detailed exploration of how atoms interact as a result of the imperfect cancellation of the electromagnetic interactions between atoms brought into close proximity. Such unbalanced interactions also give rise to contact interactions, as discussed in chapter C1.

When the two interacting charged particles also move with respect to each other, they interact *magnetically* as well as electrostatically. It turns out that the magnetic part of an interaction between two charged particles does not affect their kinetic energies, so we can ignore it in the electromagnetic potential energy. When other interactions are involved, magnetic effects can (indirectly) have energy implications. It turns out, for example, that the north and south magnetic poles of two interacting bar magnets behave *qualitatively* as positive and negative charges do, and we can treat such interactions between poles of such magnets *as if* they had potential energies with same inverse-r dependence as for point charges. But we will not worry about magnetism much until we explore it in depth in unit E.

C7.2 The Gravitational Interaction

Gravitation is observable because there is no such thing as negative mass!

It is ironic that the gravitational interaction, which is *by far* the weakest of the four fundamental interactions, is nonetheless the most obvious of the four in daily life, and more than any other shapes objects larger than asteroids. This is because the gravitational interaction acts between any pair of objects having mass, and *there is no such thing as negative mass*. Therefore, the gravitational effects of particles in an object tend to add instead of cancel out (as electromagnetic effects tend to do). Even an extraordinarily weak interaction between two elementary particles can become dominant when a huge number of particles pull together.

The potential energy formula for the gravitational interaction between two point particles is

The formula for gravitational potential energy

$$V(r) = -G\frac{m_1 m_2}{r} \qquad \text{reference separation: } V(r) \equiv 0 \text{ when } r = \infty \qquad (C7.3)$$

Purpose: This equation describes the potential energy function $V(r)$ for a gravitational interaction between two particles separated by a distance r.

Symbols: m_1 and m_2 are the particles' masses, and G is the **universal gravitational constant** (empirically, $G = 6.67 \times 10^{-11}$ J·m/kg^2).

Limitations: This equation strictly applies only to particles, and assumes neither particle is moving at a speed close to that of light. It only applies when we choose the reference separation noted.

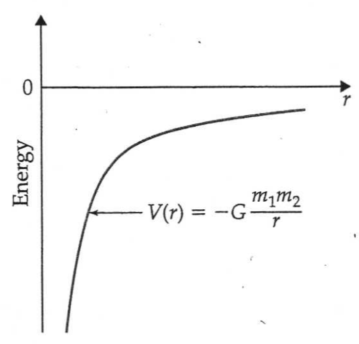

Figure C7.2
A graph of the gravitational potential energy $V(r)$ between a pair of particles with nonzero mass.

Note that, as in the case of the electrostatic potential energy function, we conventionally choose the reference separation to be $r = \infty$, as shown. Indeed, note that this function has *the same form* as the electromagnetic potential energy function given by equation C7.1, except that masses m_1 and m_2 here play the role that charges q_1 and q_2 did there, the constant G here replaces k there, and the sign of the gravitational potential energy is *always* negative. The minus sign is necessary so that the gravitational potential energy *increases* with increasing separation, which is a necessary characteristic of an *attractive* interaction, as we've seen. A graph of this potential energy function is shown in figure C7.2.