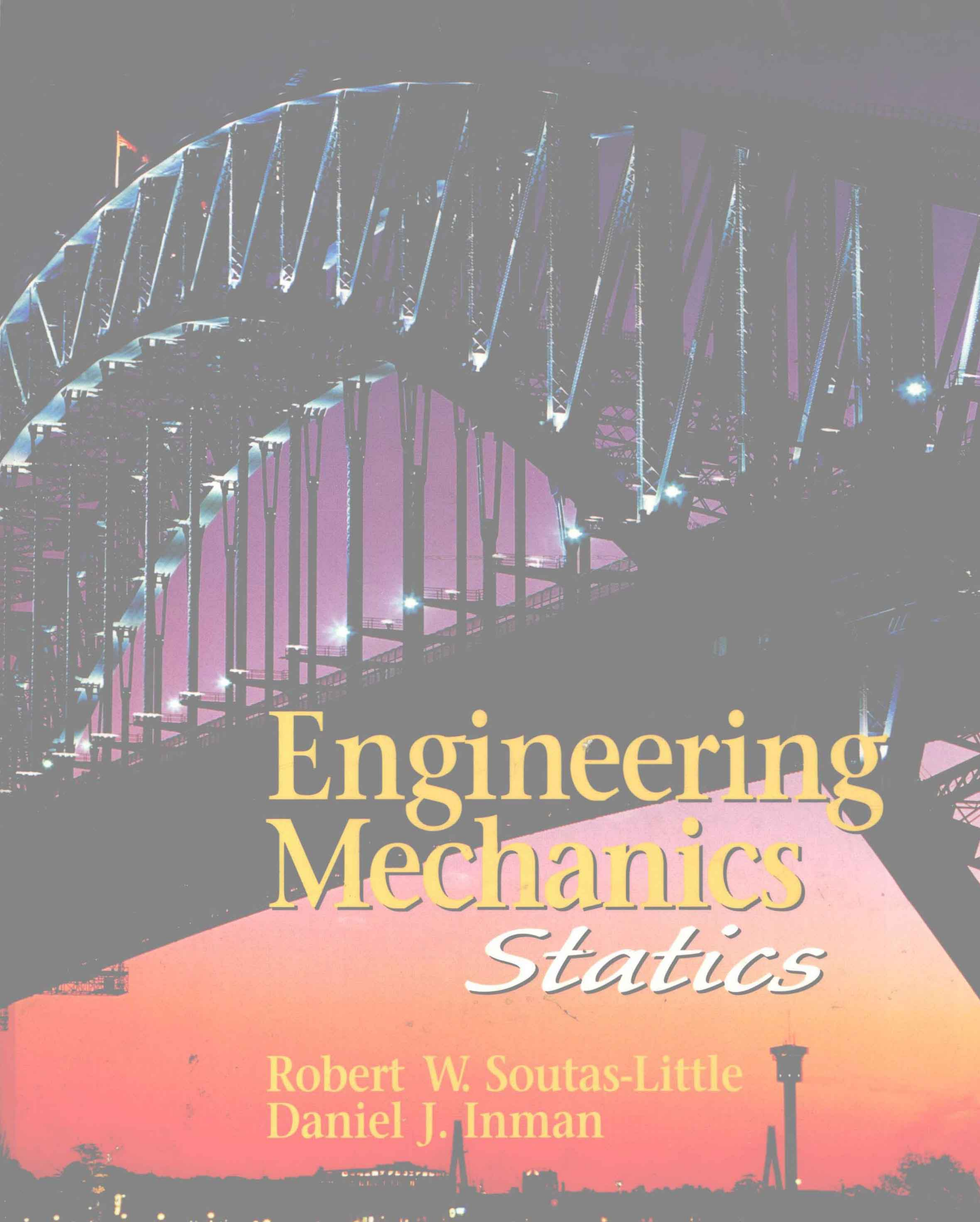

Engineering Mechanics

Statics

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Engineering Mechanics
STATICS

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Preface

A new undergraduate text in mechanics should reflect the changing aspects of engineering. New developments have occurred in the use of mechanics in practice, fundamental changes are occurring in engineering and mathematics education, and computational software is being taught to students and is used in an increasing number of engineering courses. We have not tried to revolutionize statics, but to reform the presentation and bring the material up to date with modern practice. Most texts currently available contain little new material, as it is felt that no new developments have occurred. However, the practice of mechanics has evolved, and we have incorporated this evolution into this text. The use of computational software is now as significant a change to introductory mechanics as were the slide rule and the calculator in earlier times.

