Chapter 4

Forces and Newton's Laws of Motion

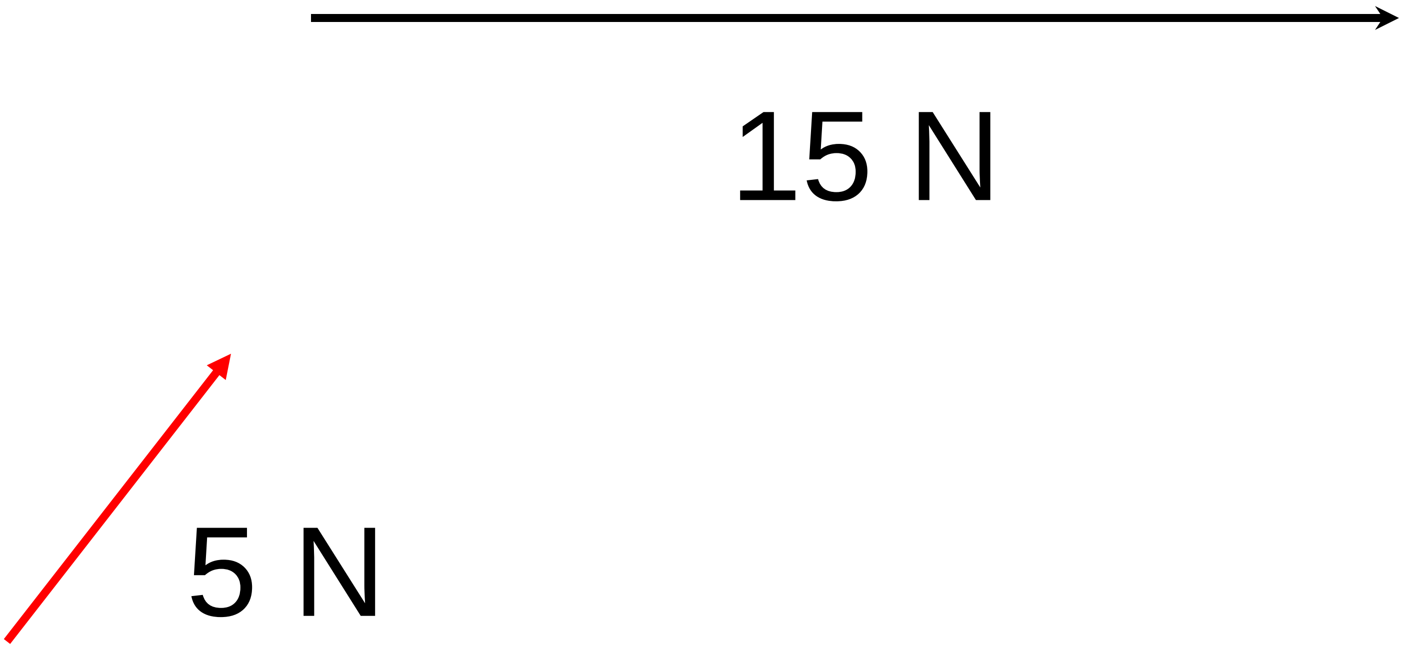
A ***force*** is a push or a pull.

Contact forces arise from physical contact .

Action-at-a-distance forces do not require contact and include gravity and electrical forces.

4.1 The Concepts of Force and Mass

Arrows are used to represent forces. The length of the arrow is proportional to the magnitude of the force.



Mass **is a measure of the amount of "stuff" contained in an object.**

Newton's First Law

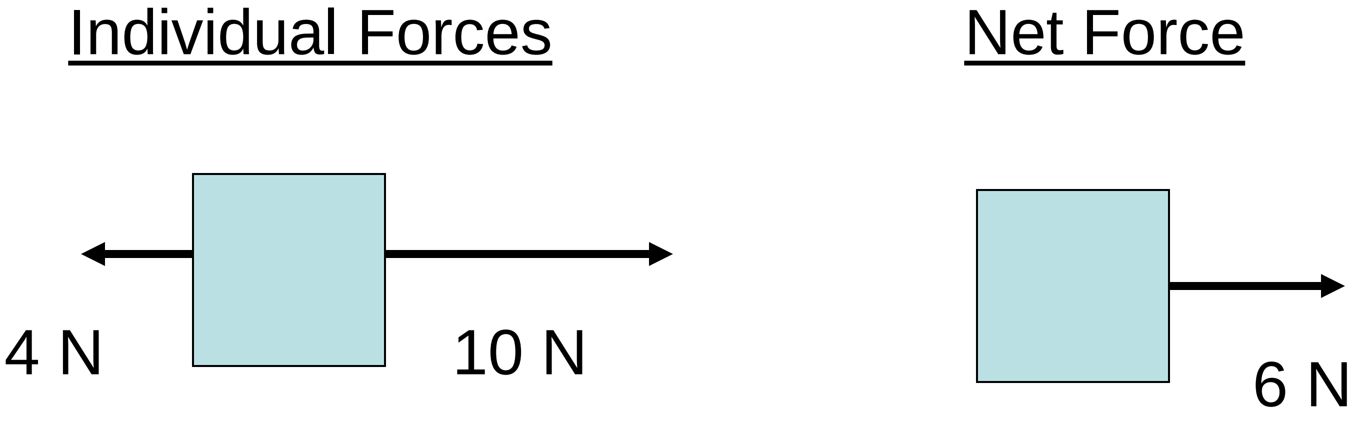
An object continues in a state of rest or in a state of motion at a constant speed along a straight line, unless compelled to change that state by a net force.

The *net force* is the vector sum of all of the forces acting on an object.

4.2 *Newton's First Law of Motion*

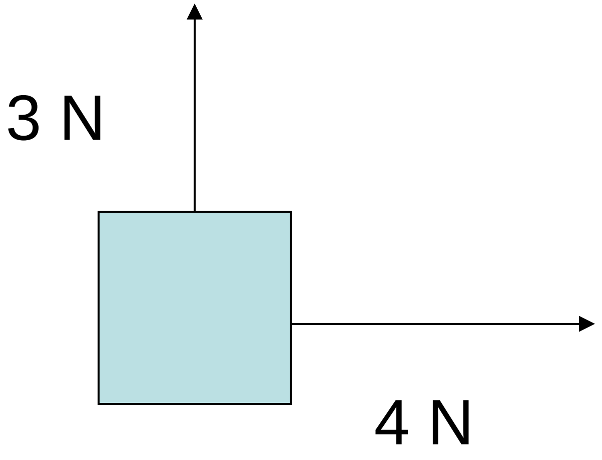
The net force on an object is the vector sum of all forces acting on that object.

The SI unit of force is the Newton (N).

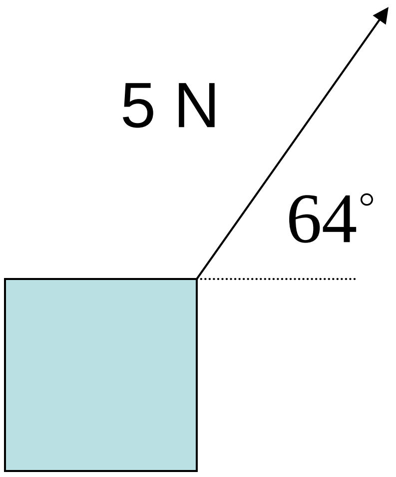


4.2 Newton's First Law of Motion

Individual Forces



Net Force



4.2 Newton's First Law of Motion

Inertia is the natural tendency of an object to remain at rest or in motion at a constant speed along a straight line.

