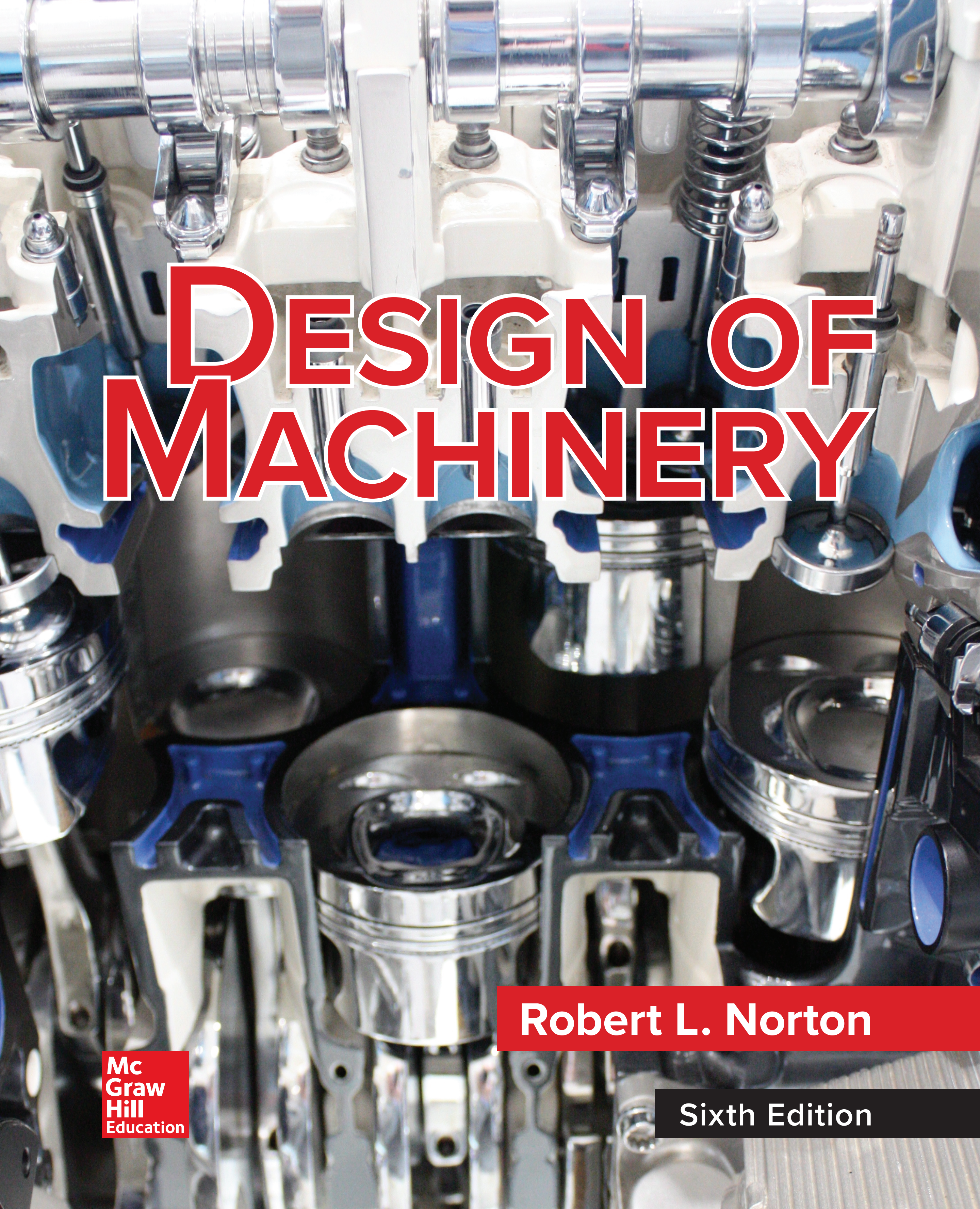

DESIGN OF MACHINERY

Robert L. Norton

Sixth Edition

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DESIGN OF MACHINERY

AN INTRODUCTION TO THE SYNTHESIS AND ANALYSIS OF MECHANISMS AND MACHINES

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DESIGN OF MACHINERY

An Introduction to the Synthesis and Analysis of Mechanisms and Machines

Sixth Edition

Robert L. Norton

Milton P. Higgins II Distinguished Professor Emeritus

Worcester Polytechnic Institute

Worcester, Massachusetts

Mc Graw Hill Education

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ABOUT THE AUTHOR

Robert L. Norton earned undergraduate degrees in both mechanical engineering and industrial technology at Northeastern University and an MS in engineering design at Tufts University. He was awarded a Dr. Eng. (h.c.) by WPI in 2012. He is a registered professional engineer in Massachusetts and Florida. He has extensive industrial experience in engineering design and manufacturing and many years' experience teaching mechanical engineering, engineering design, computer science, and related subjects at Northeastern University, Tufts University, and Worcester Polytechnic Institute.

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 (counterpulsation) devices at the Tufts New England Medical Center and Boston City Hospital. Since leaving industry to join academia, he has continued as an independent consultant on engineering projects ranging from disposable medical products to high-speed production machinery. He holds 13 U.S. patents.

Norton has been on the faculty of Worcester Polytechnic Institute since 1981 and is currently Milton Prince Higgins II Distinguished Professor Emeritus in the mechanical engineering department. He taught undergraduate and graduate courses in mechanical engineering with an emphasis on design, kinematics, vibrations, and dynamics of machinery for 31 years at WPI before retiring from active teaching.

He is the author of numerous technical papers and journal articles covering kinematics, dynamics of machinery, cam design and manufacturing, computers in education, and engineering education and of the texts *Machine Design: An Integrated Approach, 6ed* and the *Cam Design and Manufacturing Handbook, 2ed*. He is a Fellow and life member of the American Society of Mechanical Engineers and a past member of the Society of Automotive Engineers. In 2007, he was chosen as *U. S. Professor of the Year* for the State of Massachusetts 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 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*

We picked your book (years ago) because it was (and still is) the most accessible undergraduate presentation of the material I have found; although clearly theoretically based (and not afraid of the math!), you have a style and method that brings the material alive to students.

—Professor Michael Keefe, *University of Delaware*

As an instructor who has been using Design of Machinery in my classes for over 12 years, I've been especially impressed throughout by Professor Norton's care and attention in support of its users.

—Professor John Lee, *San Diego State University*

This book is dedicated to the memory of my father,

Harry J. Norton, Sr.

who sparked a young boy's interest in engineering;

to the memory of my mother,

Kathryn T. Norton

who made it all possible;

to my wife,

Nancy Norton

who provides unflagging patience and support;

and to my children,

Robert, Mary, and Thomas,

who make it all worthwhile.

