MACHINE DESIGN

An Integrated Approach

SIXTH EDITION

Robert L. Norton

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Sixth Edition

Robert L. Norton P.E.

Milton P. Higgins II Distinguished Professor Emeritus

Worcester Polytechnic Institute

Worcester, Massachusetts

Pearson

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ABOUT THE AUTHOR

Robert L. Norton earned undergraduate degrees in both mechanical engineering and industrial technology at Northeastern University, an MS in engineering design at Tufts University, and was awarded a Doctor of Engineering (h.c.) by Worcester Polytechnic Institute (WPI). He is a registered professional engineer in Massachusetts and Florida. He has over 50 years experience in engineering design and manufacturing and over 40 years experience teaching mechanical engineering, engineering design, computer science, and related subjects at Northeastern University, Tufts University, and WPI. Norton has been on the faculty of WPI since 1981, and is currently the Milton P. Higgins II Distinguished Professor Emeritus. He is also the founder and president of Norton Associates Engineering Consultants since 1970.

At Polaroid Corporation for 10 years, he designed cameras, related mechanisms, and high-speed automated machinery. He spent three years at Jet Spray Cooler Inc., designing food-handling machinery and products. For five years he helped develop artificial-heart and noninvasive assisted-circulation devices at the Tufts New England Medical Center and Boston City Hospital. Since leaving industry to join academia in 1974, he has continued as an independent consultant on engineering projects ranging from disposable medical products to high-speed production machinery. He holds thirteen U.S. patents.

He is the author of numerous technical papers and journal articles covering kinematics, dynamics of machinery, cam design and manufacturing, computers in education, engineering education, and of the texts *Design of Machinery*, *Kinematics and Dynamics of Machinery, Machine Design: An Integrated Approach*, and the *Cam Design and Manufacturing Handbook*. He is a Life Fellow of the American Society of Mechanical Engineers and a past member of the Society of Automotive Engineers and the American Society for Engineering Education. In 2007, he was selected as a U.S. Professor of the Year by the Council for the Advancement and Support of Education (CASE) and the Carnegie Foundation for the Advancement of Teaching, who jointly present the only national awards for higher-education teaching excellence given in the United States of America.

WHAT USERS SAY ABOUT THE BOOK

Your text is the best of all the texts I have used—the balance of fundamentals and practice is especially important, and you have achieved that with aplomb!

—Professor John P. H. Steele, *Colorado School of Mines*

This book is one of the best-written on any engineering subject that I have come across. We switched to the book because we felt that the students would get a lot out of reading the text.

—Professor Ed Howard, *Milwaukee School of Engineering*

(The) writing is clear and meaningful, (and the) text is much more accessible to students because of the practical nature of (its) case studies and problem sets.

—Professor Douglas Walcerz, *York College of Pennsylvania*

I'm doing my machine design homework now, and . . . your book is the single best text I have ever used in my educational career. It is straightforward, easy to understand and has good examples.

—Josh, student, *Colorado School of Mines*

This book is dedicated to the memory of:

Donald N. Zwiep

1924–2012

Provost, Department Head, and Professor Emeritus
Worcester Polytechnic Institute

A gentleman and a leader,
without whose faith and foresight,
this book would never have been written.

PREFACE

Introduction

This text is intended for the *Design of Machine Elements* courses typically given in the junior year of most mechanical engineering curricula. The usual prerequisites are a first course in *Statics and Dynamics*, and one in *Strength of Materials*. The purpose of this book is to present the subject matter in an up-to-date manner with a strong design emphasis. The level is aimed at junior-senior mechanical engineering students. A primary goal was to write a text that is very easy to read and that students will enjoy reading despite the inherent dryness of the subject matter.

This textbook is designed to be an improvement over others currently available and to provide methods and techniques that take full advantage of computer-aided analysis. It emphasizes design and synthesis as well as analysis. Example problems, case studies, and solution techniques are spelled out in detail and are self-contained. All the illustrations are done in two colors. Short problems are provided in each chapter and, where appropriate, longer unstructured design-project assignments are given.

The book is independent of any particular computer program. Computer files for the solution of all the examples and case studies written in several different languages (*Mathcad*, *MATLAB, Excel*, and *TK Solver*) are provided on the book's website at **http://www.pearsonhighered.com/norton**. Several other programs written by the author are available from the author. These include a matrix solver (MATRIX.exe). An index of the website's content is on the website.

While this book attempts to be thorough and complete on the engineering-mechanics topics of failure theory and analysis, it also emphasizes the synthesis and design aspects of the subject to a greater degree than most other texts in print on this subject. It points out the commonality of the analytical approaches needed to design a wide variety of elements and emphasizes the use of computer-aided engineering as an approach to the design and analysis of these classes of problems. The author's approach to this course is based on over 50 years of practical experience in mechanical engineering design, both in industry and as a consultant to industry. He has taught mechanical engineering design at the university level for 40 of those years as well.

What's in the Sixth Edition?

