CONCEPTUAL EXAMPLE 4–14 **The advantage of a pulley.** A mover is trying to lift a piano (slowly) up to a second-story apartment (Fig. 4–24). He is using a rope looped over two pulleys as shown. What force must he exert on the rope to slowly lift the piano's 2000-N weight?

RESPONSE The magnitude of the tension force F_T within the rope is the same at any point along the rope if we assume we can ignore its mass. First notice the forces acting on the lower pulley at the piano. The weight of the piano pulls down on the pulley via a short cable. The tension in the rope, looped through this pulley, pulls up *twice*, once on each side of the pulley. Let us apply Newton's second law to the pulley–piano combination (of mass m):

$$2F_T - mg = ma.$$

To move the piano with constant speed (set $a = 0$ in this equation) thus requires a tension in the rope, and hence a pull on the rope, of $F_T = mg/2$. The mover can exert a force equal to half the piano's weight. We say the pulley has given a **mechanical advantage** of 2, since without the pulley the mover would have to exert twice the force.

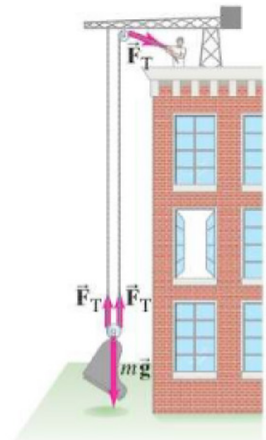

FIGURE 4–24 Example 4–14.

EXAMPLE 4–15 **Getting the car out of the mud.** Finding her car stuck in the mud, a bright graduate of a good physics course ties a strong rope to the back bumper of the car, and the other end to a boulder, as shown in Fig. 4–25a. She pushes at the midpoint of the rope with her maximum effort, which she estimates to be a force $F_P \approx 300$ N. The car just begins to budge with the rope at an angle θ (see the Figure), which she estimates to be 5°. With what force is the rope pulling on the car? Neglect the mass of the rope.

How to get out of the mud

APPROACH First, note that the tension in a rope is always along the rope. Any component perpendicular to the rope would cause the rope to bend or buckle (as it does here where $\vec{F}_P$ acts)—in other words, a rope can support a tension force only along its length. Let $\vec{F}_{BR}$ and $\vec{F}_{CR}$ be the forces on the boulder and on the car, exerted via the tension in the rope, as shown in Fig. 4–25a. Let us choose to look at the forces on the tiny section of rope where she pushes. The free-body diagram is shown in Fig. 4–25b, which shows $\vec{F}_P$ as well as the tensions in the rope (note that we have used Newton's third law: $\vec{F}_{RB} = -\vec{F}_{BR}$, $\vec{F}_{RC} = -\vec{F}_{CR}$). At the moment the car budges, the acceleration is still essentially zero, so $\vec{a} = 0$.

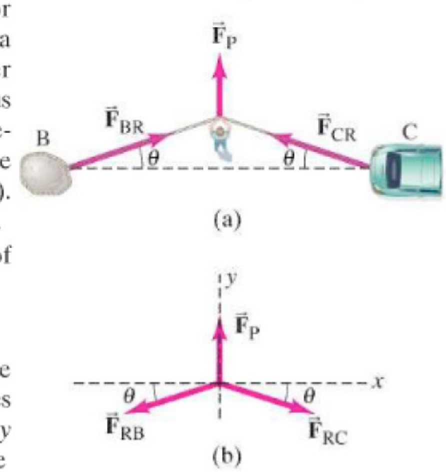

FIGURE 4–25 Example 4–15. (a) Getting a car out of the mud, showing the forces on the boulder, on the car, and exerted by the person. (b) The free-body diagram: forces on a small segment of rope.

SOLUTION For the x component of $\Sigma\vec{F} = m\vec{a} = 0$ on that small section of rope (Fig. 4–25b), we have

$$\Sigma F_x = F_{RB}\cos\theta - F_{RC}\cos\theta = 0.$$

Hence $F_{RB} = F_{RC}$, and these forces represent the magnitude of the tension in the rope, call it F_T; then we can write $F_T = F_{RB} = F_{RC}$. In the y direction, the forces acting are F_P, and the components of F_{RB} and F_{RC} that point in the negative y direction (each equal to $F_T \sin\theta$). So for the y component of $\Sigma\vec{F} = m\vec{a}$, we have

$$\Sigma F_y = F_P - 2F_T\sin\theta = 0.$$

We solve this for F_T, and insert $\theta = 5°$ and $F_P \approx 300$ N, which were given:

$$F_T = \frac{F_P}{2\sin\theta} \approx \frac{300\text{ N}}{2\sin 5°} \approx 1700\text{ N}.$$

When our physics graduate exerted a force of 300 N on the rope, the force produced on the car was 1700 N. She was able to magnify her effort almost six times using this technique!

NOTE Notice the symmetry of the problem, which ensures that $F_{RB} = F_{RC}$.

PROBLEM SOLVING

Use any symmetry present to simplify a problem

NOTE Compare Figs. 4–25a and b. Notice that we cannot write down Newton's second law using Fig. 4–25a because the force vectors are not acting on the same object. It is only by choosing a tiny section of rope as our object, and using Newton's third law (in this case, the boulder and the car pulling back on the rope with forces F_{RB} and F_{RC}), that all forces apply to the same object.