as we invite faculty to address traditional notions of liability and responsibility and also newer ideas of social and political dimensions of engineering design.

## DESIGN CASE STUDY AND INTEGRATIVE DESIGN EXAMPLES

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We use one case study and two integrative examples to follow the design process through to completion, thus showing each of the tools and techniques as they are used on a design project. In addition to numerous “one-time” examples, we detail the following case study and integrative examples:

**Design case study:** This case study, contained in full in Chapter 2, follows the design of a *microlaryngeal surgical stabilizer*, a device used to stabilize the physician's hand as he uses various instruments in throat surgery. The work we show in this case study derives from the efforts of several student teams in the Harvey Mudd College's first-year design course (“E4”), on a project sponsored by the Beckman Laser Institute of the University of California at Irvine. (Further details can be found in the Acknowledgments, the Notes at the end of Chapter 2 and the References and Bibliography.)



The first **illustrative design example** is the design of a *juice container*. This is a design project created by the authors solely to illustrate the application of various conceptual design tools that are the substance of much of this book. A design team, having a fruit juice company as a client, is asked to develop a means of delivering a new juice to a market predominantly composed of children and their parents. There are clearly a number of possibilities (e.g., mylar bags, molded plastics), and issues such as environmental effects, safety, and the costs of manufacturing are considered.

The second **illustrative design example 2** is the design of an *arm support* to be used by a child diagnosed with cerebral palsy (CP). Here we show how teams of Harvey Mudd College students in our E4 design class responded to the challenge of designing something for one such disabled student, having in mind at the same time that such a design might be useful to many other children in many other schools. We show work done by two particular teams, again to illustrate how these student teams applied the design tools they were learning. (Again, further details can be found in the Acknowledgments, the Notes at the end of Chapter 2, and the References and Bibliography.) Prototypes were subsequently built by the students and delivered to the Danbury School, a special education elementary school within the Claremont Unified School District of Claremont, California.

Finally, an accompanying *Instructor's Manual* includes a case study of the design of a *transportation network* to enable automobile commuter traffic between Boston and its northern suburbs, through Charlestown, Massachusetts. This conceptual design problem clearly illustrates the many factors that go into large-scale engineering projects in their early stages, when choices are being made between highways, tunnels, and bridges. Among the design concerns are cost, implications for future expansion, and preservation of the character, environment, and even the view of the affected neighborhoods. This project is also an example of how conceptual design thinking can significantly influence some very “real-world” events.

As noted at the outset, this edition has presented both an opportunity and a challenge for us as authors. We now share those with our readers.

*Clive L. Dym*  
*Patrick Little*  
*Elizabeth J. Orwin*  
Claremont, California  
March 7, 2013

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Finally, *to each and all of our spouses and families*, for tolerating us during the absences that such projects entail, and for listening to each of us as we worked through differences to find a common voice.

PART

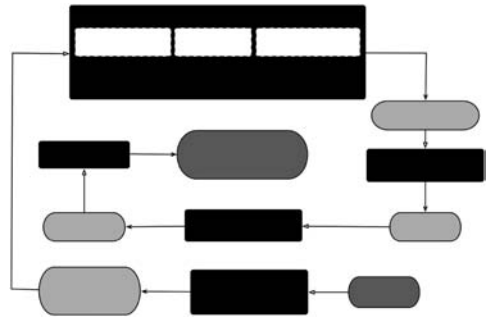
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# *INTRODUCTION*



# ENGINEERING DESIGN

*What does it mean to design something? Is engineering design different from other kinds of design?*



**P**EOPLE HAVE been designing things for as long as we can archaeologically uncover. Our earliest ancestors designed flint knives and other tools to help meet their most basic needs. Their wall paintings were designed to tell stories and to make their primitive caves more attractive. Given the long history of people designing things, it is useful to set some context for engineering design and to start developing a vocabulary and a shared understanding of what we mean by engineering design.

## 1.1 WHERE AND WHEN DO ENGINEERS DESIGN?

What does it mean for an *engineer* to design something? When do engineers design things? Where? Why? For whom?

An engineer working for a large company that processes and distributes various food products could be asked to design a container for a new juice product. She could work for a design-and-construction company, designing part of a highway bridge embedded in a larger transportation project, or for an automobile company that is developing new instrumentation clusters for its cars, or for a school system that wants to design specialized facilities to better serve students with orthopedic disabilities.

There are common features that make it possible to identify a design process and the context in which it occurs. In each of these cases, three “roles” are played as the design

unfolds. First there is a *client*, a person or group or company that wants a design conceived. There is also a *user* who will employ or operate whatever is being designed. Finally, there is a *designer* whose job is to solve the client's problem in a way that meets the user's needs. The client could be internal (e.g., a person at the food company in charge of the new juice product) or external (e.g., the government agency that contracts for the new highway system). While a designer may relate differently to internal and external clients, it is typically the client who *motivates* and presents the starting point for design. That is why a designer's first task is to *question* the client to clarify what the client really wants and translate it into a form that is useful to her as an engineer. We'll say more about this in Chapter 3 and beyond.

