speed is 11.2 km/s. If you launch a projectile at any speed greater than that, it will leave Earth, traveling slower and slower, never stopping due to Earth's gravity.[4] We can understand the magnitude of this speed from an energy point of view.

How much work would be required to lift a payload against the force of Earth's gravity to a distance very, very far ("infinitely far") away? We might think that the change of PE would be infinite because the distance is infinite. But gravity diminishes with distance by the inverse-square law. The force of gravity on the payload would be strong only near Earth. Most of the work done in launching a rocket occurs within 10,000 km or so from Earth. It turns out that the change of PE of a 1-kg body moved from the surface of Earth to an infinite distance is 63 million joules (63 MJ). So, to lift a payload infinitely far from Earth's surface requires at least 63 MJ of energy per kilogram of load. In practice, this energy is added over a distance as the payload is lifted from Earth's surface. But one can imagine launching the payload like a cannonball, with enough initial speed that it coasts to great distance. It turns out that in the absence of air drag the payload's launch speed, regardless of its mass, must be at least 11.2 km/s. This is called the escape speed from the surface of Earth.[5]

If we give a payload any more energy than 63 MJ per kilogram as it leaves Earth or, for a hypothetical cannonball launch, any more speed than 11.2 km/s, then, if we ignore air drag, the payload will escape from Earth, never to return. As it continues outward, its PE increases and its KE decreases. Its speed becomes less and less, although it is never reduced to zero. The payload outruns the gravity of Earth. It escapes.

The escape speeds from various bodies in the solar system are shown in Table 10.1. Note that the escape speed from the surface of the Sun is 618 km/s. Even at a 150,000,000-km distance from the Sun (Earth's distance), the escape

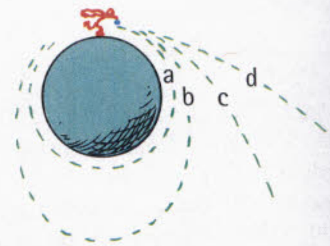

FIGURE 10.33
INTERACTIVE FIGURE MP

(a) If Superhero tosses a ball 8 km/s horizontally from the top of a mountain high enough to be just above air resistance, then about 90 minutes later he can turn around and catch it (ignoring Earth's rotation). (b) Tossed slightly faster, the ball will assume an elliptical orbit and return in a slightly longer time. (c) Tossed faster than 11.2 km/s, it will escape Earth. (d) Tossed at more than 42.5 km/s, it will escape the solar system.

TABLE 10.1 ESCAPE SPEEDS AT THE SURFACE OF BODIES IN THE SOLAR SYSTEM

Astronomical Body	Mass (Earth masses)	Radius (Earth radii)	Escape Speed (km/s)
Sun	333,000	109	618
Sun (at a distance of Earth's orbit)		23,500	42.2
Jupiter	318	11	59.5
Saturn	95.2	9.1	35.5
Neptune	17.1	3.9	23.5
Uranus	14.5	4.0	21.3
Earth	1.00	1.00	11.2
Venus	0.82	0.95	10.4
Mars	0.11	0.53	5.0
Mercury	0.055	0.38	4.3
Moon	0.0123	0.27	2.4

The mind that encompasses the universe is as marvelous as the universe that encompasses the mind.

[4] Escape speed from any planet or any body is given by $v = \sqrt{\frac{2MG}{d}}$, where G is the universal gravitational constant, M is the mass of the attracting body, and d is the distance from its center. (At the surface of the body, d is simply the radius of the body.) For a bit more mathematical insight, compare this formula with the one for orbital speed in footnote 1 a few pages back.

[5] Interestingly enough, this might well be called the *maximum falling speed*. The speed of any object, however far from Earth, released from rest and allowed to fall to Earth under only the influence of Earth's gravity, would not exceed 11.2 km/s. (With air friction, it would be less.)