The *mass* of an object is a quantitative measure of inertia.

SI Unit of Mass: kilogram (kg)

An *inertial reference frame* is one in which Newton's Law of Inertia is valid.

All accelerating reference frames are noninertial.

4.3 Newton's Second Law of Motion

Mathematically, the net force is written as

$$\sum \vec{\mathbf{F}}$$

where the Greek letter sigma denotes the vector sum.

Newton's Second Law

When a net external force acts on an object of mass *m*, the acceleration that results is directly proportional to the net force and has a magnitude that is inversely proportional to the mass. The direction of the acceleration is the same as the direction of the net force.

$$\vec{\mathbf{a}} = \frac{\sum \vec{\mathbf{F}}}{m} \qquad \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

SI Unit for Force

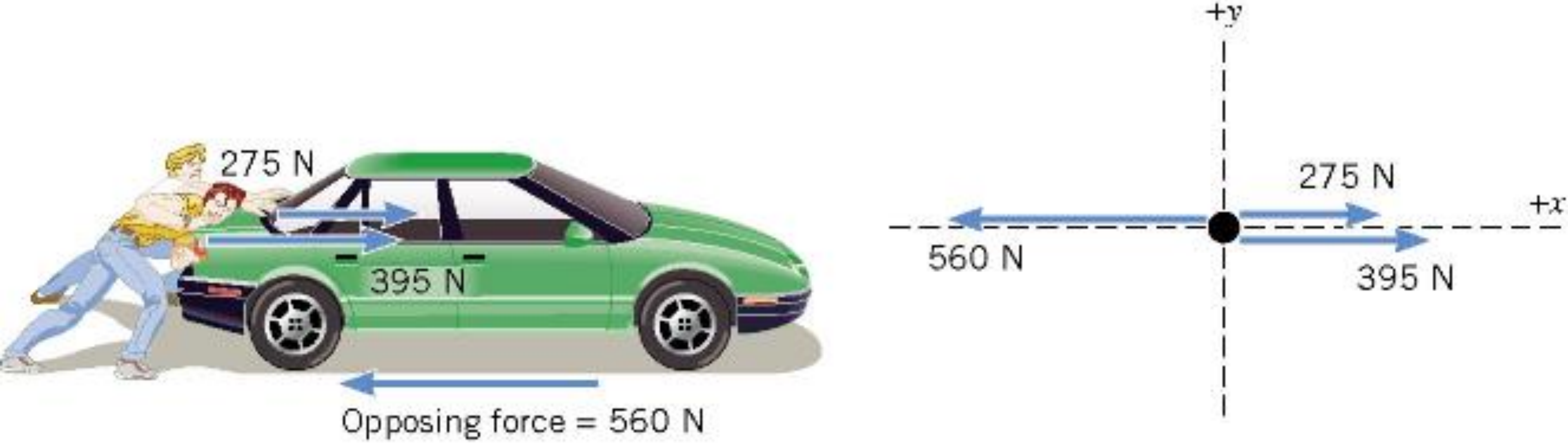
$$\left(\mathrm{kg}\right)\left(\frac{\mathrm{m}}{\mathrm{s}^2}\right)=\frac{\mathrm{kg}\cdot\mathrm{m}}{\mathrm{s}^2}$$

This combination of units is called a *newton* (N).

Table 4.1 Units for Mass, Acceleration, and Force

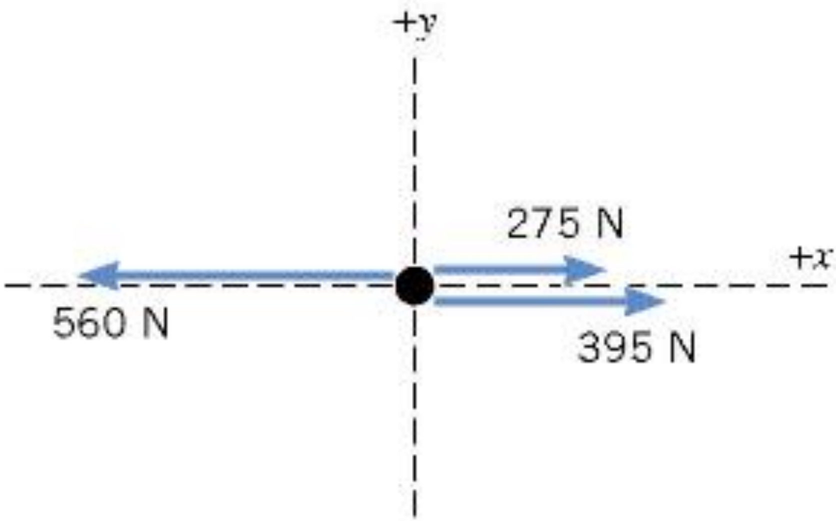
System	Mass	Acceleration	Force
SI	kilogram (kg)	meter/second^2 (m/s^2)	newton (N)
CGS	gram (g)	centimeter/second^2 (cm/s^2)	dyne (dyn)
BE	slug (sl)	foot/second^2 (ft/s^2)	pound (lb)

A ***free-body-diagram*** is a diagram that represents the object and the forces that act on it.



(a) (b) Free-body diagram of the car

(a)



(b) Free-body diagram of the car

The net force in this case is:

275 N + 395 N – 560 N = +110 N

and is directed along the + x axis of the coordinate system.

If the mass of the car is 1850 kg then, by Newton's second law, the acceleration is

$$a = \frac{\sum F}{m} = \frac{+110\,\mathrm{N}}{1850\,\mathrm{kg}} = +0.059\,\mathrm{m/s^2}$$

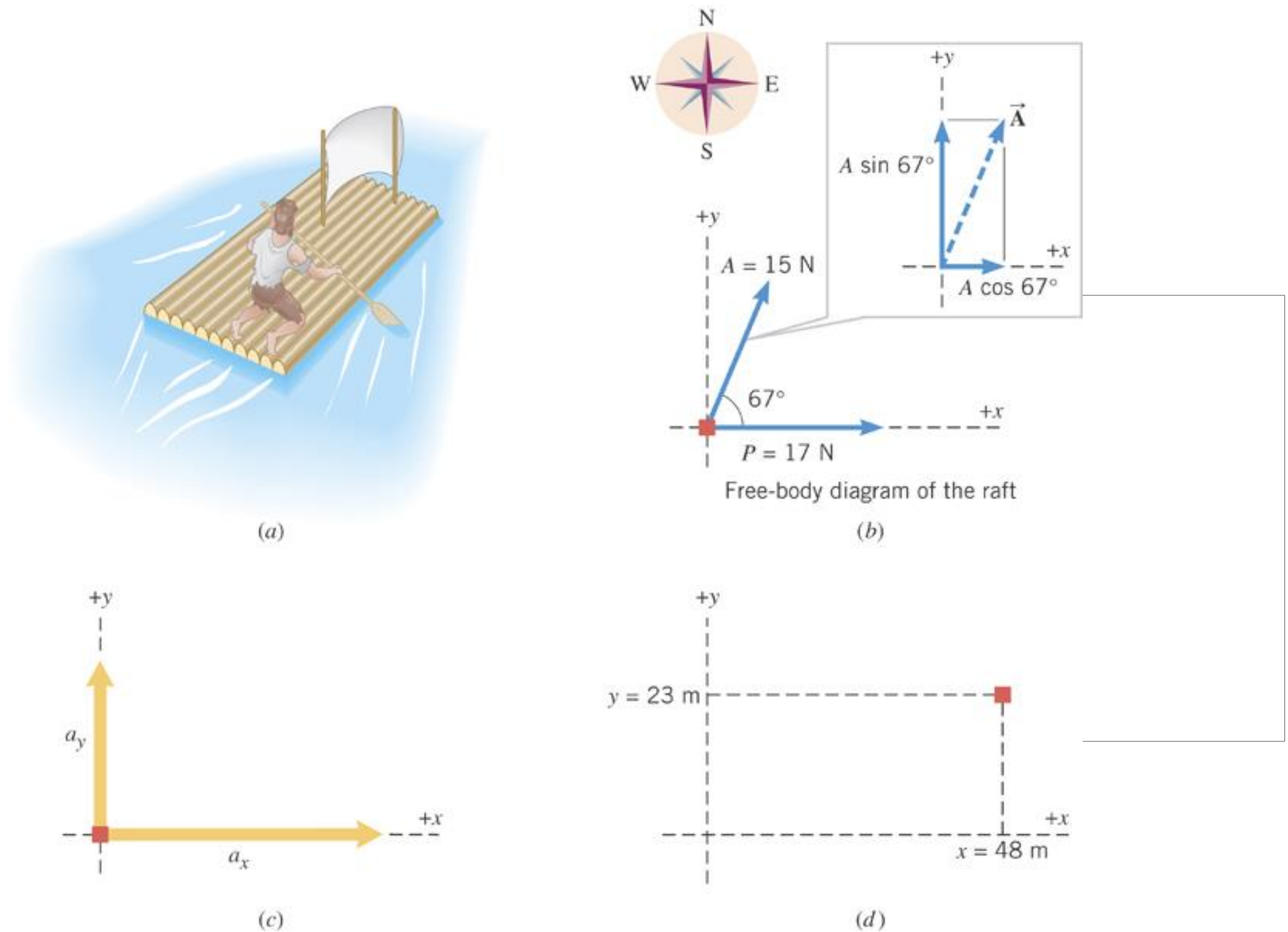
The direction of force and acceleration vectors can be taken into account by using *x* and *y* components.