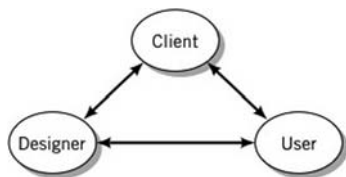
It is worth noting that the client, the user, and even the designer may not always be three or even two different people: In a small start-up, for example, the designer may be the client, and may also rely on his or her own personal experience as a user when initiating a design. Similarly, for an internal project, the roles may again merge. However, for most design projects, it is useful to distinguish between the three roles and their respective responsibilities—as anyone who has used beta versions of software can testify because all too often, software designers imagine that their own experience is sufficient for every user!

The user is a key player in the design effort. In the contexts mentioned above, the users are, respectively, consumers who buy and drink a new juice drink, drivers on a new interstate highway, and students with orthopedic disabilities (and their teachers). Users have a stake in the design process because designs have to 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 both the client and users want and need. Often the client speaks to the designer on behalf of the intended users, although anyone who has sat in a cramped seat on a commercial flight would have to ask both airlines and airplane manufacturers who they think their users are!

The *public* also has a stake in many designs, for example, a new interstate highway. While the notion of the public may seem to be implicit in the user, this is not always the case. Explicitly identifying who is affected by a design is important, because it may raise ethical issues in design projects, as we will explore in Chapter 17.

It is clear that both designer and client *have to understand what the users want and what the public demands in a design*. In Chapter 2, we will describe design processes that model how engineers interact with and communicate their design thinking to clients and potential users. In Chapters 3–5, we will identify some tools to organize and refine that thinking.

Engineering designers work in many different kinds of environments: small and large companies, start-up ventures, government, not-for-profit organizations, and engineering



**Figure 1.1** The designer–client–user triangle shows three parties involved in a design effort: a client, who has objectives that must be realized; the users of the design, who have their own wishes; the designer, who must design something that can be built and that satisfies everybody.

services firms. Designers will see differences in the size of a project, the number of colleagues on the design team, and their access to relevant information about what users want. On large projects, many designers will be working on details of a project that are so confined that much of what we describe in this book may not seem immediately useful. The designers of a bridge abutment, an airplane fuel tank, or components of a computer motherboard are not likely to be as concerned with the larger picture of what clients and users want from the entire project because the system-level design context has already been established. These are *detailed design* problems in which more general design issues have already been decided. However, all projects begin with *conceptual design*. Thinking about the size and mission of an airplane will have been done before fuel tank design begins, and the overall performance parameters of the computer motherboard will be determined prior to selecting specific chips.

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: Airplanes are



U.S. Army Corps of Engineers Sacramento District



Courtesy of USFWS



AT100C Alamy Images  
Matt York / Associated Press



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**Figure 1.2** Several aircraft, each of which “safely transports people or goods through the air,” and each of which was designed for a different mission.



Image Source / Getty Images



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Amos Winter, Daniel Frey, and Global Research Innovation and Technology (GRIT)

**Figure 1.3** A collection of “personal mobility devices to transport people unable to use their legs,” that is, a set of very different wheelchairs.

“devices to transport people and goods through the air,” and wheelchairs are “personal mobility devices for 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 clients want and then translate those wants into an engineered product.

The designer–client–user triangle also prompts us to recognize that the interests of the three players might diverge and consider the consequences of such divergence. The presence of multiple interests creates an interaction of multiple obligations, and these obligations may 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 trade-offs 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 reflect different assessments of the possible safety hazards, which in turn could lay a foundation for potential ethics problems. Ethics problems, which



we will discuss in Chapter 17, occur because *designers have obligations not only to clients and users, but also to their profession and to the public at large*, as detailed in the codes of ethics of engineering societies. Thus, ethics issues are always part of the design process.

Another aspect of engineering design practice that is increasingly common in projects and firms of all sizes is that *teams* 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 ways. This requires that teams be assembled to understand and address such different 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. In this book, we offer a framework to facilitate productive thought about the conceptual issues and the resulting choices made early in the design of many different engineered products.

## 1.2 A BASIC VOCABULARY FOR ENGINEERING DESIGN

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There are many definitions of *engineering design* in the literature, and there is a lot of variation in how engineers describe design actions and attributes. We will now define what *we* mean by engineering design and also some of the related terms that are commonly used by engineers and designers.