- Twenty-one Master Lecture videos on the topics of most chapters are provided on the website. These are taken from the author's live lectures to classes at WPI. The student can watch these videos to review and enhance their understanding of the book's topics.
- Eight short videos are provided on the website in which the author demonstrates various principles of stress analysis and shows examples of common machine parts such as springs, gears, and bearings.
- Six videos that show real machinery in operation are also provided on the website.
- Over 80 problems are added with many being in SI units.
- In addition to the printed version of the text, digital e-book versions are also available. These have hotlinks to all the videos and to the downloadable content provided. There

are 37 videos. All of these are marked in the print version as well, with their URLs provided, and they can be downloaded by print-book users. A **Video Contents** is provided, and all other downloadable items are listed in the **Downloads Index**.

- The author-written programs that come with the book have been completely rewritten to improve their interface and usability, and they are now compatible with the latest operating systems and computers. Programs Linkages and DYNACAM have been completely rewritten and are much improved. Program MATRIX is updated. These computer programs undergo frequent revision to add features and enhancements. Once installed, the programs can be updated from the Start Menu. Users should occasionally check for updates.
- All the downloadable files are accessible to digital-book users through the publisher's *Mastering* website via links in the digital book. Any instructor or student who uses the print book may register on my website, **http://www.designofmachinery.com**, either as a student or instructor, and I will send them a password to access a protected site where they can download the latest versions of my computer programs, LINKAGES, DYNACAM, and MATRIX, all videos, and all files listed in the Downloads Index. Note that I personally review each of these requests for access and approve only those that are filled out completely and correctly according to the provided instructions. I require complete information and only accept university email addresses.

Philosophy

This is often the first course that mechanical engineering students see that presents them with design challenges rather than set-piece problems. Nevertheless, the type of design addressed in this course is that of *detailed design,* which is only one part of the entire design-process spectrum. In detailed design, the general concept, application, and even general shape of the required device are typically known at the outset. We are not trying to invent a new device so much as define the shape, size, and material of a particular machine element such that it will not fail under the loading and environmental conditions expected in service.

The traditional approach to the teaching of the *Elements* course has been to emphasize the design of individual machine parts, or elements, such as gears, springs, shafts, etc. One criticism that is sometimes directed at the *Elements* course (or textbook) is that it can easily become a "cookbook" collection of disparate topics that does not prepare the student to solve other types of problems not found in the recipes presented. There is a risk of this happening. It is relatively easy for the instructor (or author) to allow the course (or text) to degenerate into the mode "Well, it's Tuesday, let's design springs—on Friday, we'll do gears." If this happens, it may do the student a disservice because it doesn't necessarily develop a fundamental understanding of the practical application of the underlying theories to design problems.

However, many of the machine elements typically addressed in this course provide superb examples of the underlying theory. If viewed in that light, and if presented in a general context, they can be an excellent vehicle for the development of student understanding of complex and important engineering theories. For example, the topic of preloaded bolts is a perfect vehicle to introduce the concept of prestressing used as a foil against fatigue loading. The student may never be called upon in practice to design a preloaded bolt, but he or she may well utilize the understanding of prestressing gained from the experience. The design of helical gears to withstand time-varying loads provides an excellent vehicle to develop the student's understanding of combined stresses, Hertzian stresses, and fatigue failure. Thus the *elements* approach is a valid and defensible one as long as the approach taken in the text is sufficiently global. That is, it should not be allowed to degenerate into a collection of apparently unrelated exercises, but rather provide an integrated approach.

Another area in which the author has found existing texts (and *Machine Elements* courses) to be deficient is the lack of connection made between the dynamics of a system and the stress analysis of that system. Typically, these texts present their machine elements with (magically) predefined forces on them. The student is then shown how to determine the stresses and deflections caused by those forces. In real machine design, the forces are not always predefined and can, in large part, be due to the accelerations of the masses of the moving parts. However, the masses cannot be accurately determined until the geometry is defined and a stress analysis done to determine the strength of the assumed part. Thus, an impasse exists that is broken only by iteration, i.e., assume a part geometry and define its geometric and mass properties, calculate the dynamic loads due in part to the material and geometry of the part. Then calculate the stresses and deflections resulting from those forces, find out it fails, redesign, and repeat.

An Integrated Approach

The text is divided into two parts. The first part presents the fundamentals of stress, strain, deflection, materials properties, failure theories, fatigue phenomena, fracture mechanics, FEA, etc. These theoretical aspects are presented in similar fashion to other texts. The second part presents treatments of specific, common design elements used as examples of applications of the theory but also attempts to avoid presenting a string of disparate topics in favor of an integrated approach that ties the various topics together via *case studies*.

Most *Elements* texts contain many more topics and more content than can possibly be covered in a one-semester course. Before writing the first edition of this book, a questionnaire was sent to 200 U.S. university instructors of the *Elements* course to solicit their opinions on the relative importance and desirability of the typical set of topics in an *Elements* text. With each revision to second through fifth editions, users were again surveyed to determine what should be changed or added. The responses were analyzed and used to influence the structure and content of this book in all editions. One of the strongest desires originally expressed by the respondents was for *case studies* that present realistic design problems.

