RESPONSE After the rocket is fired, the path of the CM of the system continues to follow the parabolic trajectory of a projectile acted on by only a constant gravitational force. The CM will thus land at a point $2d$ from the starting point. Since the masses of I and II are equal, the CM must be midway between them at any time. Therefore, part II lands a distance $3d$ from the starting point.

NOTE If part I had been given a kick up or down, instead of merely falling, the solution would have been more complicated.

EXERCISE H A woman stands up in a rowboat and walks from one end of the boat to the other. How does the boat move, as seen from the shore?

PHYSICS APPLIED
Distant planets discovered

An interesting application is the discovery of nearby stars (see Section 5–8) that seem to "wobble." What could cause such a wobble? It could be that a planet orbits the star, and each exerts a gravitational force on the other. The planets are too small and too far away to be observed directly by telescopes. But the slight wobble in the motion of the star suggests that both the planet and the star (its sun) orbit about their mutual center of mass, and hence the star appears to have a wobble. Irregularities in the star's motion can be measured to high accuracy, yielding information on the size of the planets' orbits and their masses. See Fig. 5–30 in Chapter 5.

Summary

The **linear momentum**, $\vec{\mathbf{p}}$, of an object is defined as the product of its mass times its velocity,

$$\vec{\mathbf{p}} = m\vec{\mathbf{v}}. \tag{7–1}$$

In terms of momentum, **Newton's second law** can be written as

$$\Sigma\vec{\mathbf{F}} = \frac{\Delta\vec{\mathbf{p}}}{\Delta t}. \tag{7–2}$$

That is, the rate of change of momentum of an object equals the net force exerted on it.

When the net external force on a system of objects is zero, the total momentum remains constant. This is the **law of conservation of momentum**. Stated another way, the total momentum of an isolated system of objects remains constant.

The law of conservation of momentum is very useful in dealing with **collisions**. In a collision, two (or more) objects interact with each other over a very short time interval, and the force each exerts on the other during this time interval is very large compared to any other forces acting.

The **impulse** delivered by a force on an object is defined as

$$\text{Impulse} = \vec{\mathbf{F}}\,\Delta t, \tag{7–5}$$

where $\vec{\mathbf{F}}$ is the average force acting during the (usually very short) time interval Δt. The impulse is equal to the change in momentum of the object:

$$\text{Impulse} = \vec{\mathbf{F}}\,\Delta t = \Delta\vec{\mathbf{p}}. \tag{7–4}$$

Total momentum is conserved in *any* collision as long as any net external force is zero or negligible. If $m_A\vec{\mathbf{v}}_A$ and $m_B\vec{\mathbf{v}}_B$ are the momenta of two objects before the collision and $m_A\vec{\mathbf{v}}'_A$ and $m_B\vec{\mathbf{v}}'_B$ are their momenta after, then momentum conservation tells us that

$$m_A\vec{\mathbf{v}}_A + m_B\vec{\mathbf{v}}_B = m_A\vec{\mathbf{v}}'_A + m_B\vec{\mathbf{v}}'_B \tag{7–3}$$

for this two-object system.

Total energy is also conserved. But this may not be helpful unless kinetic energy is conserved, in which case the collision is called an **elastic collision** and we can write

$$\tfrac{1}{2}m_A v_A^2 + \tfrac{1}{2}m_B v_B^2 = \tfrac{1}{2}m_A v_A'^2 + \tfrac{1}{2}m_B v_B'^2. \tag{7–6}$$

If kinetic energy is not conserved, the collision is called **inelastic**. Macroscopic collisions are generally inelastic. A **completely inelastic** collision is one in which the colliding objects stick together after the collision.

The **center of mass** (CM) of an extended object (or group of objects) is that point at which the net force can be considered to act, for purposes of determining the translational motion of the object as a whole. The x component of the CM for objects with mass m_A, m_B, …, is given by

$$x_{CM} = \frac{m_A x_A + m_B x_B + \cdots}{m_A + m_B + \cdots}. \tag{7–9a}$$

[*The center of mass of a system of total mass M moves in the same path that a particle of mass M would move if subjected to the same net external force. In equation form, this is Newton's second law for a system of particles (or extended objects):

$$Ma_{CM} = F_{net} \tag{7–11}$$

where M is the total mass of the system, a_{CM} is the acceleration of the CM of the system, and F_{net} is the total (net) external force acting on all parts of the system.]