STATICS

ANALYSIS AND DESIGN OF SYSTEMS IN EQUILIBRIUM

Sheri D. Sheppard / Benson H. Tongue

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ANALYSIS AND DESIGN OF SYSTEMS IN EQUILIBRIUM

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With special contributions by:
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San Jose State University

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This book is dedicated to Ed Carryer, Portia Carryer, and Rolf Faste—
my teachers in looking, seeing, and drawing,

to my dear friends and family who have encouraged me through its long gestation,

and

to students everywhere.

sds

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Box 1.1: Overview of Engineering Analysis Procedure

Goal: Formulate the question to be answered by the analysis; what is the analysis to find? In many textbook problems, the question is provided in the problem statement, so this step involves restating the problem in your own words to be sure you understand what is being asked. Make sure that your restatement mentions every final result you should have once you finish working the problem. In engineering practice, the question is often whether a design meets a specific requirement.

Given: Summarize and record what is known. For textbook problems, this may mean restating what is given in the problem, including creating a sketch of the situation. In engineering practice, the source of information might be a design drawing or specification, previous analysis, or a standard reference source.

Assume: Make assumptions about the behavior of the system under consideration to create a simplified representation or model that can be analyzed. This is sometimes referred to as system modeling.

Draw: Draw any diagrams necessary to clarify the model. In statics, a free-body diagram is used to clarify the assumptions made in modeling the system under consideration.

Formulate Equations: Apply engineering principles, generally in mathematical form, to set up equations that represent the model's behavior. In statics, these principles are Newton's laws expressed as equilibrium conditions.

Solve: Solve the resulting equations. In some cases, this can be done by hand. In other cases, the solution requires the use of appropriate software. Clearly state how numerical answers address goal in undertaking the analysis.

Check: Check the results using technical knowledge, engineering judgment, and common sense.