Our presentation focuses on the conceptual understanding of mechanics. This is accomplished, in part, by graphing results so that better insights can be gained into the effects of changing parameters. Such parametric studies are the basic foundation of engineering design, and we introduce them early in the text. Much greater insight can be gained by having students solve a problem for an angle or dimension and then graphing the solution to see the effects of parametric changes. Traditional texts rely too heavily on homework problems that specify geometry and loading and miss the transition to design concepts. The process of design requires the use of parametric studies to understand the importance of various parameters. A good mechanics book should encourage students to try "what-if" calculations. The student's focus needs to be on modeling, using free-body diagrams, and then writing the equations of equilibrium. Computational software can then be used to solve particular numerical problems and investigate design parameters.

A computer icon ( ) next to a problem number indicates those instances where the use of a computer could benefit the student, although a computer is not absolutely necessary to solve the problem. Two computer icons ( ) indicates a problem where the use of a computer is necessary in order to solve the problem.

Our treatment of statics uses vector mathematics. Traditionally, for most two-dimensional problems, the equilibrium equations are formulated in scalar notation rather than vector notation. When the equilibrium equations are written in vector notation, they may be solved directly or expanded and solved with matrix methods taking full advantage of a vector formulation. This approach eliminates the common confusion about linear independence.

An essential computation in statics is the solution of systems of linear equations that result from the application of equilibrium conditions. These systems of linear equations can now be handled by introducing a matrix formulation. Historically, many methods in statics have been developed to reduce the complexity of the simultaneous equations that have to be solved. For example, students are taught to take moments about support points, so the reactions do not appear explicitly in the equations. These simplifications often lead to confusion. If the students are shown that systems of linear equations can be solved by using matrix methods, the number of equations becomes of minimal importance. Matrices are introduced in Section 2.7 and matrix methods are available in all computational software packages, as well as on some calculators. Matrix notation and matrix methods are compatible with advanced courses in structures and mechanical systems. The fundamental concepts of linear algebra are presented on an "as needed" basis, so as not to digress from the main principles of mechanics.

Computational software enables easy solution of systems of nonlinear algebraic and trancendental equations. This allows consideration of equilibrium problems where, for example, the wires supporting an object deform. A smooth transition is provided to mechanics of materials courses by introducing the basic concepts of springs and spring constants. Students, therefore, gain a better understanding of the concepts of deformable materials and static indetermancy. The ability to solve nonlinear equations allows an increase in the number of applications that students will encounter in engineering practice.

One significant change in mechanics has occurred because of advances in computer technology. Computational software presents visualization and solution possibilities not available previously. Students can now learn, think, and see in both two- and three-dimensional space. Because of this, the number of three-dimensional problems in the chapter on equilibrium of the rigid body and the chapter on structures has been increased. Computational software allows us to improve the type of problems and include solutions in terms of general geometries and loadings. This is much closer to the actual methods used in engineering practice. Students can now focus on the free-body diagram and the equilibrium conditions. The analytical solution of the equilibrium equations afford students good insights and leads to discussions of design alternatives. Computational software encourages students to examine their solutions and take corrective measures. The result is students build better intuition about engineering mechanics.