PREFACE

to the Sixth Edition

The sixth edition is an evolutionary improvement over the fifth and earlier editions. See the updated *Preface to the First Edition* (overleaf) for more detailed information on the book's purpose and organization. The principal changes in this edition are:

- 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 188 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**.
- Over 50 new problem assignments have been added. The problem figures are included as downloadable PDF files so that students can easily print hard copies on which to work the solutions.
- 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. The programs FOURBAR, FIVEBAR, SIXBAR, SLIDER, and ENGINE have been combined in a new program called LINKAGES that does everything those programs collectively did with new features added. Program DYNACAM also has been completely rewritten and is much improved. Program MATRIX is updated. These computer programs undergo frequent revision to add features and enhancements. Professors who adopt the book for a course and students using the print book may register to download the latest student versions of these programs from: http://www.designofmachinery.com. Click on the *Student* or *Professor* link.
- The *Working Model* program is needed to run the Working Model files included with this text. Some universities have site licenses for this program on their lab computers. The supplier, *Design Simulation Technologies,* offers student licenses for one-semester or one-year periods at moderate cost. These are available at http://www.design-simulation.com/Purchase/studentproducts.php.
- Many small improvements have been made to the discussion of a variety of topics in many chapters, based largely on user feedback, and all known errors have been corrected.

The extensive DVD content that was introduced in the Fifth Edition is now downloadable from a website. These downloads include:

- The entire *Hrones and Nelson Atlas of Coupler Curves* and the *Zhang et al Atlas of Geared Fivebar Coupler Curves*.
- Wang's *Mechanism Simulation in a Multimedia Environment* contains 105 Working Model (WM) files based on the book's figures with AVI files and 19 Matlab® models for kinematic analysis and animation. The AVI files are linked to their figures in the e-books.
- Videos of two "virtual laboratories" that replicate labs created by the author at WPI are provided. These include demonstrations of the lab machines used and spreadsheet files of the acceleration and force data taken during the experiments. The intent is to allow students at other schools to do these exercises as virtual laboratories.

- A series of 34 *Master Lecture Videos* by the author that cover most of the topics in the book as well as 39 shorter "snippets" from these lectures are woven into the chapters. Seven *Demonstration Videos* are also provided. These were recorded over the author's thirty-one years of teaching these subjects at WPI and are listed in the **Video Contents**.

All the downloadable files are accessible to digital-book users through the publisher's 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.

ACKNOWLEDGMENTS The sources of photographs and other nonoriginal art used in the text are acknowledged in the captions and opposite the title page, but the author would also like to express his thanks for the cooperation of all those individuals and companies who generously made these items available. The author is indebted to, and would like to thank, a number of users who kindly notified him of errors or suggested improvements in all editions since the first. These include: Professors *Chad O'Neal* of Louisiana Tech, *Bram Demeulenaere* of Leuven University, *Eben Cobb* of WPI, *Diego Galuzzi* of University of Buenos Aires, *John R. Hall* of WPI, *Shafik Iskander* of U. Tennessee, *Richard Jakubek* of RPI, *Cheong Gill-Jeong* of Wonkwang University, Korea, *Swami Karunamoorthy* of St. Louis University, *Pierre Larochelle* of Florida Tech, *Scott Openshaw* of Iowa State, *Francis H. Raven* of Notre Dame, *Arnold E. Sikkema* of Dordt College, and *Donald A. Smith* of U. Wyoming.

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The author would like to express his appreciation to Professor *Sid Wang* of NCAT and his students for their efforts in creating the *Working Model* and *Matlab* files. Professor *Thomas A. Cook*, Mercer University (Emeritus), provided most of the new problem sets as well as their solutions in his impressive and voluminous solutions manual and its accompanying *Mathcad*® solution files. The author is most grateful for Dr. Cook's valuable contributions. Most of all, the author again thanks his infinitely patient wife, Nancy, who has provided unflagging support to him in all his endeavors for the past fifty-eight years.

If you find any errors or have comments or suggestions for improvement, please email the author at norton@wpi.edu. Errata as discovered, and other book information, will be posted on the author's web site at *http://www.designofmachinery.com*.

Robert L. Norton
Mattapoisett, Mass.
August, 2018

PREFACE

to the First Edition

When I hear, I forget
When I see, I remember
When I do, I understand
ANCIENT CHINESE PROVERB

This text is intended for the kinematics and dynamics of machinery topics which are often given as a single course, or two-course sequence, in the junior year of most mechanical engineering programs. The usual prerequisites are first courses in statics, dynamics, and calculus. Usually, the first semester, or portion, is devoted to kinematics and the second to dynamics of machinery. These courses are ideal vehicles for introducing the mechanical engineering student to the process of design, since mechanisms tend to be intuitive for the typical mechanical engineering student to visualize and create.

While this text attempts to be thorough and complete on the topics of analysis, it also emphasizes the synthesis and design aspects of the subject to a greater degree than most texts in print on these subjects. Also, it emphasizes the use of computer-aided engineering as an approach to the design and analysis of this class of problems by providing software that can enhance student understanding. While the mathematical level of this text is aimed at second- or third-year university students, it is presented *de novo* and should be understandable to the technical school student as well.

Part I of this text is suitable for a one-semester or one-term course in kinematics. Part II is suitable for a one-semester or one-term course in dynamics of machinery. Alternatively, both topic areas can be covered in one semester with less emphasis on some of the topics covered in the text.

The writing and style of presentation in the text are designed to be clear, informal, and easy to read. Many example problems and solution techniques are presented and spelled out in detail, both verbally and graphically. All the illustrations are done with computer-drawing or drafting programs. Some scanned photographic images are also included. The entire text, including equations and artwork, is printed directly from the author's PDF files by laser typesetting for maximum clarity and quality. Many suggested readings are provided in the bibliography. Short problems and, where appropriate, many longer, unstructured design project assignments are provided at the ends of chapters. These projects provide an opportunity for the students *to do and understand.*

The author's approach to these courses and this text is based on over 40 years' experience in mechanical engineering design, both in industry and as a consultant. He has taught these subjects since 1967, both in evening school to practicing engineers and in day school to younger students. His approach to the course has evolved a great deal in that time, from a traditional approach, emphasizing graphical analysis of many structured problems, through emphasis on algebraic methods as computers became available, through requiring students to write their own computer programs, to the current state described above.

