THE MECHANICAL DESIGN PROCESS

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PREFACE

I have been a designer all my life. I have designed vehicles, medical equipment, furniture, and sculpture, both static and dynamic. Designing has come easy for me. I have been fortunate in having whatever talents are necessary to be a successful designer. However, after a number of years of teaching mechanical design courses, I came to the realization that I didn't know how to teach what I knew so well. I could show students examples of good-quality and poor-quality design. I could give them case histories of designers in action. I could suggest design ideas. But I couldn't tell them what to do to solve a design problem. Additionally, I realized from talking with other mechanical design teachers that I was not alone.

The situation reminded me of an experience I once had on ice skates. As a novice skater I could stand up and go forward, lamely. A friend (a teacher by trade) could easily skate forward, and backward as well. He had been skating since he was a young boy and it was second nature to him. One day while we were skating together, I asked him to teach me how to skate backward. He said it was easy, told me to watch, and skated off backward. But when I tried to do what he did, I immediately fell down. As he helped me up, I asked him to *tell* me exactly what to do, not just show me. After a moment's thought, he concluded that he couldn't actually describe the feat to me. I still can't skate backward, and I suppose he still can't explain the skills involved in skating backward. The frustration that I felt falling down as my friend skated with ease must have been the same emotion felt by my design students when I failed to tell them exactly how to solve a design problem.

This realization led me to five years' study of the design process, and eventually to this book. Part of the time I devoted to original research, part to studying U.S. industry, part to studying foreign design techniques, and part to

trying different approaches in teaching design classes. I came to four basic conclusions about mechanical design as a result of these studies:

1. The only way to learn design is to do design.
2. In engineering design the designer uses three types of knowledge: knowledge to generate ideas, knowledge to evaluate ideas, and knowledge to structure the design process. Idea generation comes from experience and natural ability. Idea evaluation comes partially from experience and partially from formal training. Generative and evaluative knowledge are forms of domain-specific knowledge. Knowledge about the structure of the design process is largely independent of domain-specific knowledge.
3. A design process that results in a quality product can be learned, provided there is sufficient ability and experience to generate ideas and enough experience and training to evaluate them.
4. The design process should be learned in a dual setting—in an academic environment and, at the same time, in an environment that simulates industrial realities.

I have incorporated these concepts into this book, which is organized so that readers can learn about the design process at the same time they are developing a product design. Thus the book is broken into two parts. The first, Chaps. 1 through 5, presents background on mechanical design in the late twentieth century, defines the terms that are basic to the study of the design process, and discusses human interface with mechanical products. Part II, Chaps. 6 through 14, is the body of the book. It presents a step-by-step development of a mechanical design method that leads the reader from the realization that there is a design problem to a solution that yields a product ready for manufacture and assembly. This material is presented in a manner independent of the exact problem being solved. The techniques discussed are not only used in industry, their names have become virtual buzzwords in mechanical design: quality function deployment, Pugh's method, concurrent design, design for assembly, and Taguchi's method for robust design. These techniques have all been brought together in this book. Although they are presented sequentially and explained in a step-by-step fashion, the examples make it very clear that the steps are merely a guide; the process is highly iterative and the steps in each technique are only used when needed.

The reader with a specific design problem in mind can begin this book with Chap. 6. Then, as the techniques in Part II are applied to the problem, the reader can refer to the background material in Part I as necessary.

Many of the methods presented in the book are in current use in U.S. and/or foreign industry, and thus the material is not original. However, material presented in Chap. 3, The Human Element in Design: How Humans Design Mechanical Objects, is based on my own research. This chapter provides background for understanding human creativity and the design

process. Additionally, the material on product generation in Chap. 11 is presented here for the first time. This book is unique as well in organizing and unifying the diverse design methods available.

Domain knowledge is distinct from process knowledge. Because of this independence, a successful product can result from the design process, regardless of the knowledge of the designer or the type of design problem. Even students at the freshman level could take a course using this text and learn most of the process. However, to produce any reasonably realistic design, substantial domain knowledge is required, and it is assumed throughout the book that the reader has some background in basic engineering science, materials science, manufacturing processes, and engineering economics. Thus, this book is intended for upper-level undergraduates, graduate students, and professional engineers who have never had a formal course in the mechanical design process.

The material brought together in this book evolved as the basis for a junior-level course taught at Oregon State University as a prerequisite to the capstone design course. It has been tested in capstone courses at the University of Florida, the University of Idaho, and Seattle University. Additionally, it has been taught as a graduate-level course and as an ASME and industrial short course. It has been taught by an experienced instructor as a one-quarter (10-week), four-credit course in a format allowing three hours of lecture and in-class discussion and a laboratory where the instructor worked with small groups of students. The lecture sections for undergraduate students have been as large as 80; however, lab sections are kept to 20, with all students working in three- to four-person design teams and each team responsible for a single design problem. (Although the one-quarter class is actually too short for the students to get all the way through even a simple design problem, the major points can be covered, with only iteration and refinement needed to finalize the product.) A similar format has been used with graduate students. For industrial and professional short courses, the material can be covered in three days.