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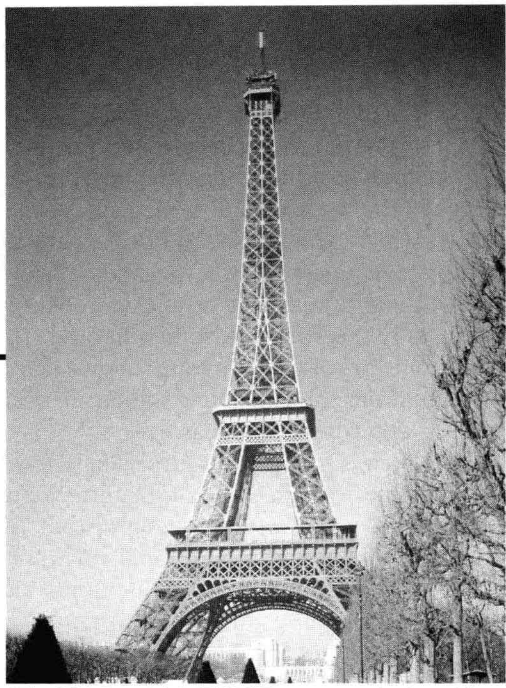
Introduction



The 984-foot-high Eiffel Tower was designed by the French engineer Alexandre Gustave Eiffel (1832–1923) and erected for the Paris Exposition of 1889. Eiffel also designed the framework of the Statue of Liberty, which is found in New York Harbor. A miniature model of the statue stands in the middle of the River Seine on a small island near the Eiffel Tower.

1.1 Mechanics

Mechanics is the oldest area of study in physics, originating with the Greek culture in 400 to 300 BC. The earliest record of the study of mechanical problems was the work of Aristotle (384–322 BC). Although historical questions remain as to the authorship of some of these early works, considerations of the equilibrium of vertical forces and the action of levers were evident in these writings. Archimedes of Syracuse (287–212 BC) introduced the formal study of levers and the concept of the center of gravity. He also examined concepts of geometry and wrote about the theory of buoyancy and the equilibrium of floating bodies. Many later scientists and mathematicians, including Kepler and Galileo, contributed to the development of mechanics, but the formal presentation of the principles of mechanics was made by Sir Isaac Newton (1642–1727).

Mechanics is a basic engineering science that lays the foundation for machine design, structural analysis, stress analysis, vibrations, electromagnetic field theory, and fluid and solid mechanics. In particular, these courses use the methods of modeling, the techniques of vector algebra and calculus, and the computational methods presented in introductory mechanics. Mechanics is the branch of physical science that deals with motion and the effects of forces on gases, liquids, and solid bodies. For ease of study, mechanics has been divided into the study of deformable solid bodies, the study of fluids and gases, and the study of rigid bodies. To further simplify the approach, the mechanics of rigid bodies is subdivided into statics, which deals with rigid bodies at rest or moving at a constant velocity, and dynamics, which is the study of rigid bodies undergoing acceleration. Although statics may be considered a special case of dynamics, it is helpful to study this special case first in order to obtain a firm understanding of the concepts of forces and moments, learn the methods of modeling physical situations, and become skilled at using the mathematical tools necessary to describe these ideas.

Statics, which is based upon surprisingly few basic principles, employs a field of mathematics called vector algebra. We will introduce another field of mathematics, called matrix algebra, that proves useful when one is working with common computational software. It is not necessary to use matrix notation to solve problems in statics, but most presently available commercial software uses this notation.

1.2 Basic Concepts

The starting point of the study of mechanics is an examination of the basic concepts upon which Newton based his three laws of motion. These concepts are as follows.

Space is a boundless expanse in which objects and events occur and have relative position and direction. Space allows the measurement of length, area, and volume. The measurement of length is made by comparison with another object of known or standard length, such as a ruler. Area is defined as the product of two lengths and allows the measurement of a two-dimensional space. Volume is three-dimensional space and is the product of three lengths. Newton considered space to be infinite, homogeneous, isotropic, and absolute. The last property, absoluteness, allowed Newton to assume the existence of a primary inertial frame of reference, which is not moving relative to the "fixed" stars and has an origin located at the center of mass of the universe. If space is isotropic, the properties of a closed system at any point in space are unaffected by the orientation of the system. "Homogeneous" means that the space is the same at every point and does not change from point to point. Our present-day understanding of space is somewhat different from Newton's, owing to Einstein's theory of relativity; however, in this book, we will assume the same idea of space that Newton did and neglect any small deviations owing to relativistic effects.