We have attempted to accomplish this goal by structuring the text around a series of ten case studies. These case studies present different aspects of the same design problem in successive chapters, for example, defining the static or dynamic loads on the device in Chapter 3, calculating the stresses due to the static loads in Chapter 4, and applying the appropriate failure theory to determine its safety factor in Chapter 5. Later chapters present more complex case studies, with more design content. The case study in Chapter 6 on fatigue design is one such example a real problem taken from the author's consulting practice. Chapter 8 presents FEA analyses of several of these case studies and compares those results to the classical solutions done in prior chapters.

The case studies provide a series of machine design projects throughout the book that contain various combinations of the elements normally dealt with in this type of text. The assemblies contain some collection of elements such as links subjected to combined axial and bending loads, column members, shafts in combined bending and torsion, gearsets under alternating loads, return springs, fasteners under fatigue loading, rolling element bearings, etc. This integrated approach has several advantages. It presents the student with a generic design problem in context rather than as a set of disparate, unrelated entities. The student can then see the interrelationships and the rationales for the design decisions that affect the individual elements. These more comprehensive case studies are in Part II of the text. The case studies in Part I are more limited in scope and directed to the engineering mechanics topics of the chapter. In addition to the case studies, each chapter has a selection of worked-out examples to reinforce particular topics.

Chapter 9, Design Case Studies, is devoted to the setup of three design case studies that are used in the following chapters to reinforce the concepts behind the design and analysis of shafts, springs, gears, fasteners, etc. Not all aspects of these design case studies are addressed as worked-out examples since another purpose is to provide material for student-project assignments. The author has used these case study topics as multi-week or term-long project assignments for groups or individual students with good success. Assigning open-ended project assignments serves to reinforce the design and analysis aspects of the course much better than set-piece homework assignments.

Problem Sets

Most of the 967 problem sets (767, or 79%) are independent within a chapter, responding to requests by users of the first edition to decouple them. The other 21% of the problem sets are built upon in succeeding chapters. These linked problems have the same dash number in each chapter and their problem number is **boldface** to indicate their commonality among chapters. For example, Problem 3-4 asks for a static force analysis of a trailer hitch; Problem 4-4 requests a stress analysis of the same hitch based on the forces calculated in Problem 3-4; Problem 5-4 asks for the static safety factor for the hitch using the stresses calculated in Problem 4-4; Problem 6-4 requests a fatigue-failure analysis of the same hitch, and Problem 7-4 requires a surface stress analysis. The same trailer hitch is used as an FEA case study in Chapter 8. Thus, the complexity of the underlying design problem is unfolded as new topics are introduced. An instructor who wishes to use this approach can assign problems with the same dash number in succeeding chapters. If one does not want to assign an earlier problem on which a later one is based, the solution manual data from the earlier problem can be provided to the students. Instructors who do not like interlinked problems can avoid them entirely and select from the 767 problems with nonbold problem numbers that are independent within their chapters.

Text Arrangement

Chapter 1 provides an introduction to the design process, problem formulation, safety factors, and units. Material properties are reviewed in Chapter 2 since even the student who has had a first course in material science or metallurgy typically has but a superficial understanding of the wide spectrum of engineering material properties needed for machine design. Chapter 3 presents a discussion of the fundamentals of kinematic linkages and cams. It also provides a review of static and dynamic loading analysis, including beam, vibration, and impact loading, and sets up a series of case studies that are used in later chapters to illustrate the stress and deflection analysis topics with some continuity.

The *Design of Machine Elements* course, at its core, is really an intermediate-level, applied stress-analysis course. Accordingly, a review of the fundamentals of stress and deflection analysis is presented in Chapter 4. Static failure theories are presented in detail in Chapter 5 since the students have typically not yet fully digested these concepts from their first stress-analysis course. Fracture-mechanics analysis for static loads is also introduced.

The *Elements* course is typically the student's first exposure to fatigue analysis since most introductory stress-analysis courses deal only with statically loaded problems. Accordingly, fatigue-failure theory is presented at length in Chapter 6 with the emphasis on stress-life approaches to high-cycle fatigue design, which is commonly used in the design of rotating machinery. Fracture-mechanics theory is further discussed with regard to crack propagation under cyclic loading. Strain-based methods for low-cycle fatigue analysis are not presented but their application and purpose are introduced to the reader and bibliographic references are provided for further study. Residual stresses are also addressed. Chapter 7 presents a thorough discussion of the phenomena of wear mechanisms, surface contact stresses, and surface fatigue.

Chapter 8 provides an introduction to Finite Element Analysis (FEA). Many instructors are using the machine elements course to introduce students to FEA as well as to instruct them in the techniques of machine design. The material presented in Chapter 8 is not intended as a substitute for education in FEA theory. That material is available in many other textbooks devoted to that subject and the student is urged to become familiar with FEA theory through coursework or self-study. Instead, Chapter 8 presents proper techniques for the application of FEA to practical machine design problems. Issues of element selection, mesh refinement, and the definition of proper boundary conditions are developed in some detail. These issues are not usually addressed in books on FEA theory. Many engineers in training today will, in their professional practice, use CAD solid modeling software and commercial finite element analysis code. It is important that they have some knowledge of the limitations and proper application of those tools. This chapter can be taken up earlier in the course if desired, especially if the students are expected to use FEA to solve assigned tasks. It is relatively independent of the other chapters. Many of various chapters' problem assignments have Solidworks models of their geometry provided on the website.