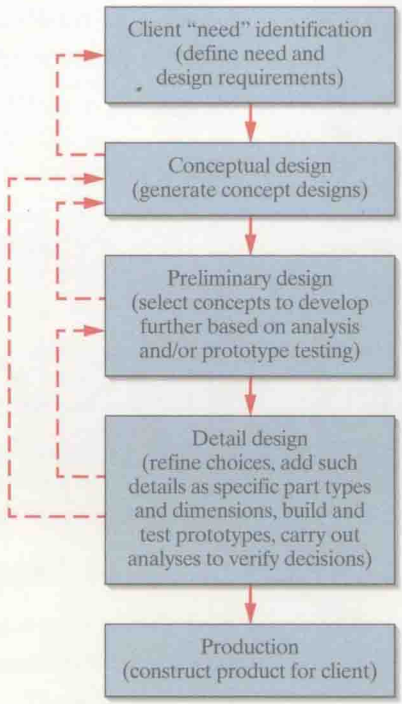

Figure 1.2 Product realization process flow chart

A2.3 Conversion Factors from U.S. Customary Units

PHYSICAL QUANTITY	U.S. CUSTOMARY UNIT	= SI EQUIVALENT
	BASIC UNITS	
Length	1 foot (ft)	= $3.048(10^{-1})$ meter (m)*
	1 inch (in.)	= $2.54(10^{-2})$ meter (m)*
	1 mile (U.S. statute)	= $1.6093(10^{3})$ meter (m)
Mass	1 slug ($lb \cdot s^2/ft$)	= 1.4594(10) kilogram (kg)
	1 pound mass (lbm)	= $4.5359(10^{-1})$ kilogram (kg)
	DERIVED UNITS	
Acceleration	1 foot/second^2 (ft/s^2)	= $3.048(10^{-1})$ meter/second^2 (m/s^2)*
	1 inch/second^2 ($in./s^2$)	= $2.54(10^{-2})$ meter/second^2 (m/s^2)*
Area	1 foot^2 (ft^2)	= $9.2903(10^{-2})$ meter^2 (m^2)
	1 inch^2 ($in.^2$)	= $6.4516(10^{-2})$ meter^2 (m^2)*
Density	1 slug/foot^3 ($lb \cdot s^2/ft^4$)	= $5.1537(10^{2})$ kilogram/meter^3 (kg/m^3)
	1 pound mass/foot^3 (lbm/ft^3)	= 1.6018(10) kilogram/meter^3 (kg/m^3)
Energy and Work	(1 joule ≡ 1 meter-newton)	
	1 foot-pound ($ft \cdot lb$)	= 1.3558 joules (J)
	1 kilowatt-hour ($kW \cdot hr$)	= $3.60(10^{6})$ joules (J)*
	1 British thermal unit (Btu)	= $1.0551(10^{3})$ joules (J)
Force	(1 newton ≡ 1 kilogram-meter/second^2)	
	1 pound (lb)	= 4.4482 newtons (N)
	1 kip (1000 lb)	= $4.4482(10^{3})$ newtons (N)
Power	(1 watt ≡ 1 joule/second)	
	1 foot-pound/second ($ft \cdot lb/s$)	= 1.3558 watt (W)
	1 horsepower (hp)	= $7.4570(10^{2})$ watt (W)
Pressure and Stress	(1 pascal ≡ 1 newton/meter^2)	
	1 pound/foot^2 (lb/ft^2)	= 4.7880(10) pascal (Pa)
	1 pound/inch^2 ($lb/in.^2$)	= $6.8948(10^{3})$ pascal (Pa)
	1 atmosphere (standard, 14.7 $lb/in.^2$)	= $1.0133(10^{5})$ pascal (Pa)
Speed	1 foot/second (ft/s)	= $3.048(10^{-1})$ meter/second (m/s)*
	1 mile/hr	= $4.4704(10^{-1})$ meter/second (m/s)
	1 mile/hr	= 1.6093 kilometer/hour (km/hr)
Volume	1 foot^3 (ft^3)	= $2.8317(10^{-2})$ meter^3 (m^3)
	1 inch^3 ($in.^3$)	= $1.6387(10^{-5})$ meter^3 (m^3)
	1 gallon (U.S. liquid)	= $3.7854(10^{-3})$ meter^3 (m^3)

*Denotes an exact factor.

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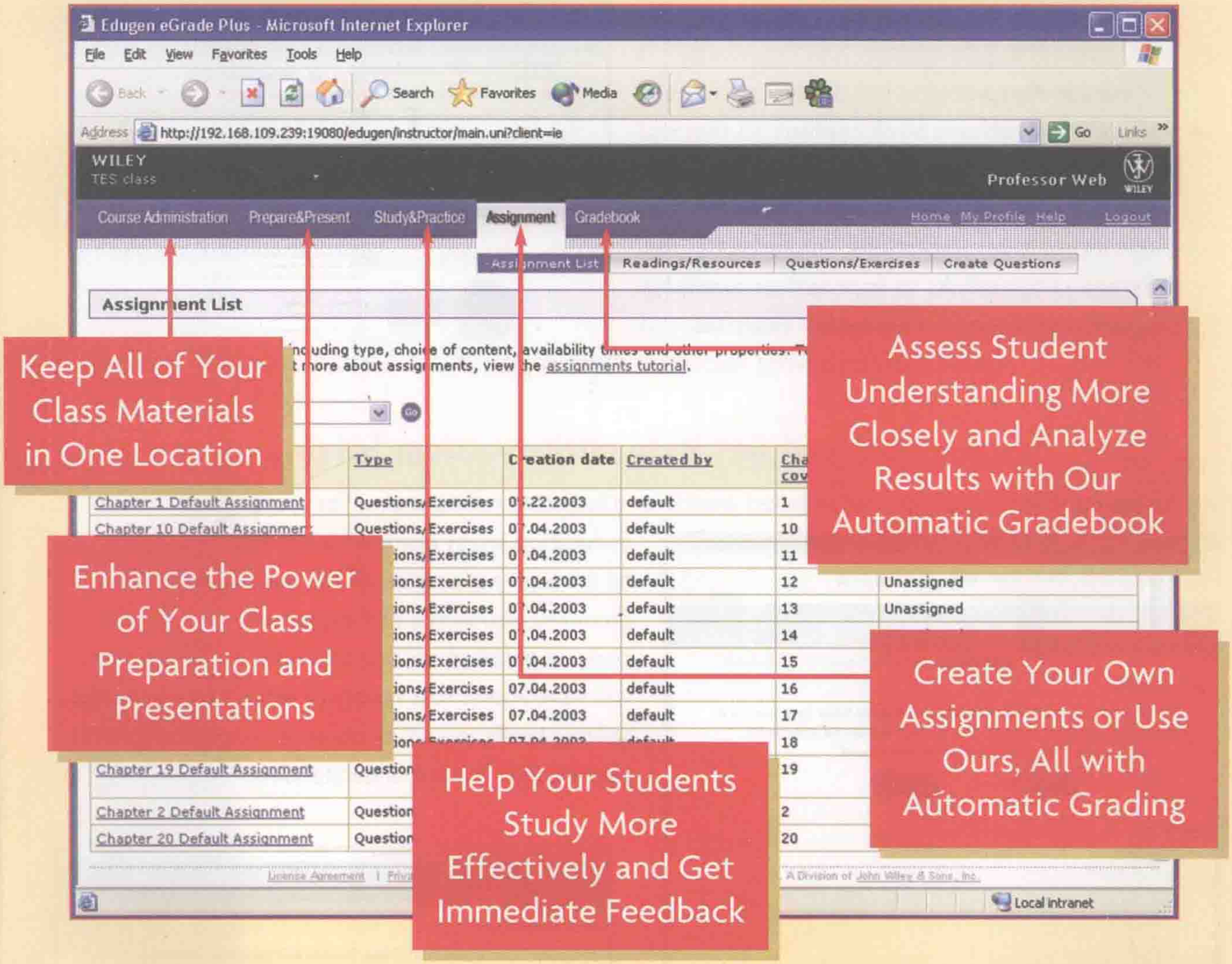

