requires the use of vector calculus, and the essentials of this topic will be developed in the text as they are needed.

Dynamics involves the frequent use of time derivatives of both vectors and scalars. As a notational shorthand, a dot over a symbol will frequently be used to indicate a derivative with respect to time. Thus, $\dot{x}$ means dx/dt and $\ddot{x}$ stands for d^2x/dt^2.

1/3 Newton's Laws

Newton's three laws of motion, stated in Art. 1/4 of *Vol. 1 Statics*, are restated here because of their special significance to dynamics. In modern terminology they are:

Law I. A particle remains at rest or continues to move with uniform velocity (in a straight line with a constant speed) if there is no unbalanced force acting on it.

Law II. The acceleration of a particle is proportional to the resultant force acting on it and is in the direction of this force.*

Law III. The forces of action and reaction between interacting bodies are equal in magnitude, opposite in direction, and collinear.

These laws have been verified by countless physical measurements. The first two laws hold for measurements made in an absolute frame of reference, but are subject to some correction when the motion is measured relative to a reference system having acceleration, such as one attached to the surface of the earth.

Newton's second law forms the basis for most of the analysis in dynamics. For a particle of mass m subjected to a resultant force $\mathbf{F}$, the law may be stated as

$$\boxed{\mathbf{F} = m\mathbf{a}} \tag{1/1}$$

where $\mathbf{a}$ is the resulting acceleration measured in a nonaccelerating frame of reference. Newton's first law is a consequence of the second law since there is no acceleration when the force is zero, and so the particle is either at rest or is moving with constant velocity. The third law constitutes the principle of action and reaction with which you should be thoroughly familiar from your work in statics.

1/4 Units

Both the International System of metric units (SI) and the U.S. customary system of units are defined and used in *Vol. 2 Dynamics*, although a stronger emphasis is placed on the metric system because it is replacing the U.S. customary system. However, numerical conversion from one system to the other will often be needed in U.S. engineering

*To some it is preferable to interpret Newton's second law as meaning that the resultant force acting on a particle is proportional to the time rate of change of momentum of the particle and that this change is in the direction of the force. Both formulations are equally correct when applied to a particle of constant mass.

The definition of the system to be analyzed is made clear by constructing its ***free-body diagram***. This diagram consists of a closed outline of the external boundary of the system. All bodies which contact and exert forces on the system but are not a part of it are removed and replaced by vectors representing the forces they exert on the isolated system. In this way, we make a clear distinction between the action and reaction of each force, and all forces on and external to the system are accounted for. We assume that you are familiar with the technique of drawing free-body diagrams from your prior work in statics.

Numerical versus Symbolic Solutions

In applying the laws of dynamics, we may use numerical values of the involved quantities, or we may use algebraic symbols and leave the answer as a formula. When numerical values are used, the magnitudes of all quantities expressed in their particular units are evident at each stage of the calculation. This approach is useful when we need to know the magnitude of each term.

The symbolic solution, however, has several advantages over the numerical solution:

1. The use of symbols helps to focus attention on the connection between the physical situation and its related mathematical description.
2. A symbolic solution enables you to make a dimensional check at every step, whereas dimensional homogeneity cannot be checked when only numerical values are used.
3. We can use a symbolic solution repeatedly for obtaining answers to the same problem with different units or different numerical values.

Thus, facility with both forms of solution is essential, and you should practice each in the problem work.

In the case of numerical solutions, we repeat from *Vol. 1 Statics* our convention for the display of results. All given data are taken to be exact, and results are generally displayed to three significant figures, unless the leading digit is a one, in which case four significant figures are displayed. An exception to this rule occurs in the area of orbital mechanics, where answers will generally receive an additional significant figure because of the necessity of increased precision in this discipline.

Solution Methods

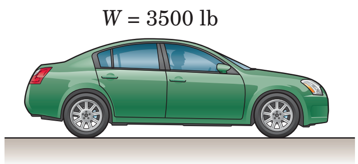
Solutions to the various equations of dynamics can be obtained in one of three ways.