The one constant throughout has been the attempt to convey the art of the design process to the students in order to prepare them to cope with *real* engineering problems in practice. Thus, the author has always promoted design within these courses. Only recently, however, has technology provided a means to more effectively accomplish this goal, in the form of the graphics microcomputer. This text attempts to be an improvement over those currently available by providing up-to-date methods and techniques for analysis and synthesis that take full advantage of the graphics microcomputer, and by emphasizing design as well as analysis. The text also provides a more complete, modern, and thorough treatment of cam design than any existing texts in print on the subject.

The author has written three interactive, student-friendly computer programs for the design and analysis of mechanisms and machines. These programs are designed to enhance the student's understanding of the basic concepts in these courses while simultaneously allowing more comprehensive and realistic problem and project assignments to be done in the limited time available than could ever be done with manual solution techniques, whether graphical or algebraic. Unstructured, realistic design problems which have many valid solutions are assigned. Synthesis and analysis are emphasized equally. The analysis methods presented are up to date, using vector equations and matrix techniques wherever applicable. Manual graphical analysis methods are deemphasized. The graphics output from the computer programs allows the student to see the results of variation of parameters rapidly and accurately and reinforces learning.

These computer programs are distributed with this book, and can be run on any Windows NT/2000/XP/Vista/Windows7/8/10 capable computer. Program LINKAGES analyzes the kinematics and dynamics of fourbar, geared fivebar, sixbar, and fourbar slider linkages. It also will synthesize fourbar linkages for two and three positions. LINKAGES also analyzes the slider-crank linkage as used in the internal combustion engine and provides a complete dynamic analysis of single- and multicylinder engine inline, V, and W configurations, allowing the mechanical dynamic design of engines to be done. DYNACAM allows the design and dynamic analysis of cam-follower systems. MATRIX is a general-purpose linear equation system solver. These are student editions of professional programs that are written by the author and that he provides to companies the world over.

All these programs, except MATRIX, provide dynamic, graphical animation of the designed devices. The reader is strongly urged to make use of these programs in order to investigate the results of variation of parameters in these kinematic devices. The programs are designed to enhance and augment the text rather than be a substitute for it. The converse is also true. Many solutions to the book's examples and to the problem sets are downloadable as files to be opened in these programs. Most of these solutions can be animated on the computer screen for a better demonstration of the concept than is possible on the printed page. The instructor and students are both encouraged to take advantage of

The author's intention is that synthesis topics be introduced first to allow the students to work on some simple design tasks early in the term while still mastering the analysis topics. Though this is not the "traditional" approach to the teaching of this material, the author believes that it is a superior method to that of initial concentration on detailed analysis of mechanisms for which the student has no concept of origin or purpose.

Chapters 1 and 2 are introductory. Those instructors wishing to teach analysis before synthesis can leave Chapters 3 and 5 on linkage synthesis for later consumption. Chapters 4, 6, and 7 on position, velocity, and acceleration analysis are sequential and build upon each other. In fact, some of the problem sets are common among these three chapters so that students can use their position solutions to find velocities and then later use both to find the accelerations in the same linkages. Chapter 8 on cams is more extensive and complete than that of other kinematics texts and takes a design approach. Chapter 9 on gear trains is introductory. The dynamic force treatment in Part II uses matrix methods for the solution of the system simultaneous equations. Graphical force analysis is not emphasized. Chapter 10 presents an introduction to dynamic systems modeling. Chapter 11 deals with force analysis of linkages. Balancing of rotating machinery and linkages is covered in Chapter 12. Chapters 13 and 14 use the internal combustion engine as an example to pull together many dynamic concepts in a design context. Chapter 15 presents an introduction to dynamic systems modeling and uses the cam-follower system as the example. Chapter 16 describes servo- and cam-driven linkages. Chapters 3, 8, 11, 13, and 14 provide open-ended project problems as well as structured problem sets. The assignment and execution of unstructured project problems can greatly enhance the student's understanding of the concepts as described by the proverb in the epigraph to this preface.

ACKNOWLEDGMENTS The sources of photographs and other nonoriginal art used in the text are acknowledged in the captions and opposite the title page, but the author would also like to express his thanks for the cooperation of all those individuals and companies who generously made these items available. The author would also like to thank those who reviewed various sections of the first edition of the text and who made many useful suggestions for improvement. Mr. John Titus of the University of Minnesota reviewed Chapter 5 on analytical synthesis and Mr. Dennis Klipp of Klipp Engineering, Waterville, Maine, reviewed Chapter 8 on cam design. Professor William J. Crochetiere and Mr. Homer Eckhardt of Tufts University, Medford, MA., reviewed Chapter 15. Mr. Eckhardt and Professor Crochetiere of Tufts, and Professor Charles Warren of the University of Alabama taught from and reviewed Part I. Professor Holly K. Ault of Worcester Polytechnic Institute thoroughly reviewed the entire text while teaching from the prepublication, class-test versions of the complete book. Professor Michael Keefe of the University of Delaware provided many helpful comments. Sincere thanks also go to the large number of undergraduate students and graduate teaching assistants who caught many typos and errors in the text and in the programs while using prepublication versions. Since the book's first printing, Profs. D. Cronin, K. Gupta and P. Jensen and Mr. R. Jantz have written to point out errors or make suggestions that I have incorporated and for which I thank them. The author takes full responsibility for any errors that may remain and invites from all readers their criticisms, suggestions for improvement, and identification of errors in the text or programs, so that both can be improved in future versions. Contact norton@wpi.edu.

Robert L. Norton
Mattapoisett, Mass.
August, 1991

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VIDEO CONTENTS

The Sixth Edition has a collection of *Master Lecture Videos and Tutorials* made by the author over a thirty-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. Some have become lectures here.

There are 82 instructional videos in total. Thirty-four are "50-minute" lectures and are labeled as such. Thirty-nine are short "snippets" from the lecture videos that are linked to the relevant topics in a chapter. Seven are demonstrations of machinery or tutorials. Two are laboratory excercises that have been "virtualized" via video demonstration and the provision of test data so that students can simulate the lab. 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 these files is in the **Downloads Index** and includes 105 video animations of figures in the book. In the digital e-book versions, these are hotlinked to the figures that they animate. The URL of each figure video is also provided in the figure for print-book readers to download them.

Because this book is about the study of motion, it is particularly well suited to digital media. The figure animations have been in the book since the third edition as files on a DVD. It is unknown how many students bothered to open and run those files. The digital versions of the book will make this much easier to do.

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. They can also view the 82 videos and download all the files listed in the Download 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 instructions. I require complete information and only accept university email addresses.