$$\sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

is equivalent to

$$\sum F_y = ma_y \qquad \sum F_x = ma_x$$

4.4 The Vector Nature of Newton's Second Law



The net force on the raft can be calculated in the following way:

Force	*x* component	*y* component
$\vec{\mathbf{P}}$	+17 N	0 N
$\vec{\mathbf{A}}$	+(15 N) cos67	+(15 N) sin67
	+23 N	+14 N

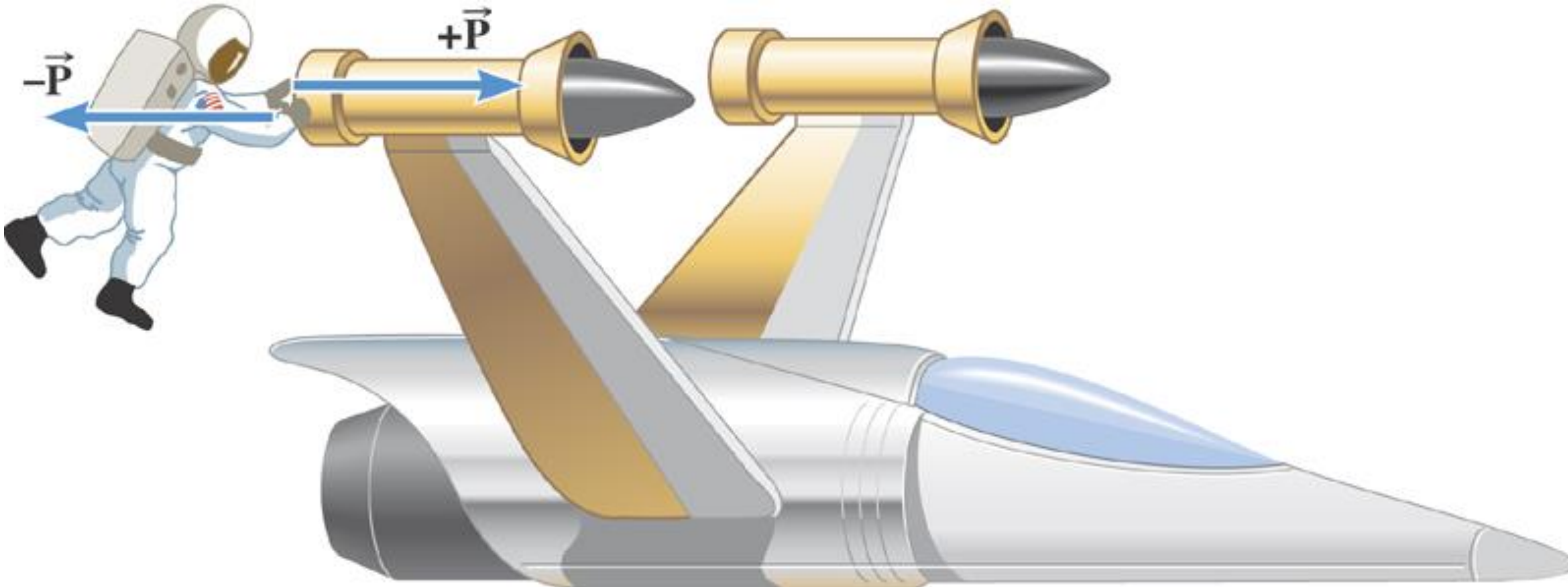
4.4 The Vector Nature of Newton's Second Law

$$a_x = \frac{\sum F_x}{m} = \frac{+23\,\text{N}}{1300\,\text{kg}} = +0.018\,\text{m/s}^2$$

$$a_y = \frac{\sum F_y}{m} = \frac{+14\,\text{N}}{1300\,\text{kg}} = +0.011\,\text{m/s}^2$$

Newton's Third Law of Motion

Whenever one body exerts a force on a second body, the second body exerts an oppositely directed force of equal magnitude on the first body.



Suppose that the magnitude of the force is 36 N. If the mass of the spacecraft is 11,000 kg and the mass of the astronaut is 92 kg, what are the accelerations?

4.5 Newton's Third Law of Motion

$$\text{On the spacecraft } \sum \vec{\mathbf{F}} = \vec{\mathbf{P}}.$$

$$\text{On the astronaut } \sum \vec{\mathbf{F}} = -\vec{\mathbf{P}}.$$

$$\vec{\mathbf{a}}_s = \frac{\vec{\mathbf{P}}}{m_s} = \frac{+36\text{ N}}{11{,}000\text{ kg}} = +0.0033\text{ m/s}^2$$

$$\vec{\mathbf{a}}_A = \frac{-\vec{\mathbf{P}}}{m_A} = \frac{-36\text{ N}}{92\text{ kg}} = -0.39\text{ m/s}^2$$

In nature there are two general types of forces, fundamental and nonfundamental.