ACKNOWLEDGMENTS

Many people here assisted me in this effort. Some, like the late Jack Brueggeman, were mentors in my early design years. Others, like Thomas Dietterich, John Corey, and Glenn Kramer, are current partners in my design efforts.

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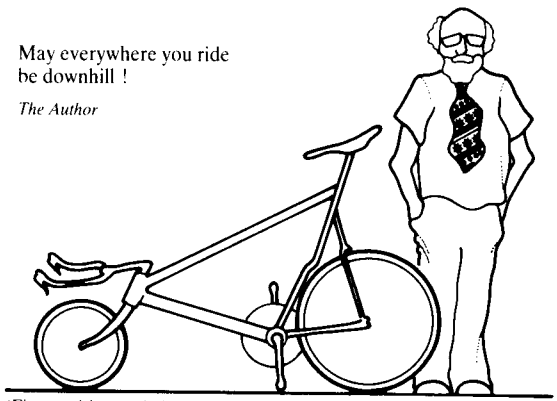
David G. Ullman



(Figure with permission of Chuck Meitle)

Remember: What you design is what you make is what you sell!

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PART I

BACKGROUND TOPICS

CHAPTER 1

INTRODUCTION TO THE MECHANICAL DESIGN PROCESS

1.1 INTRODUCTION

Beginning with a simple potter's wheel and evolving to complex consumer products and transportation systems, humans have been designing mechanical objects for nearly 5000 years. Each of these objects is the end result of a long and often difficult design process. This book is about that process.

Regardless of whether we are designing gearboxes, heat exchangers, satellites, or doorknobs, there are certain techniques that can be used during the design process to help ensure successful results. Since this book is about the *process* of mechanical design, it does not focus on the design of any one type of object but on techniques that apply to the design of all types of mechanical objects.

If humans have been designing for 5000 years and there are literally millions of mechanical objects that work and work well, then why study the design process? The answer, simply put, is that there is a continuous need for new, cost-effective, high-quality products. Further, it has been estimated that 85 percent of the problems with new products—not working as they should, taking too long to bring to market, costing too much—is the result of poor design process.

The design process is a map for how to get from the need for a specific

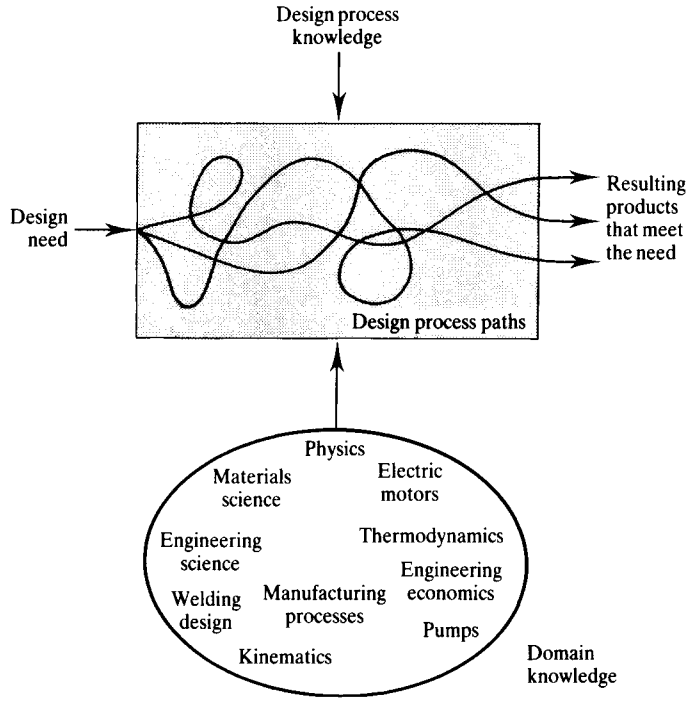

FIGURE 1.1
Knowledge used in the design process.

object to the final product. This map has some interesting features, as shown in Fig. 1.1. The route from the need to the product can be along many different paths that lead to many different products, which meet the need. In other words, there can be many different solutions to any mechanical design problem. The designer's knowledge of the process and the problem's domain determine the path. An engineer who is knowledgeable about internal combustion engine design is going to end up with a different product for a car engine than an engineer whose knowledge is focused in camera design. Similarly, an engineer with knowledge about effective design processes will generate a different product from an engineer without this knowledge.

The goal of this book is to provide a path through a design problem that best utilizes the designer's knowledge so that a high-quality product is rapidly and economically developed.

1.2 THE ORGANIZATION OF THIS BOOK

Before presenting techniques for a successful design process, we will establish the background necessary for understanding these techniques. In order to