1. Obtain a direct mathematical solution by hand calculation, using either algebraic symbols or numerical values. We can solve the large majority of the problems this way.
2. Obtain graphical solutions for certain problems, such as the determination of velocities and accelerations of rigid bodies in two-dimensional relative motion.
3. Solve the problem by computer. A number of problems in *Vol. 2 Dynamics* are designated as *Computer-Oriented Problems*. They appear

PROBLEMS

(Refer to Table D/2 in Appendix D for relevant solar-system values.)

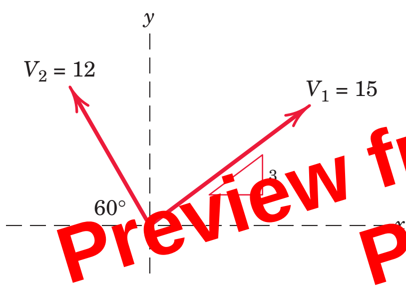
1/1 For the 3500-lb car, determine (*a*) its mass in slugs, (*b*) its weight in newtons, and (*c*) its mass in kilograms.



Problem 1/1

1/2 Determine your mass in slugs. Convert your weight to newtons and calculate the corresponding mass in kilograms.

1/3 For the given vectors $\mathbf{V}_1$ and $\mathbf{V}_2$, determine $V_1 + V_2$, $\mathbf{V}_1 + \mathbf{V}_2$, $\mathbf{V}_1 - \mathbf{V}_2$, $\mathbf{V}_1 \times \mathbf{V}_2$, $\mathbf{V}_2 \times \mathbf{V}_1$, and $\mathbf{V}_1 \cdot \mathbf{V}_2$. Consider the vectors to be nondimensional.

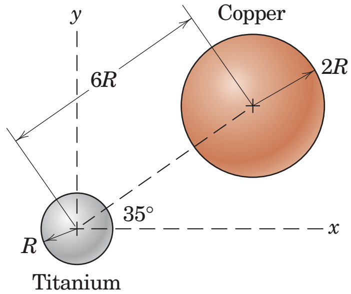


Problem 1/3

1/4 The weight of one dozen apples is 5 lb. Determine the average mass of one apple in both SI and U.S. units and the average weight of one apple in SI units. In the present case, how applicable is the “rule of thumb” that an average apple weighs 1 N?

1/5 Consider two iron spheres, each of diameter 100 mm, which are just touching. At what distance r from the center of the earth will the force of mutual attraction between the contacting spheres be equal to the force exerted by the earth on one of the spheres?

1/6 Two uniform spheres are positioned as shown. Determine the gravitational force which the titanium sphere exerts on the copper sphere. The value of R is 40 mm.



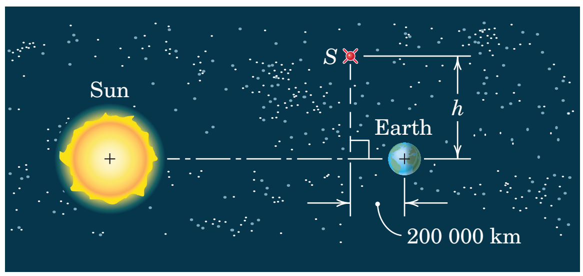
Problem 1/6

1/7 At what altitude h above the north pole is the weight of an object reduced to one-third of its earth-surface value? Assume a spherical earth of radius R and express h in terms of R.

1/8 Determine the absolute weight and the weight relative to the rotating earth of a 60-kg woman if she is standing on the surface of the earth at a latitude of 35°.

1/9 A space shuttle is in a circular orbit at an altitude of 200 mi. Calculate the absolute value of g at this altitude and determine the corresponding weight of a shuttle passenger who weighs 180 lb when standing on the surface of the earth at a latitude of 45°. Are the terms “zero-g” and “weightless,” which are sometimes used to describe conditions aboard orbiting spacecraft, correct in the absolute sense?

1/10 Determine the distance h for which the spacecraft S will experience equal attractions from the earth and from the sun. Use Table D/2 of Appendix D as needed.



Not to scale

Problem 1/10