Fundamental Forces

1. Gravitational force

2. Strong Nuclear force

3. Electroweak force

Examples of nonfundamental forces:

friction

tension in a rope

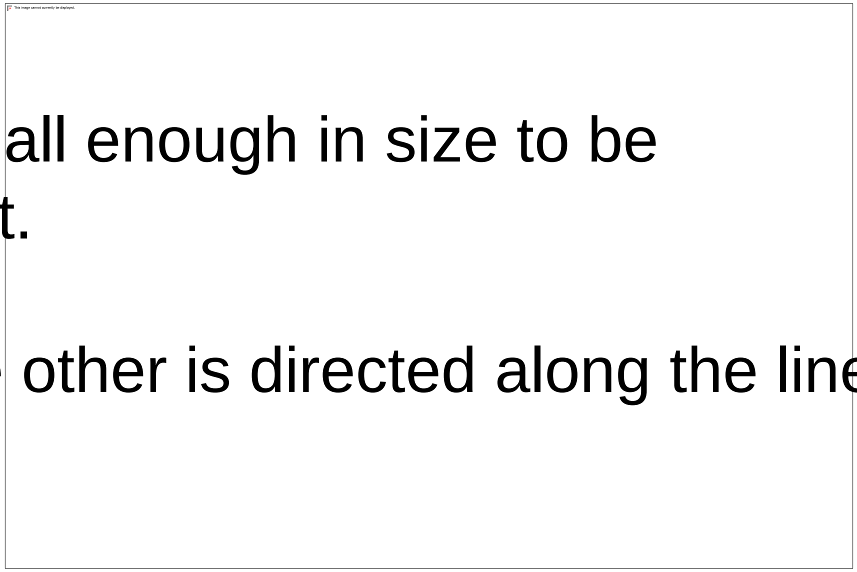
normal or support forces

Newton's Law of Universal Gravitation

Every particle in the universe exerts an attractive force on every other particle.

A particle is a piece of matter, small enough in size to be regarded as a mathematical point.

The force that each exerts on the other is directed along the line joining the particles.

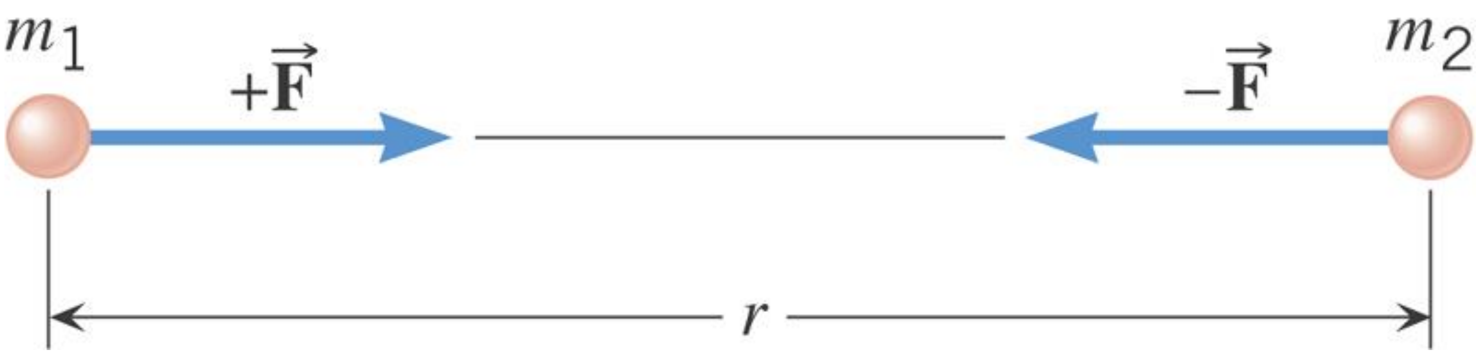


4.7 *The Gravitational Force*

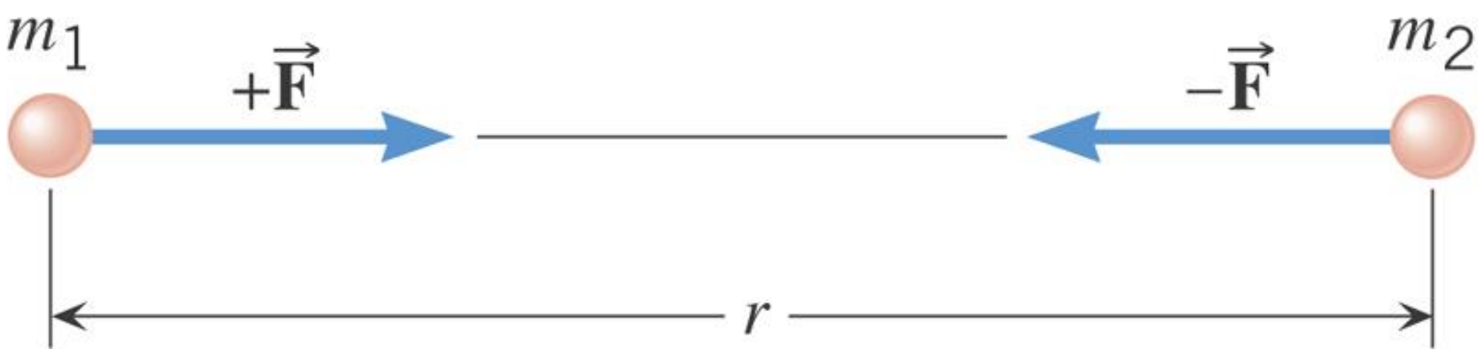
For two particles that have masses m_1 and m_2 and are separated by a distance *r*, the force has a magnitude given by