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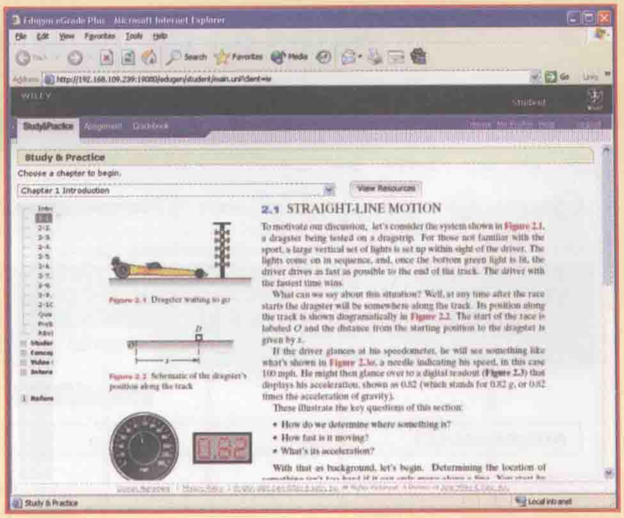
Students,
eGrade Plus Allows You to:

Study More Effectively

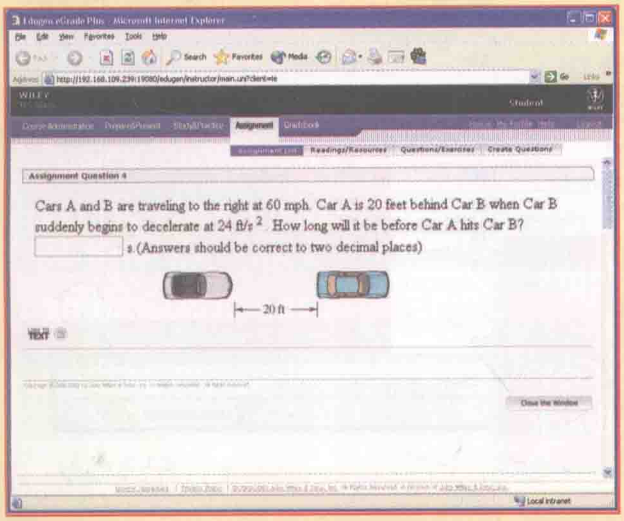
Get Immediate Feedback When You Practice on Your Own

eGrade Plus problems link directly to relevant sections of the **electronic book content,** so that you can review the text while you study and complete homework online. Additional resources include **interactive simulations, animated figures, extensive hyperlinks to appropriate examples and equations, answers to selected exercises,** and other problem-solving resources.