LECTURE VIDEOS AND SNIPPETS Part 1

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

Chapter	Lecture	Snippet	Topic	http://www.designofmachinery.com/DOM/	Run Time
1	**1**		**Introduction**	**Introduction.mp4**	39:10
1	**2**		**Design Process and Documentation**	**Design_Process_and_Documentation.mp4**	43:28
1		2A	*Design Process*	*Design_Process.mp4*	29:46
1		2B	*Documentation*	*Documentation.mp4*	15:57
1		2C	*Units of Mass*	*Units.mp4*	10:06
2	**3**		**Kinematics Fundamentals**	**Kinematics_Fundamentals.mp4**	49:12
2		3A	*Degree of Freedom*	*DOF.mp4*	03:53
2		3B	*Links and Joints*	*Links_and_Joints.mp4*	11:00
2		3C	*Grubler*	*Links_and_Joints.mp4*	14:29
2		3D	*Number Synthesis*	*Number_Synthesis.mp4*	03:47

LECTURE VIDEOS AND SNIPPETS Part 2

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

Chapter	Lecture	Snippet	Topic	http://www.designofmachinery.com/DOM/	Run Time
2		3E	*Isomers*	*Isomers.mp4*	04:15
2		3F	*Inversion*	*Inversion.mp4*	03:40
2		3G	*Grashof Condition*	*The_Grashof_Condition.mp4*	07:21
2		3H	*Fivebar Linkage*	*Fivebar.mp4*	01:33
2		3I	*Compliant Linkages*	*Compliant_Linkages.mp4*	01:27
3	**4**		**Position Synthesis**	**Position_Synthesis.mp4**	47:57
3	**5**		**Quick Return Linkages**	**Quick_Return_Linkages.mp4**	55:22
3	**6**		**Coupler Curves and Atlases**	**Coupler_Curves.mp4**	59:57
3	**7**		**Symmetrical and Straight Coupler Curves**	**Symmetrical_and_Straight_Coupler_Curves.mp4**	14:47
3		7A	*Symmetrical Coupler Curves*	*Symmetrical_Coupler_Curves.mp4*	05:47
3		7B	*Straight Line Linkages*	*Straight_Line_Linkages.mp4*	09:20
3	**8**		**Cognates of Linkages**	**Cognates_of_Linkages.mp4**	18:12
3	**9**		**Parallel Motion**	**Parallel_Motion.mp4**	21:49
3	**10**		**Dwell Linkages**	**Dwell_Mechanisms.mp4**	35:36
4	**11**		**Position Analysis**	**Position_Analysis.mp4**	49:48
5	**12**		**Analytical Linkage Synthesis**	**Analytical_Linkage_Synthesis.mp4**	48:17
6	**13**		**Instant Centers and Centrodes**	**Instant_Centers_and_Centrodes.mp4**	49:16
6		13A	*Instant Centers*	*Instant_Centers_Tutorial.mp4*	28:55
6		13B	*Centrodes*	*Centrodes.mp4*	21:01
6	**14**		**Velocity Analysis with ICs**	**Velocity_Analysis_with_ICs.mp4**	49:48
6	**15**		**Velocity Analysis with Vectors**	**Velocity_Analysis_with_Vectors.mp4**	46:41
7	**16**		**Acceleration Analysis**	**Acceleration_Analysis.mp4**	41:39
7	**Lab**		**Fourbar Virtual Laboratory Video**	**Fourbar_Machine_Virtual_Laboratory.mp4**	35:38
7	**Lab**		**Fourbar Virtual Laboratory Data**	**Fourbar_Virtual_Lab.zip**	–
8	**17**		**Cam Design I**	**Cam_Design_I.mp4**	50:42
8	**18**		**Cam Design II**	**Cam_Design_II.mp4**	51:16
8	**19**		**Cam Design III**	**Cam_Design_III.mp4**	48:54
8	**Lab**		**Cam Machine Virtual Laboratory Video**	**Cam_Machine_Virtual_Laboratory.mp4**	21:28
8	**Lab**		**Cam Machine Laboratory Data**	**Cam_Virtual_Lab.zip**	–
9	**20**		**Gear Design**	**Gear_Design.mp4**	54:45
9	**21**		**GearTrains**	**Gear_Trains.mp4**	37:53
9	**22**		**Gear Transmissions**	**Gear_Transmissions.mp4**	41:06
10	**23**		**Dynamics Fundamentals**	**Dynamics_Fundamentals.mp4**	52.01
10		23A	*Newtons Laws*	*Newtons_Laws.mp4*	04:00
10		23B	*Units of Mass*	*Mass.mp4*	10:06
10		23C	*Moments of Mass*	*Moments_of_Mass.mp4*	04:33
10		23D	*Transfer Theorem*	*Transfer_Theorem.mp4*	02:15
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10		23H	*Equivalent Systems*	*Equivalent_Systems.mp4*	14:53
10		23I	*Lumped Models*	*Lumped_Models.mp4*	19:39
10		23J	*Lever Ratios*	*Lever_Ratios.mp4*	05:16
10		23K	*Modeling Systems*	*Modeling_Systems.mp4*	06:44
10		23L	*DAlembert Force*	*DAlembert_Force.mp4*	03:36
10		23M	*Centrifugal Force*	*Centrifugal_Force.mp4*	06:58