These eight chapters comprise Part I of the text and lay the analytical foundation needed for design of machine elements. They are arranged to be taken up in the order presented and build upon each other with the exception of Chapter 8 on FEA.

Part II of the text presents the design of machine elements in context as parts of a whole machine. The chapters in Part II are essentially independent of one another and can be taken (or skipped) in any order that the instructor desires (except that Chapter 12 on spur gears should be studied before Chapter 13 on helical, bevel, and worm gears). It is unlikely that all topics in the book can be covered in a one-term or one semester course. Uncovered chapters will still serve as a reference for engineers in their professional practice.

Chapter 9 presents a set of design case studies to be used as assignments and as example case studies in the following chapters and also provides a set of suggested design project assignments in addition to the detailed case studies as described above. Chapter 10 investigates shaft design using the fatigue-analysis techniques developed in Chapter 6. Chapter 11 discusses fluid-film and rolling-element bearing theory and application using the theory developed in Chapter 7. Chapter 12 gives a thorough introduction to the kinematics, design and stress analysis of spur gears using the latest AGMA recommended procedures. Chapter 13 extends gear design to helical, bevel, and worm gearing. Chapter 14 covers spring design including helical compression, extension and torsion springs, as well as a thorough treatment of Belleville springs. Chapter 15 deals with screws and fasteners including power screws and preloaded fasteners. Chapter 16 presents an up-to-date treatment of the design of weldments for both static and dynamic loading. Chapter 17 presents an introduction to the design and specification of disk and drum clutches and brakes. The appendices contain material-strength data, beam tables, and stress-concentration factors, as well as answers to selected problems.

Supplements

A **Solutions Manual** is available to instructors from the publisher and **PowerPoint slides** of all figures and tables in the text are available on the publisher's website (password protected) at:

http://www.pearsonhighered.com/

To download these resources, choose the **Instructor Support** tab to register as an instructor and follow instructions on the site to obtain the resources provided. Mathcad files for all the problem solutions are available with the solutions manual. This computerized approach to problem solutions has significant advantages to the instructor who can easily change any assigned problem's data and instantly solve it. Thus, an essentially infinite supply of problem sets is available, going far beyond those defined in the text. The instructor also can easily prepare and solve exam problems by changing data in the supplied files.

As errata are discovered they will be posted on the author's personal website at:

http://www.designofmachinery.com/MD/errata.html

Professors who adopt the book may register at the author's personal website to obtain additional information relevant to the subject (syllabi, master lectures, project assignments, etc.) and the text and to download web content and updated software (password protected). Go to:

http://designofmachinery.com/books/machine-design/professors-using-our-books-md/

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http://designofmachinery.com/books/machine-design/machine-design-6th-ed-for-students-login/

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Two former and the current Prentice Hall editors deserve special mention for their efforts in developing this book: Doug Humphrey, who wouldn't take no for an answer in persuading me to write it and Bill Stenquist, who usually said yes to my requests and expertly shepherded the book through to completion in its first edition. Norrin Dias' support has helped marshall the sixth edition into print.

Since the book's first printing in 1995, several users have kindly pointed out errors and suggested improvements. My thanks go to Professors R. Boudreau of U. Moncton, Canada, V. Glozman of Cal Poly Pomona, John Steele of Colorado School of Mines, Burford J. Furman of San Jose State University, and Michael Ward of California State University, Chico.

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Finally, Nancy Norton, my infinitely patient wife for the past fifty-nine years, deserves renewed kudos for her unfailing support and encouragement during many summers of "book widowhood." I could not have done it without her.

Every effort has been made to eliminate errors from this text. Any that remain are the author's responsibility. He will greatly appreciate being informed of any errors that still remain so they can be corrected in future printings. An e-mail to **norton@wpi.edu** will be sufficient.

Robert L. Norton
Mattapoisett, MA.
June 1, 2019

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VIDEO CONTENTS

The Sixth Edition has a collection of **Master Lecture Videos** and **Tutorials** made by the author over a 31-year period while teaching at Worcester Polytechnic Institute. The lectures were recorded in a classroom in front of students in 2011/2012. Tutorials were done in a recording studio and were intended as supplements to class lectures. There are 37 instructional videos in total. One is a short introduction to the master lecture series and 20 are "50-minute" lectures. Eight are short tutorials and eight are demonstrations of machinery. The run times of all videos are noted in the tables.

The sixth edition is available both as a print book and as digital media. The digital, e-book versions have active links that allow these videos to be run while reading the book. The print edition notes the names and URLs of all the videos in the text at their links.

In addition to the lecture videos, all the digital content that was with the fifth and earlier editions is still available as downloads, including the author-written programs **Linkages, Dynacam**, and **Matrix**. An index of all the non-video downloadable files is in the **Downloads Index**. In the digital e-book versions, these are hotlinked to the text. The URL of each video is also provided for print-book readers to download them.

Any instructor or student who uses the book may register on my website, http://www.designofmachinery.com, either as a student or instructor, and I will send them a password to access a protected site where they can download the latest versions of my computer programs, **Linkages, Dynacam**, and **Matrix**. They can also download the 33 videos and all the files listed in the **Downloads Index**. Note that I personally review each of these requests for access and will approve only those that are filled out completely and correctly according to the provided instructions. I require complete information and only accept university email addresses.

