Thus he proposed his **law of universal gravitation**, which we can state as follows:

> **Every particle in the universe attracts every other particle with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them. This force acts along the line joining the two particles.**

NEWTON'S LAW OF UNIVERSAL GRAVITATION

The magnitude of the gravitational force can be written as

$$F = G\frac{m_1 m_2}{r^2}, \qquad \textbf{(5–4)}$$

where m_1 and m_2 are the masses of the two particles, r is the distance between them, and G is a universal constant which must be measured experimentally and has the same numerical value for all objects.

The value of G must be very small, since we are not aware of any force of attraction between ordinary-sized objects, such as between two baseballs. The force between two ordinary objects was first measured by Henry Cavendish in 1798, over 100 years after Newton published his law. To detect and measure the incredibly small force between ordinary objects, he used an apparatus like that shown in Fig. 5–20. Cavendish confirmed Newton's hypothesis that two objects attract one another, and that Eq. 5–4 accurately describes this force. In addition, because Cavendish could measure F, m_1, m_2, and r accurately, he was able to determine the value of the constant G as well. The accepted value today is

$$G = 6.67 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}.$$

[Strictly speaking, Eq. 5–4 gives the magnitude of the gravitational force that one particle exerts on a second particle that is a distance r away. For an extended object (that is, not a point), we must consider how to measure the distance r. This is often best done using integral calculus, which Newton himself invented. Newton showed that for two uniform spheres, Eq. 5–4 gives the correct force where r is the distance between their centers. When extended objects are small compared to the distance between them (as for the Earth–Sun system), little inaccuracy results from considering them as point particles.]

EXAMPLE 5–10 ESTIMATE Can you attract another person gravitationally? A 50-kg person and a 75-kg person are sitting on a bench. Estimate the magnitude of the gravitational force each exerts on the other.

APPROACH This is an estimate: we let the distance between the people be $\frac{1}{2}$ m, and round off G to $10^{-10}\ \mathrm{N \cdot m^2/kg^2}$.

SOLUTION We use Eq. 5–4:

$$F = G\frac{m_1 m_2}{r^2} \approx \frac{(10^{-10}\ \mathrm{N \cdot m^2/kg^2})(50\ \mathrm{kg})(75\ \mathrm{kg})}{(0.5\ \mathrm{m})^2} \approx 10^{-6}\ \mathrm{N},$$

which is unnoticeably small unless very delicate instruments are used.

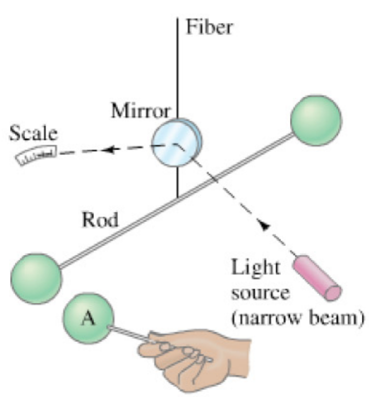

FIGURE 5–20 Schematic diagram of Cavendish's apparatus. Two spheres are attached to a lightweight horizontal rod, which is suspended at its center by a thin fiber. When a third sphere labeled A is brought close to one of the suspended spheres, the gravitational force causes the latter to move, and this twists the fiber slightly. The tiny movement is magnified by the use of a narrow light beam directed at a mirror mounted on the fiber. The beam reflects onto a scale. Previous determination of how large a force will twist the fiber a given amount then allows one to determine the magnitude of the gravitational force between two objects.