LECTURE VIDEOS AND SNIPPETS Part 3

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

Chapter	Lecture	Snippet	Topic	http://www.designofmachinery.com/DOM/	Run Time
11	**24**		**Dynamic Force Analysis**	**Dynamic_Force_Analysis.mp4**	27:28
11		24A	*Single Link in Rotation*	*Single_Link_in_Rotation.mp4*	15:29
11		24B	*Fourbar Force Analysis*	*Fourbar_Force_Analysis.mp4*	12:18
11	**Lab**		**Fourbar Virtual Laboratory Video**	**Fourbar_Machine_Virtual_Laboratory.mp4**	35:38
11	**Lab**		**Fourbar Virtual Laboratory Data**	**Fourbar_Virtual_Lab.zip**	–
11	**25**		**Virtual Work and Flywheels**	**Virtual Work_and_Flywheels.mp4**	34:50
11		25A	*Virtual Work*	*Virtual_Work.mp4*	10:52
11		25B	*Flywheels*	*Flywheels.mp4*	24:07
12	**26**		**Balancing**	**Balancing.mp4**	48:09
12		26A	*Static Balance*	*Static_Balance.mp4*	09:58
12		26B	*Dynamic Balance*	*Dynamic_Balance.mp4*	09:42
12		26C	*Linkage Balancing*	*Linkage_Balancing.mp4*	26:55
12		26D	*Field Balancing*	*Field_Balancing.mp4*	02:43
12	**Lab**		**Fourbar Virtual Laboratory Video**	**Fourbar_Machine_Virtual_Laboratory.mp4**	35:38
12	**Lab**		**Fourbar Virtual Laboratory Data**	**Fourbar_Virtual_Lab.zip**	–
13	**27**		**Engine Kinematics**	**Engine_Kinematics.mp4**	48:17
13	**28**		**Engine Dynamics**	**Engine Dynamics.mp4**	53:17
13	**29**		**Engine Balancing and Pin Forces**	**Engine_Balancing_and_Pin_Forces.mp4**	42:38
13		29A	*Pin Forces*	*Pin_Forces.mp4*	20:03
13		29B	*Dynamic Balance*	*Balancing_One_Cylinder.mp4*	21:46
14	**30**		**Multicylinder Engines**	**Multicylinder_Engines.mp4**	44:25
14	**31**		**Even Firing**	**Even_Firing.mp4**	47:29
14	**32**		**Vee Engines**	**Vee_Engines.mp4**	48:25
14	**33**		**Balancing Multicylinders**	**Balancing_Multicylinders.mp4**	31:12
15	**34**		**Cam Dynamics**	**Cam_Dynamics.mp4**	48:29

DEMONSTRATION VIDEOS

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

Topic	http://www.designofmachinery.com/DOM/	Run Time
Boot Testing Machine	**Boot_Tester.mp4**	19:02
Bottle Printing Machine	**Bottle_Printing_Machine.mp4**	09:38
Grashof Condition	**The_Grashof_Condition.mp4**	24:12
High-Speed Spring Failure	**Spring_Failure.mp4**	03:46
Pick and Place Mechanism	**Pick_and_Place_Mechanism.mp4**	38:35
Spring Manufacturing Machinery	**Spring_Manufacturing.mp4**	12:23
Vibration Testing	**Vibration_Testing.mp4**	05:51

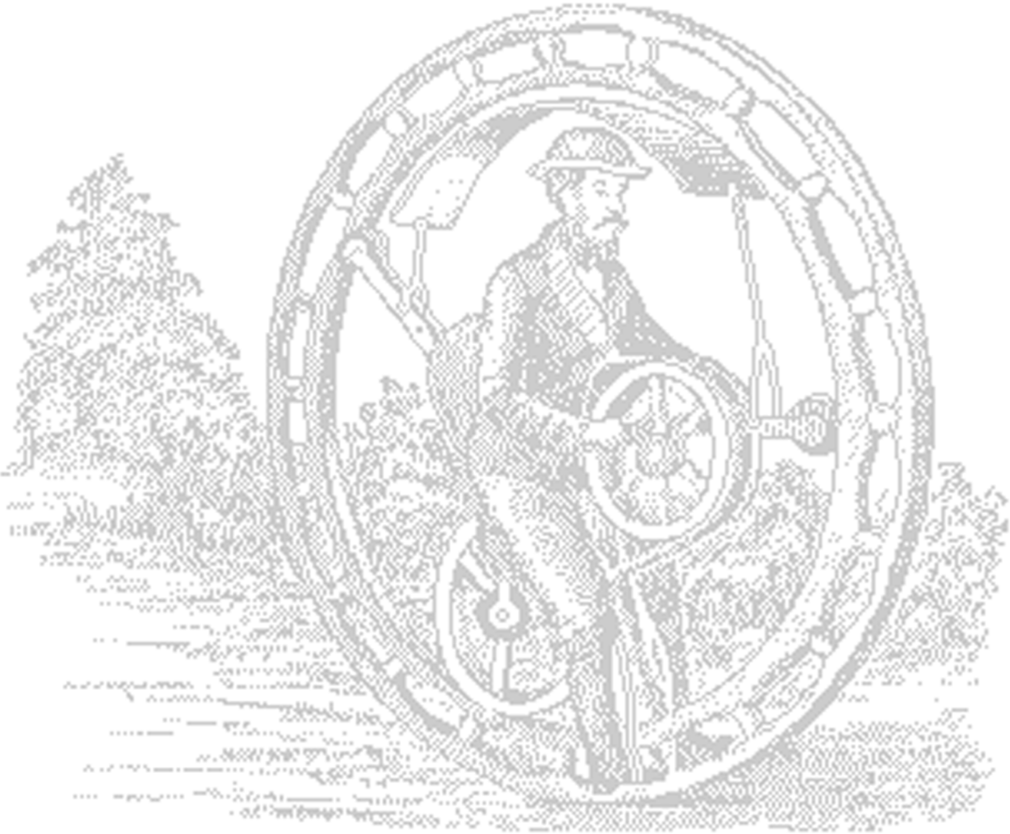
Note that you can download a PDF file containing hyperlinks to all the video content listed in the above tables. This allows print-book readers to easily access the videos without having to type in each URL as noted in the tables. Download the file:

http://www.designofmachinery.com/DOM/Video_Links_for_DOM_6ed.pdf

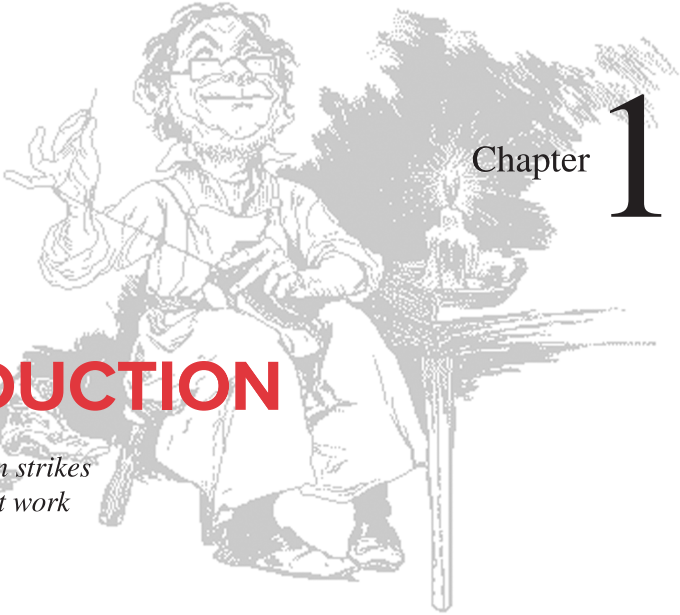
Take to Kinematics. It will repay you. It is
more fecund than geometry;
it adds a fourth dimension to space.