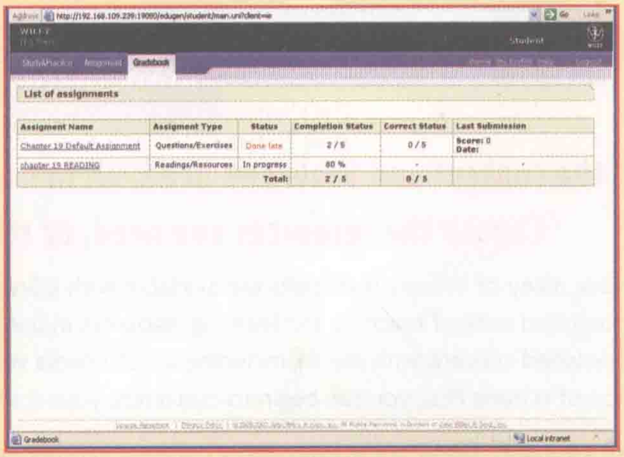


Complete Assignments and Get Help with Problem Solving

An **Assignment** area keeps all your assigned work in one location, making it easy for you to stay "on task."



In addition, many homework problems contain a link to the relevant section of the **multimedia book,** providing you with a text explanation to help you conquer problem-solving obstacles as they arise. You will have access to a variety of **interactive problem-solving tools,** as well as other resources for building your confidence and understanding.



Keep Track of How You're Doing

A **Personal Gradebook** allows you to view your results from past assignments at any time.

A letter to professors:

It is a rare pleasure when a project like this comes across an editor's desk. While there are many historically sound books in mechanics, we recognized that more could be done to motivate and involve students. In 1998 Sheri Sheppard proposed writing a book that taught mechanics principles through the study of a bicycle. Through various concept iterations (including an idea for a "hands-on" approach to statics), and with the addition of Benson Tongue in 2000, the project evolved into an introduction to engineering mechanics from a very practical and applied standpoint.

From the beginning we received enthusiastic and positive response from reviewers and students. We were delighted to find that many faculty were interested in contributing exercises and cases that fit the approach of the project—read about them in the Contributor section of the Preface. Over 250 reviewers provided both supportive and critical comments, and the authors carefully incorporated their input. Sheri and Benson also bravely put their ideas to the test by class-testing various versions of the manuscript with faculty and students at Stanford, Berkeley, Colorado School of Mines, University of Iowa, Cal Poly—SLO, and University of South Florida (thanks to all those reviewers and students!).

Because many professors are concerned with possible errors in first editions, we have taken extraordinary steps to ensure accuracy. More than fifteen professors (one of whom worked on the project while on assignment in the oil fields of Iraq), a developmental editor, several graduate students, and several hundred undergraduate students all had a hand in checking for errors during development, including a group of Benson's students who were paid per error found (this turned out to be a very small sum)! Read more about these efforts in the Commitment to Accuracy section of the Preface.

We invite you to browse through the Preface to learn about all the innovative features of this new project. It is with great pleasure that we offer to you this new text by Sheri D. Sheppard of Stanford University and Benson H. Tongue of University of California at Berkeley.

Sincerely,

Joseph P. Hayton
Editor

"I like the down-to-earth format! The illustrations coupled with the dialog makes this a great text!"
Duane Jardin, University of New Orleans

"[The greatest strength of the text is] the sample sketch in the example. They are more like handwritten and are great guide for student doing homework."
Anonymous

"This is the only [statics] book I have come across that aims to be almost a self-teaching book. It does a great job of explaining what's going on—something other books are traditionally weak at."
Colin Ratcliffe, U.S. Naval Academy

"I also like the six-step process and how it is highlighted throughout."
Lisa Hailey, Brookdale Community College

"This author speaks to the students in a manner that engages their minds in today's world. Students will grasp how statics enables us to analyze practical, everyday problems and as well as advanced designs. It is much more practical than similar texts."
Roy Henk, LeTourneau University

"Based on the two chapters I have reviewed, this text is well-written and organized in an appropriate manner for effective instruction. The inclusion of a separate chapter on free-body diagrams and loads/supports is very good. The quality of examples and exercises is another strong point. They convey the body of knowledge very effectively."
Manoj Chopra, University of Central Florida

"I would rate all the chapters as excellent. The examples in this book and the approach are very good."
M. Zikry, North Carolina State University

"I like the idea that students start with a concrete experience (bicycle). That will help them understand why we are presenting what we are presenting . . ."
Paul Barr, New Mexico State University

"As the free-body diagram is the most important tool for the equilibrium analysis, it is an excellent idea to give it a full chapter to strengthen the student's concept and methodology."
George Weng, Rutgers University

"I really like the simple experiments that illustrate concepts from the material and the system analysis exercises at the end of the chapters."
John Krohn, Arkansas Tech

Mechanics courses have historically confronted engineering students with a precise, mathematical, and, dare we say it, less than engaging treatment of the material. This approach has appeal in that it presents mechanics as a relatively uncluttered "science," but the material often comes across as a somewhat mysterious body of facts and "tricks" that allow idealized cases to be solved. When confronted with more realistic systems, students are often at a loss as to how to proceed. What is lacking is an appreciation for and understanding of the material that will empower the students to tackle meaningful problems at an early stage in their undergraduate education.