$$F = G\frac{m_1 m_2}{r^2}$$

$$G = 6.673 \times 10^{-11}\ \mathrm{N \cdot m^2 / kg^2}$$



4.7 The Gravitational Force

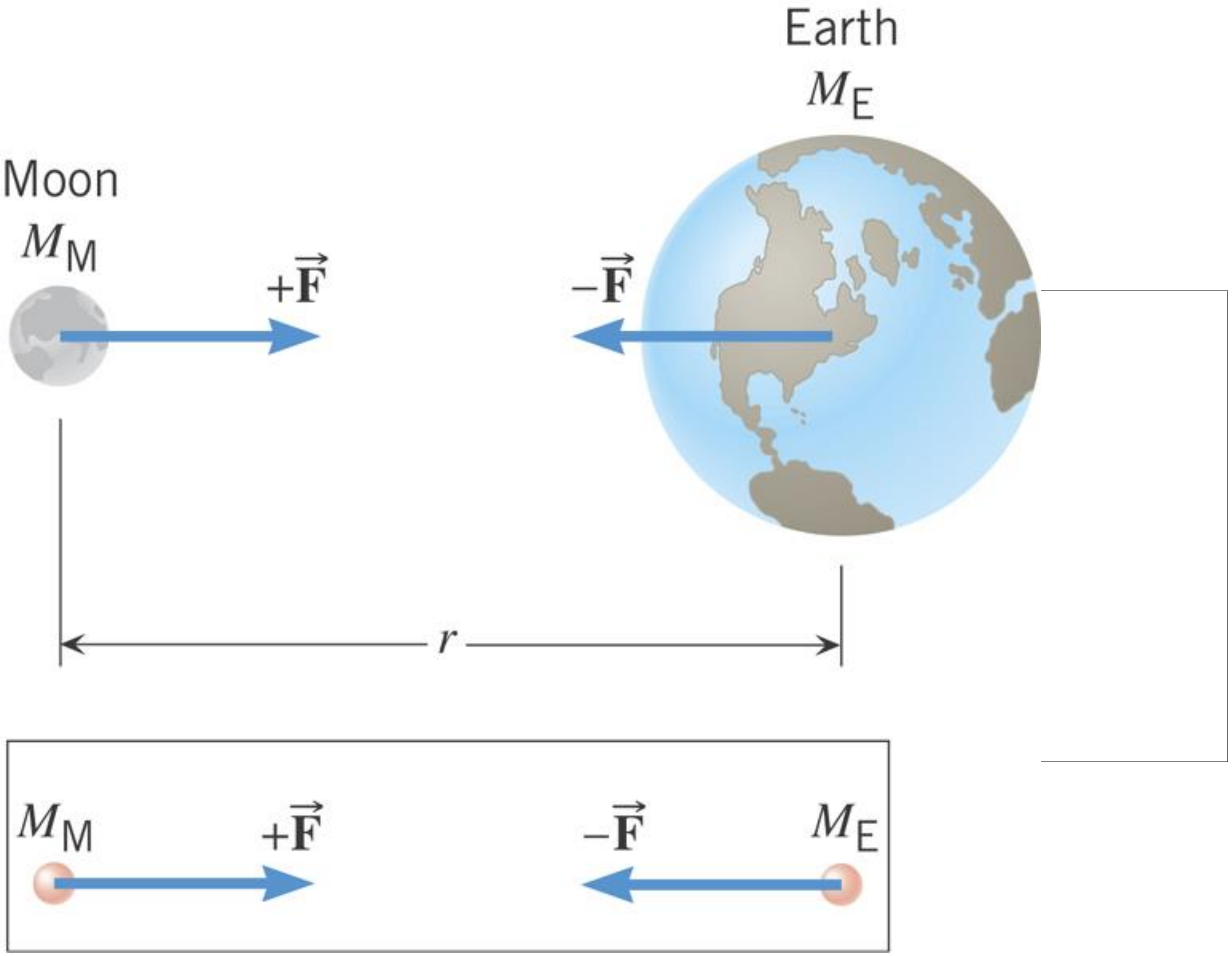


$$F = G\frac{m_1 m_2}{r^2}$$

$$= \left(6.67\times10^{-11}\ \mathrm{N\cdot m^2/kg^2}\right)\frac{(12\ \mathrm{kg})(25\ \mathrm{kg})}{(1.2\ \mathrm{m})^2}$$

$$= 1.4\times10^{-8}\ \mathrm{N}$$

4.7 The Gravitational Force



Definition of Weight

The weight of an object on or above the earth is the gravitational force that the earth exerts on the object. The weight always acts downwards, toward the center of the earth.

On or above another astronomical body, the weight is the gravitational force exerted on the object by that body.

SI Unit of Weight: newton (N)

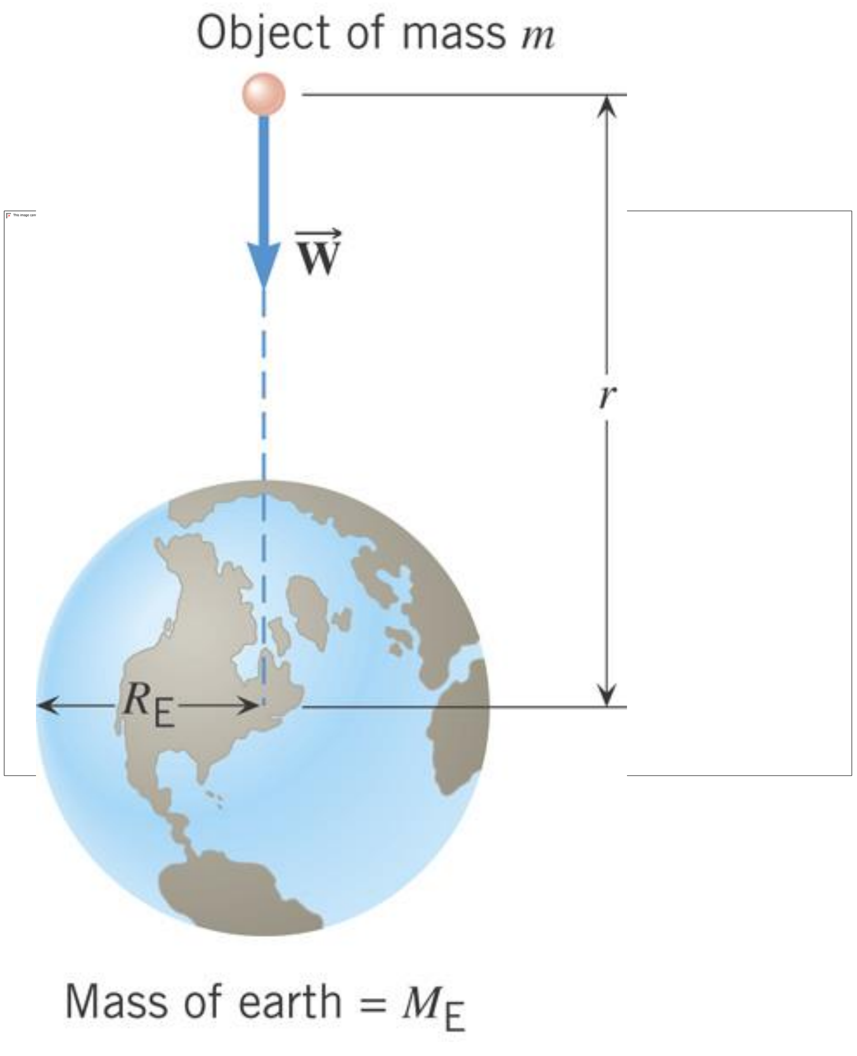
4.7 The Gravitational Force

Relation Between Mass and Weight

$$W = G\frac{M_E m}{r^2}$$

$$W = mg$$

$$g = G\frac{M_E}{r^2}$$



4.7 The Gravitational Force

On the earth's surface:

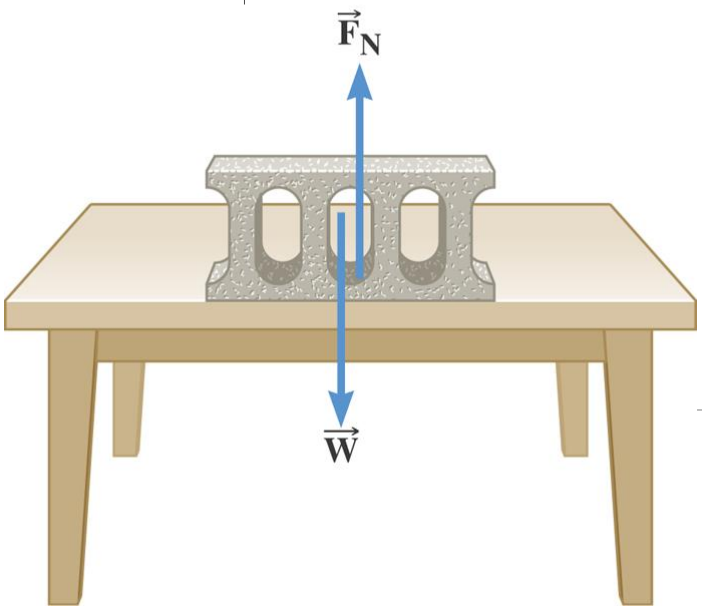
$$g = G\frac{M_E}{R_E^2}$$

$$= \left(6.67\times10^{-11}\ \mathrm{N\cdot m^2/kg^2}\right)\frac{\left(5.98\times10^{24}\ \mathrm{kg}\right)}{\left(6.38\times10^{6}\ \mathrm{m}\right)^2}$$

$$= 9.80\ \mathrm{m/s^2}$$

Definition of the Normal Force

The normal force is one component of the force that a surface exerts on an object with which it is in contact – namely, the component that is perpendicular to the surface.