CHEBYSCHEV TO SYLVESTER, 1873

PART I



KINEMATICS OF MECHANISMS



Chapter 1

INTRODUCTION

Inspiration most often strikes
those who are hard at work
ANONYMOUS

1.0 PURPOSE *Watch a lecture video (39:10)*[*]

In this text we will explore the topics of **kinematics** and **dynamics of machinery** in respect to the **synthesis of mechanisms** in order to accomplish desired motions or tasks, and also the **analysis of mechanisms** in order to determine their rigid-body dynamic behavior. These topics are fundamental to the broader subject of **machine design**. On the premise that we cannot analyze anything until it has been synthesized into existence, we will first explore the topic of **synthesis of mechanisms**. Then we will investigate techniques of **analysis of mechanisms**. All this will be directed toward developing your ability to design viable mechanism solutions to real, unstructured engineering problems by using a **design process**. We will begin with careful definitions of the terms used in these topics.

1.1 KINEMATICS AND KINETICS

KINEMATICS *The study of motion without regard to forces.*

KINETICS *The study of forces on systems in motion.*

These two concepts are really *not* physically separable. We arbitrarily separate them for instructional reasons in engineering education. It is also valid in engineering design practice to first consider the desired kinematic motions and their consequences, and then subsequently investigate the kinetic forces associated with those motions. The student should realize that the division between **kinematics** and **kinetics** is quite arbitrary and is done largely for convenience. One cannot design most dynamic mechanical systems without taking both topics into thorough consideration. It is quite logical to consider them in the order listed since, from Newton's second law, $\mathbf{F} = m\mathbf{a}$, one typically needs to know the **accelerations** (**a**) in order to compute the dynamic **forces** (**F**) due to the motion of the

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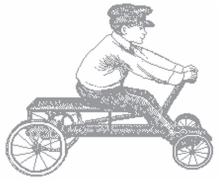
[*] http://www.designofmachinery.com/DOM/Introduction.mp4

system's **mass** (m). There are also many situations in which the applied forces are known and the resultant accelerations are to be found.

One principal aim of **kinematics** is to create (design) the desired motions of the subject mechanical parts and then mathematically compute the positions, velocities, and accelerations that those motions will create on the parts. Since, for most earthbound mechanical systems, the mass remains essentially constant with time, defining the accelerations as a function of time then also defines the dynamic forces as a function of time. **Stresses**, in turn, will be a function of both applied and inertial ($m\mathbf{a}$) forces. Since engineering design is charged with creating systems that will not fail during their expected service life, the goal is to keep stresses within acceptable limits for the materials chosen and the environmental conditions encountered. This obviously requires that all system forces be defined and kept within desired limits. In machinery that moves (the only interesting kind), the largest forces encountered are often those due to the dynamics of the machine itself. These dynamic forces are proportional to acceleration, which brings us back to kinematics, the foundation of mechanical design. Very basic and early decisions in the design process involving kinematic principles can be crucial to the success of any mechanical design. A design that has poor kinematics will prove troublesome and perform badly.

1.2 MECHANISMS AND MACHINES

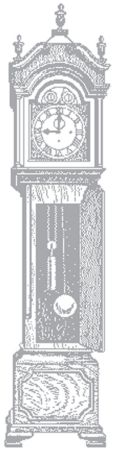
A **mechanism** is a device that transforms motion to some desirable pattern and typically develops very low forces and transmits little power. Hunt[1] defines a mechanism as "a means of *transmitting, controlling, or constraining relative movement*." A **machine** typically contains mechanisms that are designed to provide significant forces and transmit significant power.[1] Some examples of common mechanisms are a pencil sharpener, a camera shutter, an analog clock, a folding chair, an adjustable desk lamp, and an umbrella. Some examples of machines that possess motions similar to the mechanisms listed above are a food blender, a bank vault door, an automobile transmission, a bulldozer, a robot, and an amusement park ride. There is no clear-cut dividing line between mechanisms and machines. They differ in degree rather than in kind. If the forces or energy levels within the device are significant, it is considered a machine; if not, it is considered a mechanism. A useful working **definition of a mechanism** is *a system of elements arranged to transmit* **motion** *in a predetermined fashion.* This can be converted to a definition of a **machine** by adding the words **and energy** after **motion**.


A mechanism

Mechanisms, if lightly loaded and run at slow speeds, can sometimes be treated strictly as kinematic devices; that is, they can be analyzed kinematically without regard to forces. Machines (and mechanisms running at higher speeds), on the other hand, must first be treated as mechanisms; a kinematic analysis of their velocities and accelerations must be done, and then they must be subsequently analyzed as dynamic systems in which their static and dynamic forces due to those accelerations are analyzed using the principles of kinetics. **Part I** of this text deals with **Kinematics of Mechanisms**, and **Part II** with **Dynamics of Machinery**. The techniques of mechanism synthesis presented in Part I are applicable to the design of both mechanisms and machines, since in each case some collection of movable members must be created to provide and control the desired motions and geometry.


A machine

1.3 A BRIEF HISTORY OF KINEMATICS



Machines and mechanisms have been devised by people since the dawn of history. The ancient Egyptians devised primitive machines to accomplish the building of the pyramids and other monuments. Though the wheel and pulley (on an axle) were not known to the Old Kingdom Egyptians, they made use of the lever, the inclined plane (or wedge), and probably the log roller. The origin of the wheel and axle is not definitively known. Its first appearance seems to have been in Mesopotamia about 3000 to 4000 B.C.

A great deal of design effort was spent from early times on the problem of timekeeping as more sophisticated clockworks were devised. Much early machine design was directed toward military applications (catapults, wall scaling apparatus, etc.). The term **civil engineering** was later coined to differentiate civilian from military applications of technology. **Mechanical engineering** had its beginnings in machine design as the inventions of the industrial revolution required more complicated and sophisticated solutions to motion control problems. **James Watt** (1736-1819) probably deserves the title of first kinematician for his synthesis of a straight-line linkage (see Figure 3-29a) to guide the very long stroke pistons in the then new steam engines. Since the planer was yet to be invented (in 1817), no means then existed to machine a long, straight guide to serve as a crosshead in the steam engine. Watt was certainly the first on record to recognize the value of the motions of the coupler link in the fourbar linkage. **Oliver Evans** (1755-1819), an early American inventor, also designed a straight-line linkage for a steam engine. **Euler** (1707-1783) was a contemporary of Watt, though they apparently never met. Euler presented an analytical treatment of mechanisms in his *Mechanica Sive Motus Scienta Analytice Exposita* (1736-1742), which included the concept that planar motion is composed of two independent components, namely, translation of a point and rotation of the body about that point. Euler also suggested the separation of the problem of dynamic analysis into the "geometrical" and the "mechanical" in order to simplify the determination of the system's dynamics. Two of his contemporaries, **d'Alembert** and **Kant**, also proposed similar ideas. This is the origin of our division of the topic into kinematics and kinetics as described on a previous page.