In statics, we have tried to present the best of both worlds. Chapters 1–3 present a readable overview of the concepts of mechanics. While we introduce important equations, the emphasis is on developing a "feel" for forces and moments, and for how loads are transferred through structures and machines. This introduction of the material helps lay a motivational framework for the more mathematically complete presentation of statics found in Chapters 4–10.

Throughout this volume, our emphasis is to present and illustrate:

a. *The physical principles* and concepts that describe non-accelerating objects. These principles and concepts are grounded in the reader's own experiences—this approach serves to motivate and provide a context for formal mathematical representations.

b. *An analytical problem-solving methodology* for describing and assessing physical systems, so that the reader is able to apply the principles in a systematic manner in evaluating engineered systems. Furthermore, throughout the book, the methodology and its application are framed within the context of broader engineering practice.

Features

The goals outlined above are supported by a number of unique features in this text:

Emphasis on sketching: The importance of communicating solutions through graphics is continuously emphasized. Most engineering students are visual learners.[1] This, coupled with the importance of graphical information and communication in engineering practice (e.g., the use of sketching during conceptual design), makes graphical representation of information an inviting and key element of the book. Chapter 1 discusses the importance of visualization and sketching skills in successful implementation of structured evaluation procedures, and provides some guidelines for sketching objects. Other elements reinforcing the importance of drawing include:

a. A full chapter (Chapter 6) devoted to the key skill of drawing correct free-body diagrams.

b. An innovative illustration program that uses engineering graph paper background and a ***hand-sketched*** look that shows

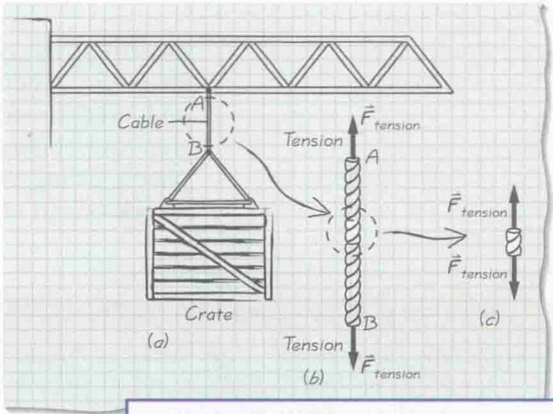


Figure 4.13 (b) Looking
transmitted a

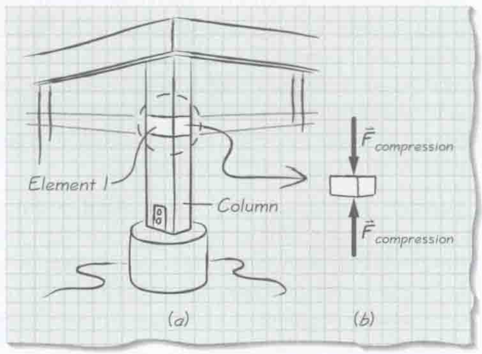


Figure 4.14 (a) A column holds up a deck; (b) Compression is transmitted along the length of the column

[1]Felder, Richard, "Reaching the Second Tier: Learning and Teaching Styles in College Science Education." *J. College Science Teaching*, 23(5), 286–290 (1993).

students how they should be documenting their solutions. An ideal response from a reader regarding a graphical element of the book would be, "the sketch in Figures 4.13 and 4.14 made the concept more understandable AND I think that I could create a similar drawing to illustrate the concept to someone else."

c. A **Draw** step included in every worked example.

To reinforce the drawing concept, vectors in the "hand-drawn" figures appear with an "arrow over top" notation, mirroring how they would be drawn in a hand-written solution.