LECTURE VIDEOS

(Concatenate this URL with any filename below to run a video)

Chapter	Lecture	Topic	http://www.designofmachinery.com/MD/	Run Time
1	1	Introduction	01_Introduction.mp4	03:30
4	2	Stress Review	02_Stress_Review.mp4	53:40
4	3	Stress Distribution	03_Stress_Distribution.mp4	50:52
4	4	Combined Stress, Stress Concentration, Columns	04_Combined_stress_stress_concentration_columns.mp4	54:11
5	5	Ductile Failure Theory	05_Ductile_Failure_Theory.mp4	46:02
5	6	Brittle Failure Theory	06_Brittle_Failure_Theory.mp4	51:02
6	7	Fatigue Failure Theory	07_Fatigue_Failure_Theory.mp4	55:49
6	8	Fully Reversed Loads	08_Fully_Reversed_Loads.mp4	52:59
6	9	Fluctuating Loads	09_Fluctuating_Loads.mp4	54:14
10	10	Shaft Design I	10_Shaft_Design_I.mp4	44:44
10	11	Shaft Design II	11_Shaft_Design_II.mp4	47:20
7	12	Wear and Surface Fatigue	12_Wear_and_Surface_Fatigue.mp4	52:25
12	13	Spur Gear Design I	13_Spur_Gear_Design_I.mp4	51:31
12	14	Spur Gear Design II	14_Spur_Gear_Design_II.mp4	50:37
14	15	Spring Design I	15_Spring_Design_I.mp4	52:20
14	16	Spring Design II	16_Spring_Design_II.mp4	47:46
11	17	Bearings and Lubrication	17_Bearings_and_Lubrication.mp4	50:07
11	18	Rolling Element Bearings	18_Rolling_Element_Bearings.mp4	46:54
15	19	Power Screws and Fasteners	19_Power_Screws_and_Fasteners.mp4	44:42
15	20	Preloaded Fasteners	20_Preloaded_Fasteners.mp4	48:22
8	21	Finite Element Analysis	21_Finite_Element_Analysis.mp4	52:28

TUTORIAL VIDEOS

(Concatenate this URL with any filename below to run a video)

Topic	http://www.designofmachinery.com/MD/	Run Time
Bearings	Bearings.mp4	09:11
Bending Stress	Bending_Stress.mp4	05:57
Columns	Columns.mp4	01:52
Failure Modes	Failure_Modes.mp4	09:41
Gears	Gears.mp4	22:07
Springs	Springs.mp4	20:06
Stress Cube	Stress_Cube.mp4	05:04
Torsion	Torsion.mp4	03:13

DEMONSTRATION VIDEOS

(Concatenate this URL with any filename below to run a video)

Topic	http://www.designofmachinery.com/MD/	Run Time
Boot Testing Machine	Boot_Tester.mp4	19:02
Bottle Printing Machine	Bottle_Printing_Machine.mp4	09:49
Cam Machine	Cam_Machine.mp4	21:28
Fourbar Machine	Fourbar_Machine.mp4	35:38
Pick and Place Mechanism	Pick_and_Place_Mechanism.mp4	36:35
Spring Manufacturing Machinery	Spring_Manufacturing.mp4	12:23
Spring Surge and Spring Failure	Fatigue_Failure.mp4	03:46
Vibration Testing	Vibration_Testing.mp4	05:51

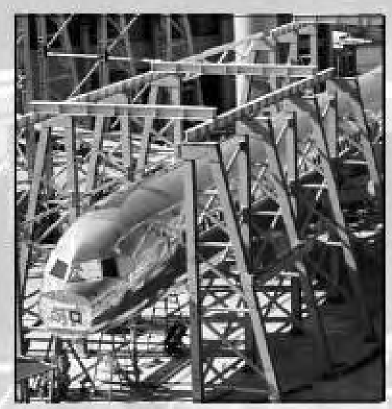
Note that you can download a PDF file containing hyperlinks to all the video content listed in the above tables. This allows print-book readers to easily access the videos without having to type in each URL as noted in the tables. Download the file:

http://www.designofmachinery.com/MD/Video_Links_for_Machine_Design_6ed.pdf

Part I

FUNDAMENTALS

1



INTRODUCTION TO DESIGN

Learning without thought is labor lost;
thought without learning is perilous.
CONFUCIUS, 6TH CENTURY B.C.

1.1 DESIGN *View the introductory video* (03:30)[†]

What is design? Wallpaper is designed. You may be wearing "designer" clothes. Automobiles are "designed" in terms of their external appearance. The term *design* clearly encompasses a wide range of meaning. In the above examples, design refers primarily to the object's aesthetic appearance. In the case of the automobile, all of its other aspects also involve design. Its mechanical internals (engine, brakes, suspension, etc.) must be designed, more likely by engineers than by artists, though even the engineer gets to exhibit some artistry when designing machinery.