In the early 1800s, L'Ecole Polytechnic in Paris, France, was the repository of engineering expertise. **Lagrange** and **Fourier** were among its faculty. One of its founders was **Gaspard Monge** (1746-1818), inventor of descriptive geometry (which incidentally was kept as a military secret by the French government for 30 years because of its value in planning fortifications). Monge created a course in elements of machines and set about the task of classifying all mechanisms and machines known to mankind! His colleague, **Hachette**, completed the work in 1806 and published it as what was probably the first mechanism text in 1811. **Andre Marie Ampere** (1775-1836), also a professor at L'Ecole Polytechnic, set about the formidable task of classifying "all human knowledge." In his *Essai sur la Philosophie des Sciences*, he was the first to use the term **cinematique**, from the Greek word for motion,[*] to describe *the study of motion without regard to forces*, and suggested that "this science ought to include all that can be said with respect to motion in its different kinds, independently of the forces by which it is produced." His term was later anglicized to *kinematics* and germanized to *kinematik*.

Robert Willis (1800-1875) wrote the text *Principles of Mechanism* in 1841 while a professor of natural philosophy at the University of Cambridge, England. He attempted to systematize the task of mechanism synthesis. He counted five ways of obtaining

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[*] Ampere is quoted as writing "(The science of mechanisms) must therefore not define a machine, as has usually been done, as an instrument by the help of which the direction and intensity of a given *force* can be altered, but as an instrument by the help of which the direction and *velocity* of a given motion can be altered. To this science . . . I have given the name Kinematics from Κινμα—motion." in Maunder, L. (1979). "Theory and Practice." *Proc. 5th World Cong. on Theory of Mechanisms and Machines*, Montreal, p. 1.

relative motion between input and output links: rolling contact, sliding contact, linkages, wrapping connectors (belts, chains), and tackle (rope or chain hoists). **Franz Reuleaux** (1829-1905) published *Theoretische Kinematik* in 1875. Many of his ideas are still current and useful. **Alexander Kennedy** (1847-1928) translated Reuleaux into English in 1876. This text became the foundation of modern kinematics and is still in print! (See bibliography at end of chapter.) He provided us with the concept of a kinematic pair (joint), whose shape and interaction define the type of motion transmitted between elements in the mechanism. Reuleaux defined six basic mechanical components: the link, the wheel, the cam, the screw, the ratchet, and the belt. He also defined "higher" and "lower" pairs, higher having line or point contact (as in a roller or ball bearing) and lower having surface contact (as in pin joints). Reuleaux is generally considered the father of modern kinematics and is responsible for the symbolic notation of skeletal, generic linkages used in all modern kinematics texts.

In the 20th century, prior to World War II, most theoretical work in kinematics was done in Europe, especially in Germany. Few research results were available in English. In the United States, kinematics was largely ignored until the 1940s when **A. E. R. de Jonge** wrote *What Is Wrong with 'Kinematics' and 'Mechanisms'?*[2] which called upon the U.S. mechanical engineering education establishment to pay attention to the European accomplishments in this field. Since then, much new work has been done, especially in kinematic synthesis, by American and European engineers and researchers such as **J. Denavit**, **A. Erdman**, **F. Freudenstein**, **A. S. Hall**, **R. Hartenberg**, **R. Kaufman**, **B. Roth**, **G. Sandor**, and **A. Soni** (all of the United States) and **K. Hain** (of Germany). Since the fall of the "iron curtain" much original work done by Soviet Russian kinematicians has become available in the United States, such as that by **Artobolevsky.**[3] Many U.S. researchers have applied the computer to solve previously intractable problems, of both analysis and synthesis, making practical use of many of the theories of their predecessors.[4] This text will make much use of the availability of computers to allow more efficient analysis and synthesis of solutions to machine design problems. Several computer programs are included with this book for your use.

1.4 APPLICATIONS OF KINEMATICS

One of the first tasks in solving any machine design problem is to determine the kinematic configuration(s) needed to provide the desired motions. Force and stress analyses typically cannot be done until the kinematic issues have been resolved. This text addresses the design of kinematic devices such as linkages, cams, and gears. Each of these terms will be fully defined in succeeding chapters, but it may be useful to show some examples of kinematic applications in this introductory chapter. You probably have used many of these systems without giving any thought to their kinematics.

Virtually any machine or device that moves contains one or more kinematic elements such as links, cams, gears, belts, and chains. Your bicycle is a simple example of a kinematic system that contains a chain drive to provide torque multiplication and simple cable-operated linkages for braking. An automobile contains many more examples of kinematic devices. Its steering system, wheel suspensions, and piston engine all contain linkages; the engine's valves are opened by cams; and the transmission is full of gears. Even the windshield wipers are linkage-driven. Figure 1-1a shows a linkage used to control the rear wheel movement over bumps of a modern automobile.

(*a*) Auto suspension linkage

(*b*) Utility tractor with backhoe
Photo by the author

(*c*) Linkage-driven exercise mechanism
Photo by the author

FIGURE 1-1

Examples of kinematic devices in general use

Construction equipment such as tractors, cranes, and backhoes all use linkages extensively in their design. Figure 1-1b shows a small backhoe that is a linkage driven by hydraulic cylinders. Another application using linkages is that of exercise equipment as shown in Figure 1-1c. The examples in Figure 1-1 are all of consumer goods that you may encounter in your daily travels. Many other kinematic examples occur in the realm of producer goods—machines used to make the many consumer products that we use. You are less likely to encounter these outside of a factory environment. Once you become familiar with the terms and principles of kinematics, you will no longer be able to look at any machine or product without seeing its kinematic aspects.

1.5 A DESIGN PROCESS *Watch a lecture video (29:47)**

Design, Invention, Creativity

These are all familiar terms but may mean different things to different people. These terms can encompass a wide range of activities from styling the newest look in clothing, to creating impressive architecture, to engineering a machine for the manufacture of facial tissues. **Engineering design**, which we are concerned with here, embodies all three of these activities as well as many others. The word **design** is derived from the Latin **designare**, which means *"to designate, or mark out."* Design can be simply defined as creating something new. Design is a common human activity. Artwork, clothing, geometric patterns, automobile bodies, and houses are just a few examples of things that are designed. Design is a universal constituent of engineering practice. **Engineering design** typically involves the creation of a device, system, or process using engineering principles.