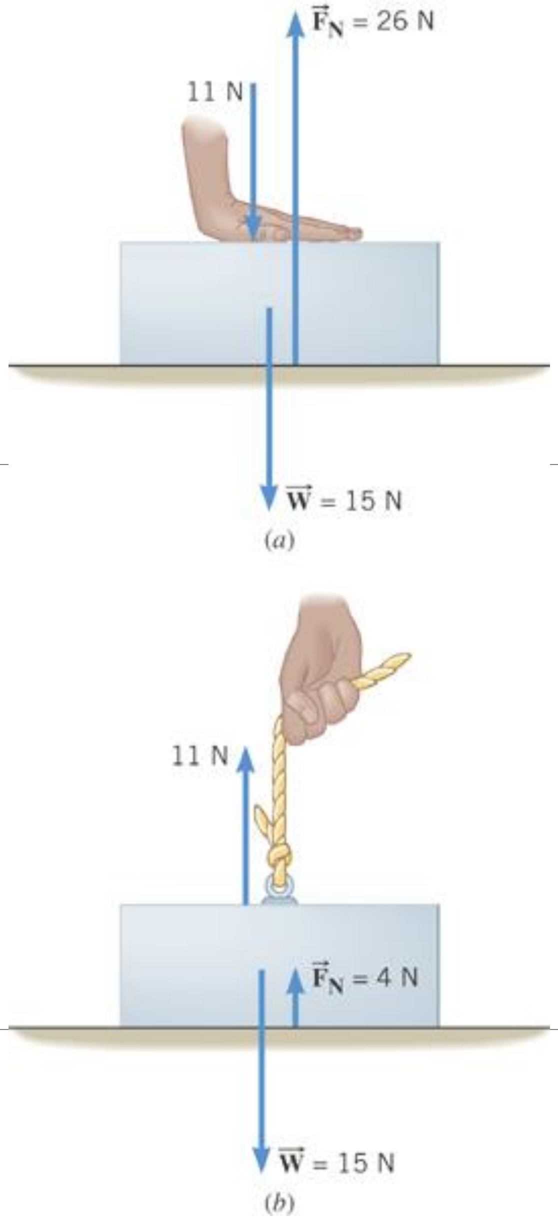
4.8 The Normal Force

$$F_N - 11\ \text{N} - 15\ \text{N} = 0$$

$$F_N = 26\ \text{N}$$

$$F_N + 11\ \text{N} - 15\ \text{N} = 0$$

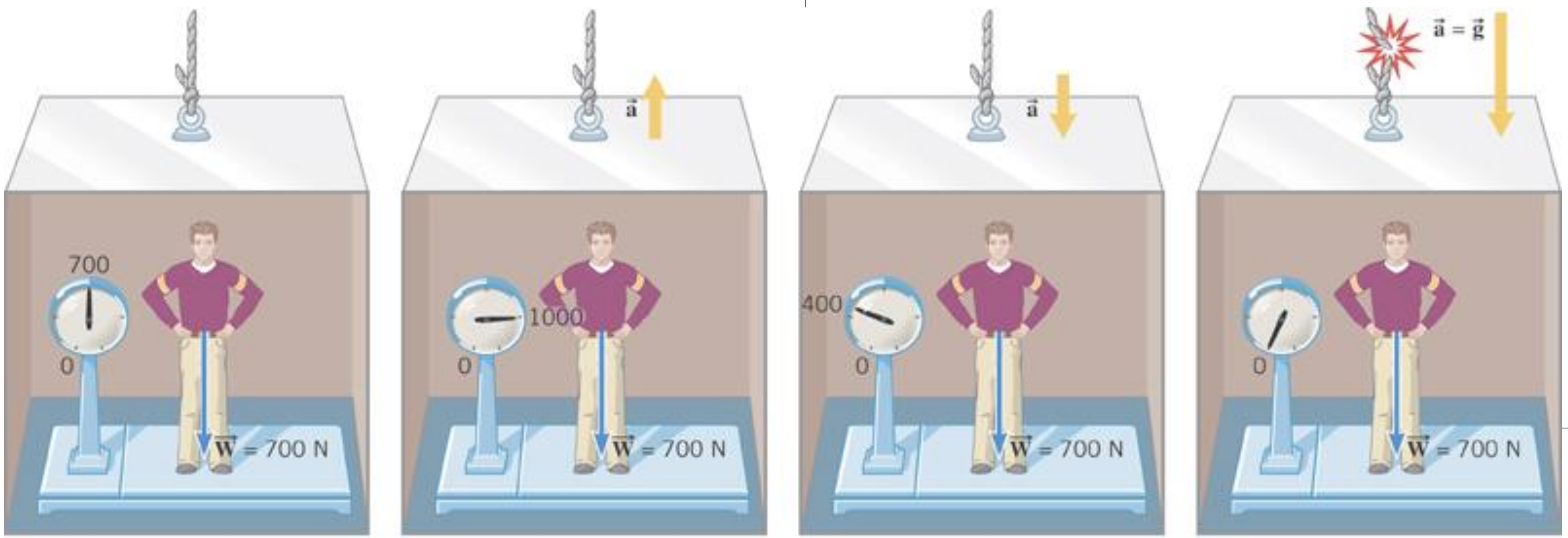
$$F_N = 4\ \text{N}$$



Apparent Weight

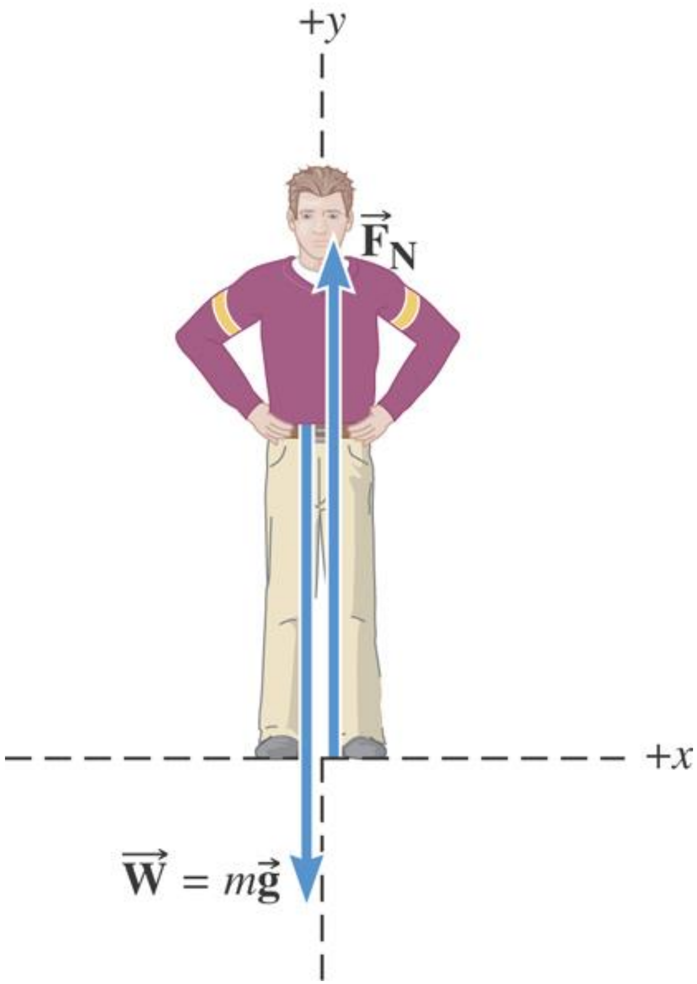
The apparent weight of an object is the reading of the scale.

It is equal to the normal force the man exerts on the scale.