The word design is from the Latin word *designare* meaning *to designate, or mark out*. Design means many things. It can refer to the design of an artistic work or the appearance of a product. We are more concerned here with engineering design than with artistic design. **Engineering design** can be defined as *The process of applying the various techniques and scientific principles for the purpose of defining a device, a process, or a system in sufficient detail to permit its realization.*

Machine Design

This text is concerned with one aspect of engineering design—**machine design**. Machine design deals with the creation of machinery that works safely, reliably, and well. A **machine** can be defined as: *A system of elements arranged to transmit motion and energy in a predetermined and controlled fashion*, or even more simply as: *A system to control force and motion.*

[†] http://www.designofmachinery.com/MD/01_Introduction.mp4

Title-page photograph courtesy of Boeing Commercial Airplane Co. Inc., Seattle, Wash.

The notion of **useful work** is basic to a machine's function, as there is almost always some energy transfer involved. The mention of **forces** and **motion** is also critical to our concerns, as, in converting energy from one form to another, machines **create motion** and **develop forces**. It is the engineer's task to define and calculate those motions, forces, and changes in energy in order to determine the sizes, shapes, and materials needed for each of the interrelated parts in the machine. This is the essence of **machine design**.

While one must, of necessity, design a machine one part at a time, it is crucial to recognize that each part's function and performance (and thus its design) are dependent on many other interrelated parts within the same machine. Thus, we are going to attempt to "design the whole machine" here, rather than simply designing individual elements in isolation from one another. To do this we must draw upon a common body of engineering knowledge encountered in previous courses, e.g., statics, dynamics, mechanics of materials (stress analysis), and material properties. Brief reviews and examples of these topics are included in the early chapters of this book.

The ultimate goal in machine design is to size and shape the parts (machine elements) and choose appropriate materials and manufacturing processes so that the resulting machine can be expected to perform its intended function without failure. This requires that the engineer be able to calculate and predict the mode and conditions of failure for each element and then design it to prevent that failure. This in turn requires that a **stress and deflection analysis** be done for each part. Since stresses are a function of the applied and inertial loads, and of the part's geometry, an analysis of the forces, moments, torques, and the dynamics of the system must be done before the stresses and deflections can be completely calculated.

If the "machine" in question has no moving parts, then the design task becomes much simpler, because only a static force analysis is required. But if the machine has no moving parts, it is not much of a machine (and doesn't meet the definition above); it is then a **structure**. Structures also need to be designed against failure, and, in fact, large external structures (bridges, buildings, etc.) are also subjected to dynamic loads from wind, earthquakes, traffic, etc., and thus must also be designed for these conditions. Structural dynamics is an interesting subject but one which we will not address in this text. We will concern ourselves with the problems associated with machines that move. If the machine's motions are very slow and the accelerations negligible, then a static force analysis will suffice. But if the machine has significant accelerations within it, then a dynamic force analysis is needed and the accelerating parts become "victims of their own mass."

In a static structure, such as a building's floor, designed to support a particular weight, the safety factor of the structure can be increased by adding appropriately distributed material to its structural parts. Though it will be heavier (more "dead" weight), if properly designed it may nevertheless carry more "live" weight (payload) than it did before, still without failure. In a dynamic machine, adding weight (mass) to moving parts may have the opposite effect, reducing the machine's safety factor, its allowable speed, or its payload capacity. This is because some of the loading that creates stresses in the moving parts is due to the inertial forces predicted by **Newton's second law**, $F = ma$. Since the accelerations of the moving parts in the machine are dictated by its kinematic design and by its running speed, adding mass to moving parts will increase the inertial loads on those same parts unless their kinematic accelerations are reduced by slowing its operation. Even though the added mass may increase the strength of the part, that benefit may be reduced or cancelled by the resultant increases in inertial forces.

Iteration

Thus, we face a dilemma at the initial stages of machine design. Generally, before reaching the stage of sizing the parts, the kinematic motions of the machine will have already been defined. External forces provided by the "outside world" on the machine are also often known. Note that in some cases, the external loads on the machine will be very difficult to predict—for example, the loads on a moving automobile. The designer cannot predict with accuracy what environmental loads the user will subject the machine to (potholes, hard cornering, etc.). In such cases, statistical analysis of empirical data gathered from actual testing can provide some information for design purposes.

What remain to be defined are the inertial forces that will be generated by the known kinematic accelerations acting on the as yet undefined masses of the moving parts. The dilemma can be resolved only by **iteration**, which means *to repeat, or to return to a previous state*. We must assume some trial configuration for each part, use the mass properties (mass, *CG* location, and mass moment of inertia) of that trial configuration in a dynamic force analysis to determine the forces, moments, and torques acting on the part, and then use the cross-sectional geometry of the trial design to calculate the resulting stresses. In general, accurately determining all the loads on a machine is the most difficult task in the design process. If the loads are known, the stresses can be calculated.

Most likely, on the first trial, we will find that our design fails because the materials cannot stand the levels of stress presented. We must then redesign the parts (iterate) by changing shapes, sizes, materials, manufacturing processes, or other factors in order to reach an acceptable design. It is generally not possible to achieve a successful result without making several iterations through this design process. Note also that a change to the mass of one part will also affect the forces applied to parts connected to it and thus require their redesign also. It is truly the design of **interrelated parts**.