The complexity of engineering subjects usually requires that the beginning student be served with a collection of **structured**, **set-piece problems** designed to elucidate a

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* http://www.designofmachinery.com/DOM/Design_Process.mp4

TABLE 1-1
A Design Process

1 Identification of Need
2 Background Research
3 Goal Statement
4 Performance Specifications
5 Ideation and Invention
6 Analysis
7 Selection
8 Detailed Design
9 Prototyping and Testing
10 Production

particular concept or concepts related to the particular topic. These textbook problems typically take the form of "*given A, B, C, and D, find E.*" Unfortunately, real-life engineering problems are almost never so structured. Real design problems more often take the form of "*What we need is a framus to stuff this widget into that hole within the time allocated to the transfer of this other gizmo.*" The new engineering graduate will search in vain among his or her textbooks for much guidance to solve such a problem. This **unstructured problem** statement usually leads to what is commonly called "**blank paper syndrome**." Engineers often find themselves staring at a blank sheet of paper pondering how to begin solving such an ill-defined problem.

Much of engineering education deals with topics of **analysis**, which means *to decompose, to take apart, to resolve into its constituent parts.* This is quite necessary. The engineer must know how to analyze systems of various types, mechanical, electrical, thermal, or fluid. Analysis requires a thorough understanding of both the appropriate mathematical techniques and the fundamental physics of the system's function. But, before any system can be analyzed, it must exist, and a blank sheet of paper provides little substance for analysis. Thus the first step in any engineering design exercise is that of **synthesis**, which means *putting together.*

The design engineer, in practice, regardless of discipline, continuously faces the challenge of *structuring the unstructured problem*. Inevitably, the problem as posed to the engineer is ill-defined and incomplete. Before any attempt can be made to *analyze the situation,* he or she must first carefully define the problem, using an engineering approach, to ensure that any proposed solution will solve the right problem. Many examples exist of excellent engineering solutions that were ultimately rejected because they solved the wrong problem, i.e., a different one than the client really had.


Blank paper syndrome

Much research has been devoted to the definition of various "design processes" intended to provide means to structure the unstructured problem and lead to a viable solution. Some of these processes present dozens of steps, others only a few. The one presented in Table 1-1 contains 10 steps and has, in the author's experience, proved successful in over 40 years of practice in engineering design.

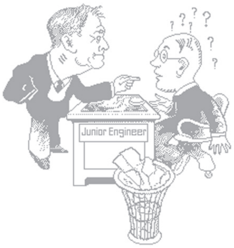
ITERATION Before we discuss each of these steps in detail, it is necessary to point out that this is not a process in which one proceeds from step one through ten in a linear fashion. Rather it is, by its nature, an iterative process in which progress is made haltingly, two steps forward and one step back. It is inherently *circular*. To **iterate** means *to repeat, to return to a previous state.* If, for example, your apparently great idea, upon analysis, turns out to violate the second law of thermodynamics, you can return to the ideation step and get a better idea! Or, if necessary, you can return to an earlier step in the process, perhaps the background research, and learn more about the problem. With the understanding that the actual execution of the process involves iteration, for simplicity, we will now discuss each step in the order listed in Table 1-1.

Identification of Need

This first step is often done for you by someone, boss or client, saying, "What we need is . . .." Typically this statement will be brief and lacking in detail. It will fall far short of providing you with a structured problem statement. For example, the problem statement might be "We need a better lawn mower."

Background Research

This is the most important phase in the process, and is unfortunately often the most neglected. The term **research**, used in this context, should *not* conjure up visions of white-coated scientists mixing concoctions in test tubes. Rather this is research of a more mundane sort, gathering background information on the relevant physics, chemistry, or other aspects of the problem. Also it is desirable to find out if this, or a similar problem, has been solved before. There is no point in reinventing the wheel. If you are lucky enough to find a ready-made solution on the market, it will no doubt be more economical to purchase it than to build your own. Most likely this will not be the case, but you may learn a great deal about the problem to be solved by investigating the existing "art" associated with similar technologies and products. Many companies purchase, disassemble, and analyze their competitors' products, a process sometimes referred to as "**benchmarking**."



Identifying the need

The **patent** literature and technical publications in the subject area are obvious sources of information and are accessible via the World Wide Web. The U.S. Patent and Trademark Office operates a web site at www.uspto.gov where you can search patents by keyword, inventor, title, patent number, or other data. You can print a copy of the patent from the site. A commercial site at www.delphion.com also provides copies of extant patents including those issued in European countries. The "disclosure" or "specification" section of a patent is required to describe the invention in such detail that anyone "skilled in the art" could make the invention. In return for this full disclosure, the government grants the inventor a 20-year monopoly on the claimed invention. After that term expires, anyone can use it. Clearly, if you find that the solution exists and is covered by a patent still in force, you have only a few ethical choices: buy the patentee's existing solution, design something that does not conflict with the patent, or drop the project.

Reinventing the wheel

Technical publications in engineering are numerous and varied and are provided by a large number of professional organizations. For the subject matter of this text, the *American Society of Mechanical Engineers* (ASME), which offers inexpensive student memberships, and the *International Federation for the Theory of Machines and Mechanisms* (IFToMM) both publish relevant journals, the ASME *Journal of Mechanical Design* and *Mechanism and Machine Theory*, respectively. Your school library may subscribe to these, and you can purchase copies of articles from their web sites at http://mechanicaldesign.asmedigitalcollection.asme.org/journal.aspx and http://www.journals.elsevier.com/mechanism-and-machine-theory/, respectively.

Grass shorteners

The World Wide Web provides an incredibly useful resource for the engineer or student looking for information on any subject. The many search engines available will deliver a wealth of information in response to selected keywords. The web makes it easy to find sources for purchased hardware, such as gears, bearings, and motors, for your machine designs. In addition, much machine design information is available from the web. A number of useful web sites are catalogued in the bibliography of this chapter.

It is very important that sufficient energy and time be expended on this research and preparation phase of the process in order to avoid the embarrassment of concocting a great solution to the wrong problem. Most inexperienced (and some experienced) engineers give too little attention to this phase and jump too quickly into the ideation and invention stage of the process. *This must be avoided!* You must discipline yourself to *not* try to solve the problem before thoroughly preparing yourself to do so.