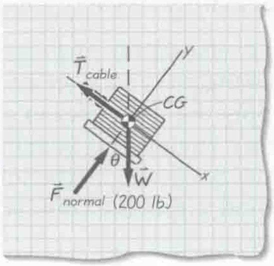


Figure 4.25

Draw The external loads acting on the structure are the cable tension ($\boldsymbol{T}_{\text{cable}}$), the gravitational force acting on the pallet and tiles ($\boldsymbol{W}$), and the normal contact force exerted by the roof on the pallet ($\boldsymbol{F}_{\text{normal}}$).

See Figure 4.25 (which is the answer to (a)). In creating this drawing, we assumed that the normal contact force acts at the center of the bottom of the pallet. We have drawn each force in the direction we think it acts on the structure. Finally, we have placed a set of coordinate axes with the origin at the center of gravity. We could have oriented these axes horizontally and vertically, but as we will see in the next step, orienting them along the roof pitch will make force addition easier. **Figure 4.25** is a free-body diagram of the pallet–tile unit.

Development of structured problem solving procedures: A consistent analysis procedure is introduced early in the text and used consistently throughout all worked examples. Several key steps are emphasized here more than in most other texts, including explicitly listing the **Assumptions** made and the importance of **Draw** and **Check** as part of the solution.

Box 1.1: Overview of Engineering Analysis Procedure

Goal: Formulate the question to be answered by the analysis; what is the analysis to find? In many textbook problems, the question is provided in the problem statement, so this step involves restating the problem in your own words to be sure you understand what is being asked. Make sure that your restatement mentions every final result you should have once you finish working the problem. In engineering practice, the question is often whether a design meets a specific requirement.

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Solve: Solve the resulting equations. In some cases, this can be done by hand. In other cases, the solution requires the use of appropriate software. Clearly state how numerical answers address goal in undertaking the analysis.

Check: Check the results using technical knowledge, engineering judgment, and common sense.

Application of principles to engineering systems: End-of-chapter **System Analysis (SA) Exercises** offer students the opportunity to apply mechanics principles to broader systems. These exercises are more open-ended than those in other parts of the text, and sometimes have more than one "correct" answer. We hope that these exercises will provide opportunities for group work, exploration of similar systems near the students' own campus, and in general show how the principles in the text apply to analysis of real artifacts.

SYSTEM ANALYSIS (SA) EXERCISES

SA 4.3 Problem: Forces to Hold the Scoreboard in Place

The basketball facility inside the Reynolds Coliseum at North Carolina State University contains a heavy scoreboard that is suspended from the ceiling with two cables, shown in **Figure SA4.3.1**. Two electric winches make it possible to lower the entire structure to the floor where signs can be changed or maintained.

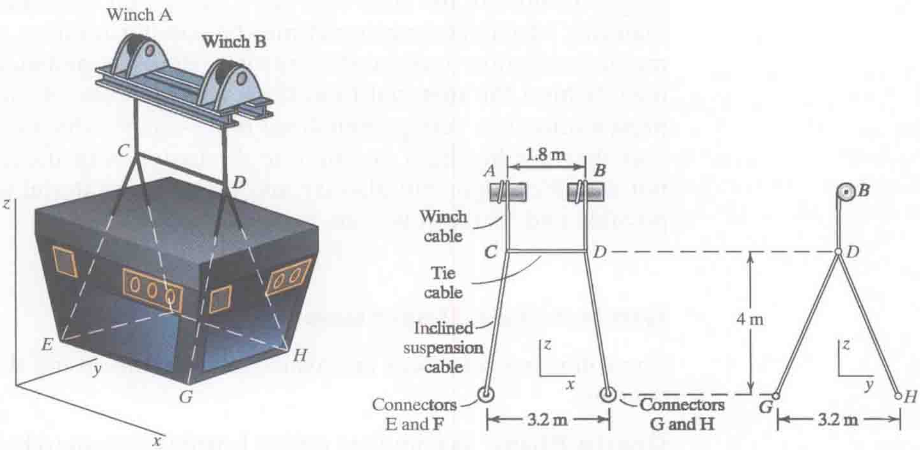
The 4500-N scoreboard can be lowered using two winches, *A* and *B*, which are attached to the bottom flange of a main roof beam girder. **Figure SA4.3.2** presents a view of the key suspension elements when standing directly underneath.