1.2 A DESIGN PROCESS*

The process of design is essentially an exercise in applied creativity. Various "design processes" have been defined to help organize the attack upon the "unstructured problem," i.e., one for which the problem definition is vague and for which many possible solutions exist. Some of these design process definitions contain only a few steps and others a detailed list of 25 steps. One version of a design process is shown in Table 1-1, which lists ten steps.[2] The initial step, **Identification of Need**, usually consists of an ill-defined and vague problem statement. The development of **Background Research** information (step 2) is necessary to fully define and understand the problem, after which it is possible to restate the **Goal** (step 3) in a more reasonable and realistic way than in the original problem statement.

Step 4 calls for the creation of a detailed set of **Task Specifications** which bound the problem and limit its scope. The **Synthesis** step (5) is one in which as many alternative design approaches as possible are sought, usually without regard (at this stage) for their value or quality. This is also sometimes called the **Ideation and Invention** step, in which the largest possible number of creative solutions are generated.

In step 6, the possible solutions from the previous step are **Analyzed** and either accepted, rejected, or modified. The most promising solution is **Selected** at step 7. Once an acceptable design is selected, the **Detailed Design** (step 8) can be done, in which all the loose ends are tied up, complete engineering drawings made, vendors identified,

* Adapted from Norton, *Design of Machinery*, 5ed. McGraw-Hill, New York, 2012, with the publisher's permission.

Table 1-1 A Design Process

1	Identification of need
2	Background research
3	Goal statement
4	Task specifications
5	Synthesis
6	Analysis
7	Selection
8	Detailed design
9	Prototyping and testing
10	Production

manufacturing specifications defined, etc. The actual construction of the working design is first done as a **Prototype** in step 9 and finally in quantity in **Production** at step 10. A more complete discussion of this design process can be found in reference 2, and a number of references on the topics of creativity and design are provided in the bibliography at the end of this chapter.

The above description may give an erroneous impression that this process can be accomplished in a linear fashion as listed. On the contrary, **iteration is required within the entire process**, moving from any step back to any previous step, in all possible combinations, and doing this repeatedly. The best ideas generated at step 5 will invariably be discovered to be flawed when later analyzed. Thus, a return to at least the Ideation step will be necessary in order to generate more solutions. Perhaps a return to the Background Research phase may be necessary to gather more information. The Task Specifications may need to be revised if it turns out that they were unrealistic. In other words, anything is "fair game" in the design process, including a redefinition of the problem, if necessary. One cannot design in a linear fashion. It's three steps forward and two (or more) back, until you finally emerge with a working solution.

Theoretically, we could continue this iteration on a given design problem forever, continually creating small improvements. Inevitably, the incremental gains in function or reductions in cost will tend toward zero with time. At some point, we must declare the design "good enough" and ship it. Often someone else (most likely, the boss) will snatch it from our grasp and ship it over our protests that it isn't yet "perfect." Machines that have been around a long time and that have been improved by many designers reach a level of "perfection" that makes them difficult to improve upon. One example is the ordinary bicycle. Though inventors continue to attempt to improve this machine, the basic design has become fairly static after more than a century of development.

In machine design, the early design-process steps usually involve the **Type Synthesis** of suitable kinematic configurations, which can provide the necessary motions. Type synthesis involves the choice of the *type of mechanism best suited to the problem.* This is a difficult task for the student, as it requires some experience and knowledge of the various types of mechanisms that exist and that might be feasible from a performance and manufacturing standpoint. As an example, assume that the task is to design a device to track the constant-speed, straight-line motion of a part on a conveyor belt and attach a second part to it as it passes by. This has to be done with good accuracy and repeatability and must be reliable and inexpensive. You might not be aware that this task could be accomplished by any of the following devices:

- a straight-line linkage
- a cam and follower
- an air cylinder
- a hydraulic cylinder
- a robot
- a solenoid

Each of these solutions, while possible, may not be optimal or even practical. Each has good and bad points. The straight-line linkage is large and may have undesirable accelerations; the cam and follower is expensive but is accurate and repeatable. The air cylinder is inexpensive but noisy and unreliable. The hydraulic cylinder and the robot are more expensive. The inexpensive solenoid has high impact loads and velocities. So, the choice of device type can have a big effect on design quality. A bad choice at the type-synthesis stage can create major problems later on. The design might have to be changed after completion at great expense. Design is essentially an exercise in trade-offs. There is usually no clear-cut solution to a real engineering design problem.

Once the type of required mechanism is defined, its detailed kinematics must be synthesized and analyzed. The motions of all moving parts and their time derivatives through acceleration must be calculated in order to be able to determine the dynamic forces on the system. (See reference 2 for more information on this aspect of machine design.)

In the context of machine design addressed in this text, we will not exercise the entire design process as described in Table 1-1. Rather, we will propose examples, problems, and case studies that already have had steps 1–4 defined. The type synthesis and kinematic analysis will already be done, or at least set up, and the problems will be structured to that degree. The tasks remaining will largely involve steps 5 through 8, with a concentration on **synthesis** (step 5) and **analysis** (step 6).