### 1.2.1 Defining Engineering Design

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

- **Engineering design** is a systematic, intelligent process in which engineers generate, evaluate, and specify solutions for devices, systems, or processes whose form(s) and function(s) achieve clients' objectives and users' needs while satisfying a specified set of constraints. In other words, *engineering design is a thoughtful process for generating plans or schemes for devices, systems, or processes that attain given objectives while adhering to specified constraints.*

It is important to recognize that when we are designing devices, systems, and processes, we are designing *artifacts*: artificial, manmade objects, the “things” or devices that are being designed. They are most often physical objects such as airplanes, wheelchairs, ladders, cell phones, and carburetors. But “paper” products (or their electronic versions) such as drawings, plans, computer software, articles, and books are also artifacts in this sense. In this text we will use device, artifact, or system rather interchangeably as the objects of our design.

With further recourse to our “design dictionary,” we note the following definitions:

- **design objective** *n*: a feature or behavior that we wish the design to have or exhibit.
- **design constraint** *n*: a limit or restriction on the features or behaviors of the design. A proposed design is unacceptable if these limits are violated.

- **functions** *n*: things a designed device or system is supposed to do. Engineering functions almost always involve transforming or transferring energy, information, or material. We view energy transformation or transfer quite broadly: It includes supporting and transmitting forces, the flow of current, the flow of charge, the transfer of material, and so on.
- **means** *n*: a way or a method to make a function happen. For example, *friction* is a *means* of fulfilling a function of *applying a braking force*.
- **form** *n*: the shape and structure of something as distinguished from its material. We will not deal with form very much in this book, but form is central to industrial design, a very important part of product design.

Note that *objectives for a design are different from the constraints placed on a design*. Objectives may be completely or partially achieved, or may not be achieved at all. Constraints, on the other hand, *must be* satisfied or the design is not acceptable. That is, they are binary (yes or no): There are no intermediate states. If we were designing a corn degrainer for Nicaraguan farmers to be cheaply built of indigenous (local) materials, one objective might be to make it as cheap as possible, while a constraint might limit the cost to less than US\$20.00. Making the degrainer of indigenous materials could be an objective if it is a *desired* attribute, or a constraint if it is a *required* attribute.

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. There are, however, 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 this book, are not formulas or algorithms. Rather, they are ways of asking questions and of presenting and reviewing the answers to those questions as the design process unfolds.

## 1.2.2 Assumptions Underlying Our Definition of Engineering Design

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*, and therefore both taught and learned. Without meaning to spoil the magic of creativity or the importance of innovation in design, people *think* while designing. So it is important to have tools to support that thinking, to support design decision making and even design project management.

The *formal methods* we use to generate design alternatives follow naturally from our inclination to think about design. This might seem pretty obvious: 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. Thus, our formal methods are part of the (formal) process we use to identify and clarify what a client *wants* (i.e., objectives), *needs* (i.e., constraints), and intends the *design to do* (i.e., its functions). We will describe such a process in Chapter 2, and we will show how it begins with a client's problem statement and ends with a *functionally complete* design that does everything the client wants it to do, has the desired attributes, and stays within the client's constraints.

### 1.2.3 Measuring the Success of an Engineered Design

How do we know whether our design is successful? We make measurements. What do we measure? Early in the design process we establish a set of *metrics* to ascertain or measure the extent to which a proposed design meets our design objectives:

- **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 as far as possible. A metric for such a jump might be based on using a ruler to measure the distance jumped (in feet or meters). There are interesting issues that must be addressed when talking about metrics: All objectives are not easily quantified, their quantifications are not readily compared, and not all measurements are easily made. We discuss these issues in Chapter 4. *We will use metrics to mean rulers or standards specifically for objectives.*

Later in the design process, we establish *specifications* to express in engineering terms a design's functional behavior. Setting out such specifications is an essential aspect of the "best practices" of engineering design as it is currently done in industry:

- **specification(s) *n***: a scale on which the achievement of a design's functions can be measured. Specifications are engineering statements of the extent to which functions are performed by a design.

Design specifications are stated in a number of different ways, depending on what the designer intends to articulate. Thus, specifications may specify *values* for particular functions or design features, *procedures* for calculating functions or behaviors of the design, or *performance levels* that must be attained by the design.

It is important to note that the vocabulary of design practice varies across different engineering disciplines and related fields such as computer science. In fact, the terms *specifications* and *requirements* are often taken as synonymous descriptors of a design's features and behaviors, as well as its functions. For the sake of clarity, we will, in Chapters 2 and 5, take a specific stance about these two terms, as follows: We will normally use *requirements* as shorthand for *customer requirements*, which are the client's statement of objectives, constraints, and functions. We will use *specifications* as shorthand for *engineering specifications* or *design specifications*, which are the designer's expression of what a design is intended to do in engineering terms. We will define requirements and specifications in greater detail in Chapter 2, and will explore the nature of design specifications extensively in Chapter 5.

### 1.2.4 Form and 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, function is an altogether different aspect of a design that may not have an obvious relationship to its shape or form. In particular, while we can often infer the purpose of a device from its form or structure, we