(*a*) No acceleration ($\vec{v}$ = constant) (*b*) Upward acceleration (*c*) Downward acceleration (*d*) Free-fall

4.8 The Normal Force



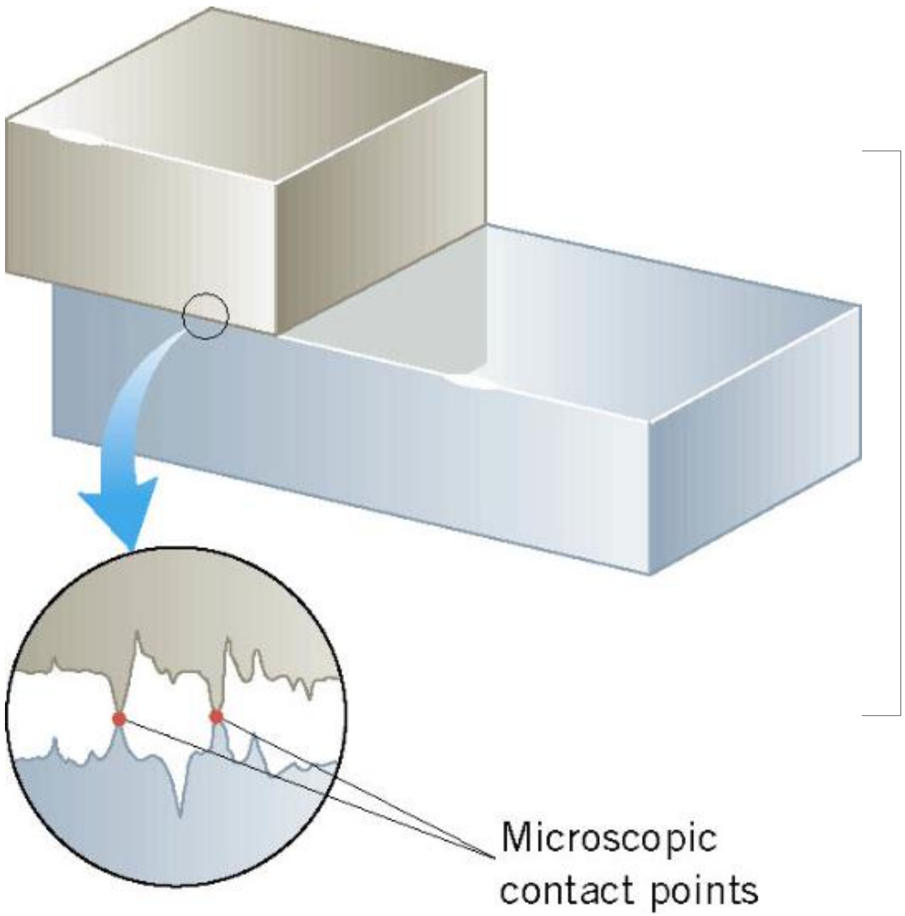
$$\sum F_y = +F_N - mg = ma$$

$$F_N = mg + ma$$

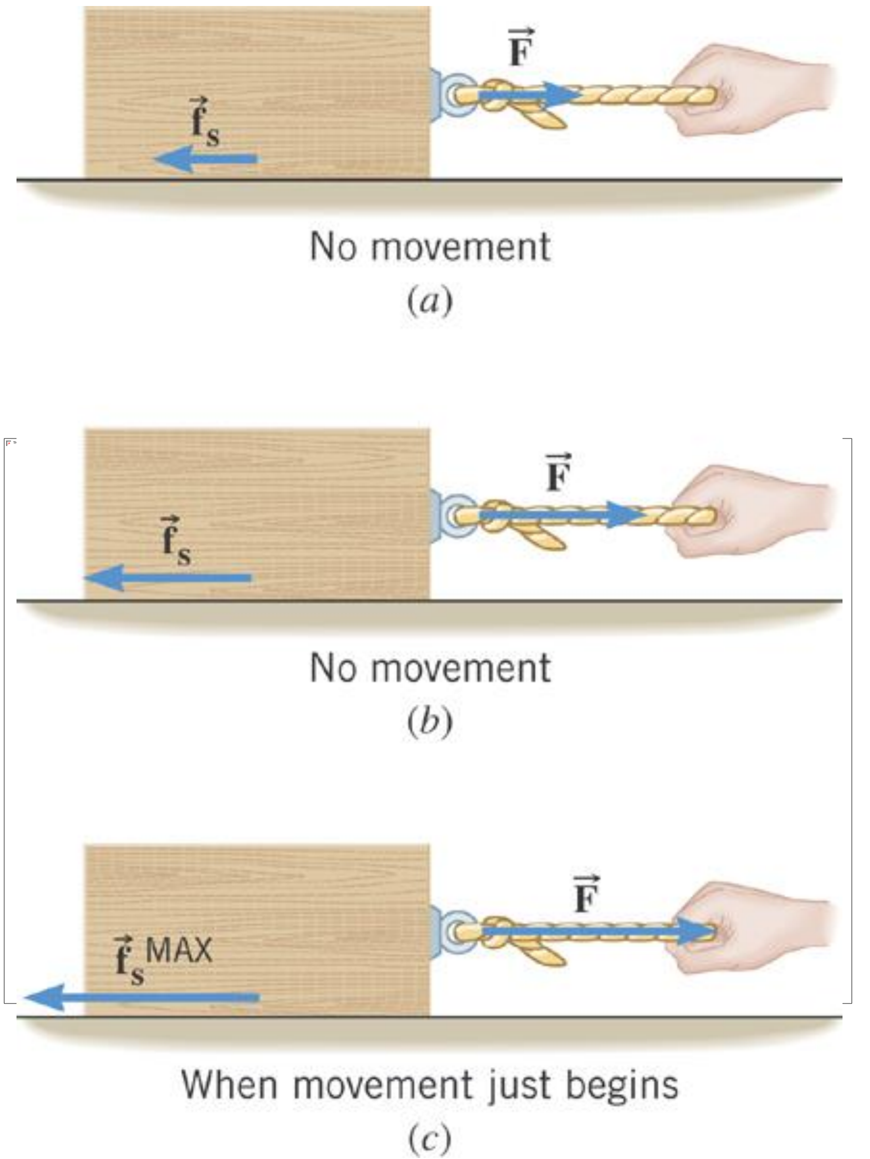
apparent weight (F_N)

true weight (mg)

When an object is in contact with a surface there is a force acting on that object. The component of this force that is parallel to the surface is called the ***frictional force***.



When the two surfaces are not sliding across one another the friction is called ***static friction***.