Time is the concept used to order the flow of events. Time is assumed to be absolute—that is, time is the same for all observers and is independent of all objects in the world. Physicists now consider time to be an abstraction arrived at by changes in the physical world; in other words, the flow of a series of events *defines* time, and time depends upon that flow of events. We use Newton's definition of absolute time, and time is measured by comparison with some repeatable event, such as the rotation of the Earth, the oscillation of a pendulum, or atomic vibrations (i.e., a transition frequency in the element cesium).

Newton defined ***mass*** as a "quantity of matter" that related an object's volume to its density. He stated that *gravitational mass,* as defined by the law of gravitational attraction, is equivalent to *inertial mass,* which measures an object's resistance to being accelerated. In current times, this statement is called the "principle of equivalence" and is a postulate of Einstein's theory of relativity. In this book, we assume that the mass of a body is independent of its motion, neglecting any relativistic effects.

Force is defined as the action of one body on another. This action may be the result of direct contact between the two bodies, or it may arise from gravitational, magnetic, or electrical effects between two bodies separated by a distance. Newton postulated that forces always occur in pairs, equal and opposite, each acting on one of the two bodies. Force is not measured directly; only the effect a force produces can be measured. For example, the force required to stretch a spring is measured by determining the distance the spring stretches.

Newton formulated four axioms, or laws, that are the basis of the study of rigid-body statics and dynamics. The first three laws, known as ***Newton's laws*** of motion, may be stated as follows:

1. *Every body or particle continues in a state of rest or of uniform motion (constant velocity) in a straight line, unless it is compelled to change that state by forces acting upon it.* That is, the body will remain at rest or continue to move with the same speed and direction if no net external forces act on it.
2. *The change of motion of a body is proportional to the net force imposed on the body and is in the direction of the net force.* That is, the net force is equal to the change in the product of the mass and the velocity. The mass is the resistance of the body to acceleration.
3. *If one body exerts a force on a second body, then the second body exerts a force on the first that is equal in magnitude, opposite in direction, and collinear.*

Newton's final law is the law of universal gravitational attraction.

4. *Any two particles are attracted to each other with a force whose magnitude is proportional to the product of their gravitational masses and inversely proportional to the square of the distance between them.* An example of a gravitational attraction force is shown in Figure 1.1.

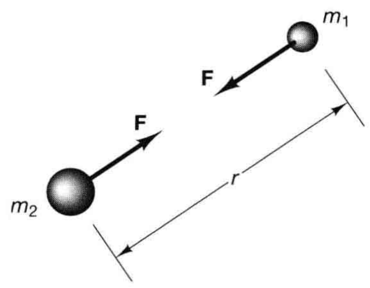


Figure 1.1 The gravitational force F between two bodies of masses m_1 and m_2 separated by a distance r between their centers.

The magnitude of the gravitational force F is stated mathematically as

$$F = \frac{Gm_1m_2}{r^2} \tag{1.1}$$

where

$$G = 66.73 \times 10^{-12}\ \mathrm{m^3/kg \cdot s^2}$$

is the ***universal gravitational constant.***

The ***weight*** of a body on the Earth's surface is the force due to the gravitational attraction of an object to the mass of the Earth. Weight is expressed as

$$W = \frac{GmM}{R^2} \tag{1.2}$$

where G is the universal gravitational constant, m is the mass of the object (in kilograms), M is the mass of the Earth (in kilograms), and R is the radius of the Earth (in meters). For the gravitational attraction of an object on the surface of the Earth, the ratio

$$g = (GM)/R^2$$

is taken to be a constant, and the value of g is 9.807 $\mathrm{m/s^2}$ or 32.17 $\mathrm{ft/s^2}$. This value differs at different points on the Earth, as the Earth is not a perfect sphere of radius R, and elevations vary. However, for most engineering problems, g is considered to be a constant. The weight of an object near the surface of the Earth is caused by the gravitational attraction and is equal to

$$W = mg \tag{1.3}$$

The constant g has the units of acceleration and is sometimes called the ***gravitational acceleration*** or *the acceleration due to gravity.* This concept will be discussed in detail when the subject of particle dynamics is presented. For the present, consider g to be a constant that relates the mass of an object to its weight on the surface of the Earth.