Assume that you are attending a basketball game with your buddy George, who has not studied statics. Before the game, you are explaining how the heavy scoreboard is being secured in the air, which stimulates him to ask whether the maximum tension in the cables that run from *E*, *F*, *G*, and *H* to tie cable locations *C* and *D* will be 1/4 of the weight of the scoreboard. He also wonders what the purpose is of the tie cable *CD*. Having just studied this chapter, you should have no problem addressing his questions. Consider George's curiosity as a wonderful opportunity to understand the material, since we all know that the best way to learn something well is by teaching it. **Figure SA4.3.3** provides you with the dimensions and labels that you need to "teach."

Figure SA4.3.1 View of the 49-meter-wide field with suspended scoreboard

Here is how you work with George to address his questions:

1. **Figure SA4.3.4** shows the forces acting at point *D* of the rigging.
   (a) Find forces $\boldsymbol{F}_{DC}$, $\boldsymbol{F}_{DB}$, $\boldsymbol{F}_{DG}$, and $\boldsymbol{F}_{DH}$. Write in vector notation.
   (b) If the magnitude of $\boldsymbol{F}_{DB}$ is 4500/2 N (is this reasonable?) and the sum of the forces acting at point *D* is zero, what are the magnitudes of $\boldsymbol{F}_{DC}$, $\boldsymbol{F}_{DG}$, and $\boldsymbol{F}_{DH}$?



(*a*) 3-D view of board (*b*) Front view of rigging (*c*) Side view of rigging

Figure SA4.3.3 Models of the rigging system suspending the scoreboard from the roof

Use of case studies to motivate discussion of principles: Chapters 2 and 3 of this volume contain two case studies that illustrate the application of statics principles in understanding how and why artifacts behave the way they do—one is the bicycle and the other is San Francisco's Golden Gate Bridge. These two cases preview many of the key concepts in statics, concepts that are developed in detail in subsequent chapters. These cases give a real-world feel and motivation for the study of mechanics, and are revisited throughout the book in examples and homework problems.

One or both of these cases can be used in conjunction with example and exercises on the bicycle and the Golden Gate Bridge contained in Chapters 4–10. In this manner the student will gain an increasingly sophisticated understanding of the role of analysis in understanding particular systems and an appreciation of the appropriateness (or inappropriateness) of various simplifications. The instructor's manual provides an example syllabus—listing topics, examples, and exercises in each chapter that use the bridge or bicycle as a theme. However, if time does not allow, both chapters can be skipped (or assigned as background reading) without loss of continuity.

Inclusion of useful study tools: Most students will read and review the text to find key information as quickly as possible. To facilitate speedy access to key content, we have included review and study tools, such as **Chapter Objectives** at the start of each chapter, and a **Just the Facts** section at the end of each chapter that summarizes key terms, key equations, and key concepts from the chapter. To the greatest extent possible, all in-text figures include ***descriptive figure captions*** that show at a glance what is being illustrated. ***Key equations*** are highlighted in yellow, and ***key terms*** are in bold blue type when they first appear.

This text has been written very explicitly with the student in mind. We are not trying to talk to the professors teaching the course but rather to those in the class who are trying to get their minds around the material. Mechanics can sometimes be counterintuitive, and it can be a major frustration to those students who don't immediately relate to the logic behind the material (and this includes many of them!). Thus the presentation is a very personalized one—one in which the students feel that they are having a one-on-one discussion with the authors. We do not skimp on rigor but also try and make the material as accessible as possible and, as far as we can, make it fun to learn.

Instructor Resources

The following resources are available to faculty using this text in their courses:

Grade Plus: A complete online learning system to help prepare and present lectures, assign and manage homework, keep track of student progress, and customize your course content and course delivery. See the two-page description in front of the book for more information regarding eGrade Plus, and talk to your local Wiley representative for details on setting up your eGrade Plus course.

Solutions Manual: Fully worked solutions to all exercises in the text, using the same solution procedure as the worked examples.

Electronic figures: All figures from the text are available electronically, for use in creating your own lectures.

Animations and simulations: A collection of animations and simulations that enhance visualization skills and allow "what if" analysis are available from the text website, www.wiley.com/college/sheppard, and are also available as part of the eGrade Plus package.

Student Resources

The following resources are available to students:

Answers to selected exercises: The text website, www.wiley.com/college/sheppard, includes answers to selected exercises from the text, to help students check that they have solved the exercise correctly.

Animations and simulations: A collection of animations and simulations that enhance visualization skills and allow "what if" analysis are available from the text website, and are also available as part of the eGrade Plus package.

Commitment to Accuracy

From the beginning we have committed to providing accurate and error-free coverage of the material. In this mission we have benefited from the help of many, many people.