Synthesis and analysis are the "two faces" of machine design, like two sides of the same coin. **Synthesis** means *to put together* and **analysis** means *to decompose, to take apart, to resolve into its constituent parts.* Thus, they are opposites, but they are symbiotic. We cannot take apart "nothing," thus we must first synthesize something in order to analyze it. When we analyze it, we will probably find it lacking, requiring further synthesis, and then further analysis *ad nauseam*, finally iterating to a better solution. You will need to draw heavily upon your understanding of statics, dynamics, and mechanics of materials to accomplish this.

1.3 PROBLEM FORMULATION AND CALCULATION

It is extremely important for every engineer to develop good and careful computational habits. Solving complicated problems requires an organized approach. Design problems also require good record-keeping and documentation habits in order to record the many assumptions and design decisions made along the way so that the designer's thought process can be later reconstructed if redesign is necessary.

A suggested procedure for the designer is shown in Table 1-2, which lists a set of subtasks appropriate to most machine-design problems of this type. These steps should be documented for each problem in a neat fashion, preferably in a bound notebook in order to maintain their chronological order.*

* If there is a possibility of a patentable invention resulting from the design, then the notebook should be permanently bound (not loose-leaf), and its pages should be consecutively numbered, dated, and witnessed by someone who understands the technical content.

Definition Stage

In your design notebook, first **Define the Problem** clearly in a concise statement. The "**givens**" for the particular task should be clearly listed, followed by a record of the **assumptions** made by the designer about the problem. Assumptions expand upon the given (known) information to further constrain the problem. For example, one might assume the effects of friction to be negligible in a particular case, or assume that the weight of the part can be ignored because it will be small compared to the applied or dynamic loads expected.

Preliminary Design Stage

Once the general constraints are defined, some **Preliminary Design Decisions** must be made in order to proceed. The reasons and justifications for these decisions should be documented. For example, we might decide to try a solid, rectangular cross section for a connecting link and choose aluminum as a trial material. On the other hand, if we recognized from our understanding of the problem that this link would be subjected to significant accelerations of a time-varying nature that would repeat for millions of cycles, a better design decision might be to use a hollow or I-beam section in order to reduce its mass and also to choose steel for its infinite fatigue life. Thus, these design decisions can have significant effect on the results and will often have to be changed or abandoned as we iterate through the design process. It has often been noted that 90% of a design's characteristics may be determined in the first 10% of the total project time, during which these preliminary design decisions are made. If they are bad decisions, it may not be possible to save the bad design through later modifications without essentially starting over. The preliminary design concept should be documented at this stage with clearly drawn and labeled **Design Sketches** that will be understandable to another engineer or even to oneself after some time has passed.

Detailed Design Stage

With a tentative design direction established we can create one or more **engineering** (mathematical) **models** of the element or system in order to analyze it. These models will usually include a loading model consisting of free-body diagrams which show all forces, moments, and torques on the element or system and the appropriate equations for their calculation. Models of the stress and deflection states expected at locations of anticipated failure are then defined with appropriate stress and deflection equations.

Analysis of the design is then done using these models and the safety or failure of the design determined. The results are **evaluated** in conjunction with the properties of the chosen **engineering materials** and a decision made whether to proceed with this design or iterate to a better solution by returning to an earlier step of the process.

Table 1-2 Problem Formulation and Calculation

1	Define the problem	Definition stage
2	State the givens	
3	Make appropriate assumptions	
4	Preliminary design decisions	Preliminary design stage
5	Design sketches	
6	Mathematical models	Detailed design stage
7	Analysis of the design	
8	Evaluation	
9	Document results	Documentation stage

Documentation Stage

Once sufficient iteration through this process provides satisfactory results, the **documentation** of the element's or system's design should be completed in the form of detailed engineering drawings, material and manufacturing specifications, etc. If properly approached, a great deal of the documentation task can be accomplished concurrent with the earlier stages simply by keeping accurate and neat records of all assumptions, computations, and design decisions made throughout the process.

1.4 THE ENGINEERING MODEL

The success of any design is highly dependent on the validity and appropriateness of the engineering models used to predict and analyze its behavior in advance of building any hardware. Creating a useful engineering model of a design is probably the most difficult and challenging part of the whole process. Its success depends a great deal on experience as well as skill. Most important is a thorough understanding of the first principles and fundamentals of engineering. The engineering model that we are describing here is an amorphous thing that may consist of some sketches of the geometric configuration and some equations that describe its behavior. It is a mathematical model that describes the physical behavior of the system. This engineering model invariably requires the use of computers to exercise it. Using computer tools for analyzing engineering models is discussed in the next section. A physical model or prototype usually comes later in the process and is needed to prove the validity of the engineering model through experiments.

Estimation and First-Order Analysis

The value of making even very simplistic engineering models of your preliminary designs cannot be overemphasized. Often, at the outset of a design, the problem is so loosely and poorly defined that it is difficult to develop a comprehensive and thorough model in the form of equations that fully describe the system. The engineering student is used to problems that are fully structured, of a form such as "*Given A, B, and C, find D*." If one can identify the appropriate equations (model) to apply to such a problem, it is relatively easy to determine an answer (which might even match the one in the back of the book).