While writing the book, eighty-seven faculty provided detailed content reviews on individual chapters—some of it quite pointed, and all of it helpful. More than three hundred students class-tested full manuscripts at Stanford and UC—Berkeley in the last two years, reporting and helping to correct any typographical errors found.

While writing solutions (approximately 1,800 exercises and solutions were written!), each solution was solved and checked at least twice, and often three or more times, by a combination of authors, accuracy checkers, and graduate students.

During production, more than 15 faculty served as accuracy checkers, and were specifically tasked with reviewing pages at two stages to check for accuracy of text, equations, examples, figures, and exercises—we specifically recognize them below. All text and art were reviewed line by line by a developmental editor. A proofreader compared all corrections to final pages to confirm that any and all corrections were made. Finally, and certainly not least, the authors themselves spent countless hours checking all elements of the project at every step of the way to guarantee accuracy.

Acknowledgments

Contributors: The following faculty contributed content, System Analysis Exercises, and/or additional assignments, and we would like to recognize their important contributions to this project.

Thalia Anagnos is Professor of Civil and Environmental Engineering and Director of Assessment at San Jose State University. She has taught classes in statics, strength of materials, structural analysis, concrete design, probability, finite elements, and catastrophic events. Thalia received her Ph.D. from Stanford University, and has been involved in NSF-funded research on educational applications of the George E. Brown Network for Earthquake Engineering Simulation (NEES), and improving science education at the middle school level. Thalia is co-author or contributor on three texts, including this one.

Leonhard E. Bernold is Associate Professor of Civil Engineering at North Carolina State University, and founder and director of the Construction Automation & Robotics Laboratory there. Leonhard received his Ph.D. from Georgia Institute of Technology. He teaches courses in civil engineering and conducts NSF-sponsored research related to engineering education. He founded the international student competition "Lunar Construction," which is sponsored by the American Society of Civil Engineers.

George T. Flowers is Professor of Mechanical Engineering at Auburn University and is a licensed practicing engineer in the state of Alabama. He received his Ph.D. from Georgia Institute of Technology. His area of expertise is the dynamics, vibration, and control of rotating machinery.

Major Joseph (Joe) P. Hanus received an M.S. from University of Minnesota and is a member of the U.S. Army Corps of Engineers. He served as an Assistant Professor in the Civil Engineering Department at the U.S. Military Academy, West Point, New York, and is currently studying for his Ph.D. at the University of Wisconsin.

Nels H. Madsen is Associate Professor of Mechanical Engineering and Associate Dean for Assessment and Special Programs in the Samuel Ginn College of Engineering at Auburn University. He received his Ph.D. from University of Iowa in 1978. Nels's research area is biomechanics and motion capture. As Vice President for Research and Development at Motion Reality, Incorporated, he is among the principal developers of the motion capture system used in the *Lord of the Rings* movie trilogy. Nels has contributed throughout the project, and helped guide thinking on the development of the bridge case study material and System Analysis Exercises in this text.

Eric Nauman is an Assistant Professor of Mechanical Engineering at Purdue University. He received his Ph.D. from University of California—Berkeley. His current research interests include tissue engineering, dynamics of biological systems, and mechanics of materials with microstructure.

Brian Self is an Associate Professor of Engineering Mechanics at the U.S. Air Force Academy. He received his B.S. and M.S. in Engineering Mechanics from Virginia Tech and his Ph.D. in Bioengineering from University of Utah. He has four years of experience with the Air Force Research Laboratory and is in his fifth year of teaching in the Department of Engineering Mechanics at the U.S. Air Force Academy. His areas of research include impact injury mechanisms, sports biomechanics, and aerospace physiology.

Accuracy checkers: The following faculty were closely involved in reading and accuracy-checking the project throughout the production process. We could not have completed it without them.

Makola Abdullah, Florida State University
Mark Evans, U.S. Military Academy
George Flowers, Auburn University
Mark Hanson, University of Kentucky
Joe Hanus, U.S. Military Academy
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M. Mahinfaleh, North Dakota State University
Masami Nakagawa, Colorado School of Mines
Eric Nauman, Purdue University
Wilfrid Nixon, University of Iowa
Nipon Raatanawangcharoen, University of Manitoba, Canada
Joe Slater, Wright State University
Ted Stathopoulos, Concordia University, Canada
Warren White, Kansas State University

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