4.9 Static and Kinetic Frictional Forces

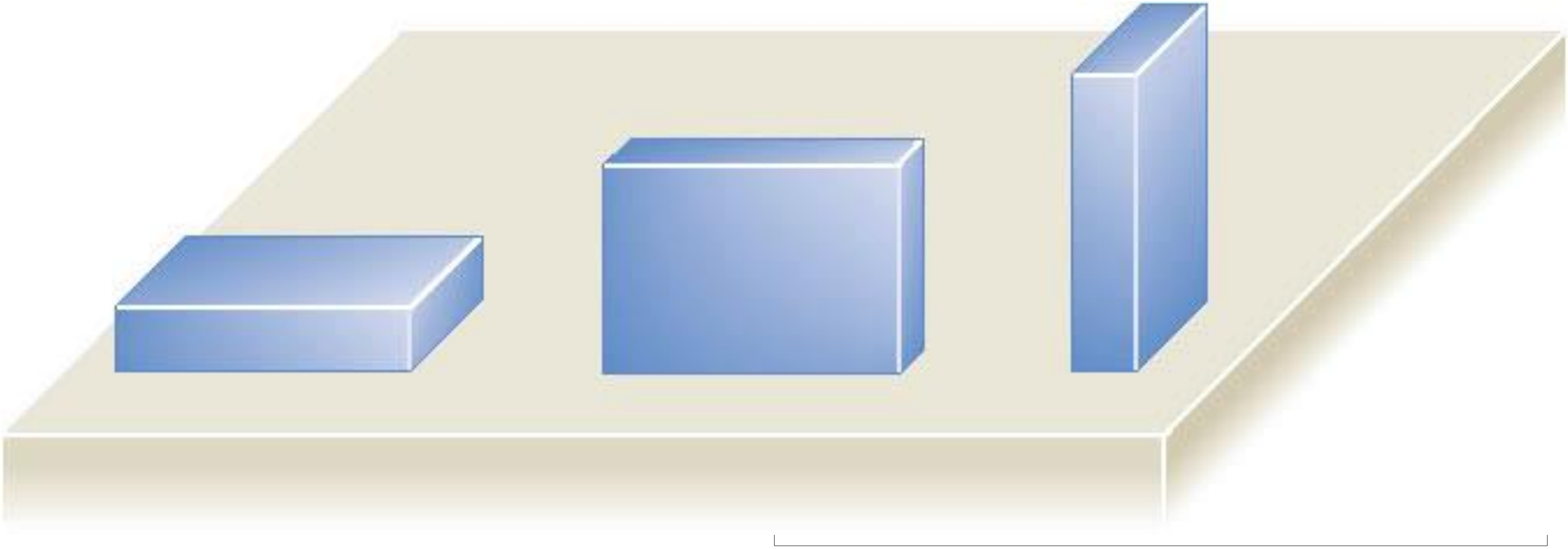
The magnitude of the static frictional force can have any value from zero up to a maximum value.

$$f_s \leq f_s^{MAX}$$

$$f_s^{MAX} = \mu_s F_N$$

$$0 \leq \mu_s$$ is called the coefficient of static friction.

Note that the magnitude of the frictional force does not depend on the contact area of the surfaces.



4.9 *Static and Kinetic Frictional Forces*

Static friction opposes the *impending* relative motion between two objects.

Kinetic friction opposes the relative sliding motion motions that actually does occur.

$$f_k = \mu_k F_N$$

$0 \leq \mu_k$ is called the coefficient of kinetic friction.

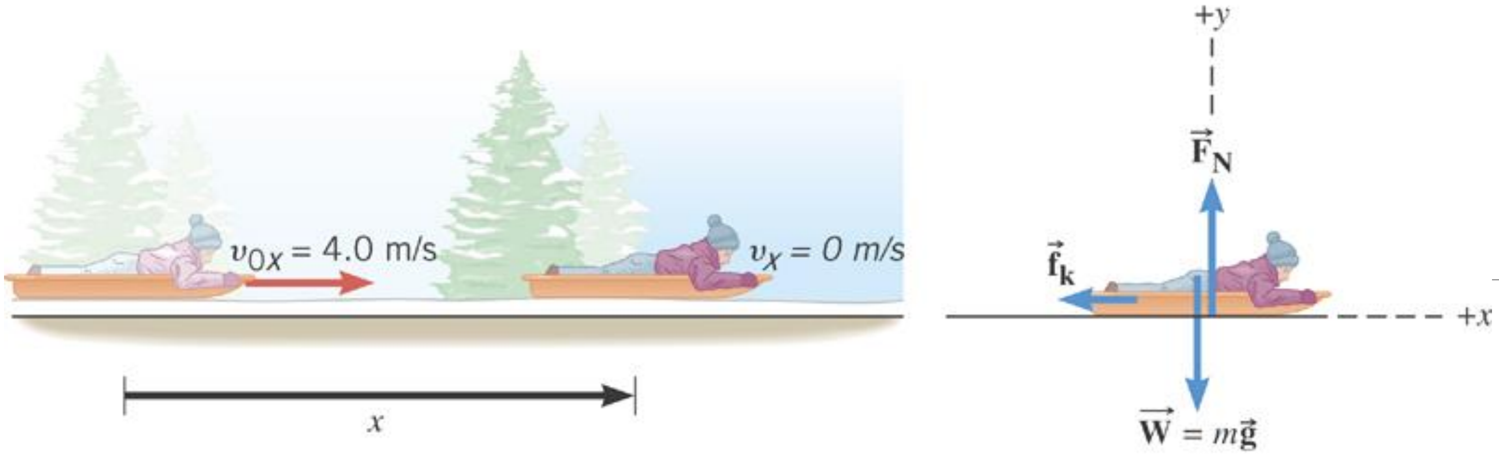
4.9 Static and Kinetic Frictional Forces

Table 4.2 **Approximate Values of the Coefficients of Friction for Various Surfaces***

Materials	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Glass on glass (dry)	0.94	0.4
Ice on ice (clean, 0 °C)	0.1	0.02
Rubber on dry concrete	1.0	0.8
Rubber on wet concrete	0.7	0.5
Steel on ice	0.1	0.05
Steel on steel (dry hard steel)	0.78	0.42
Teflon on Teflon	0.04	0.04
Wood on wood	0.35	0.3

*The last column gives the coefficients of kinetic friction, a concept that will be discussed shortly.

4.9 Static and Kinetic Frictional Forces

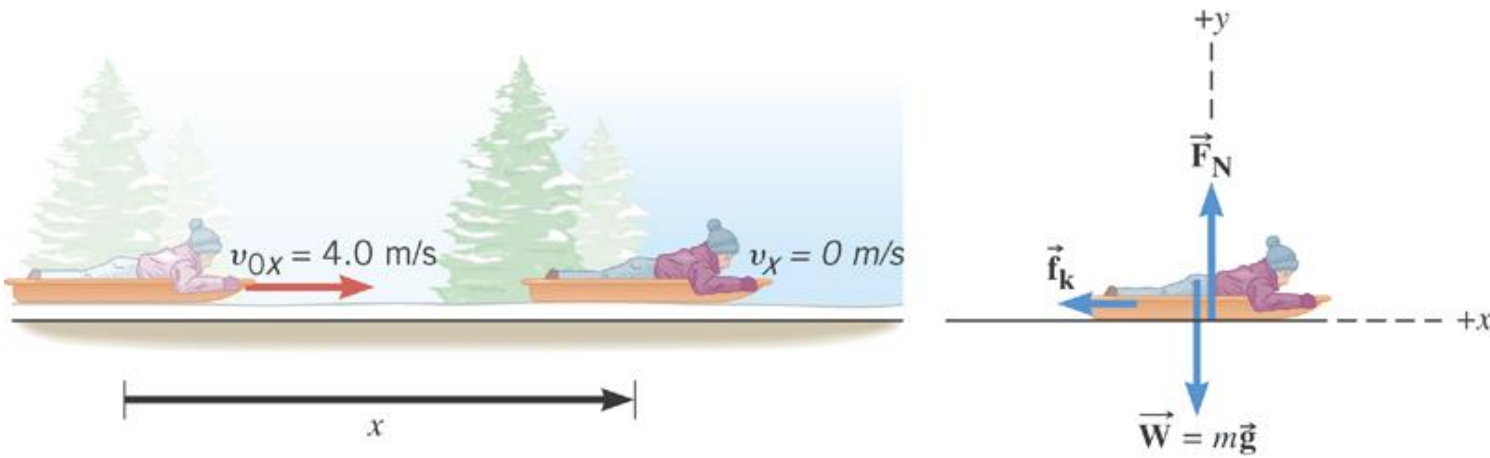


(a)

(b) Free-body diagram for the sled and rider

The sled comes to a halt because the kinetic frictional force opposes its motion and causes the sled to slow down.

4.9 Static and Kinetic Frictional Forces



(a)

(b) Free-body diagram for the sled and rider

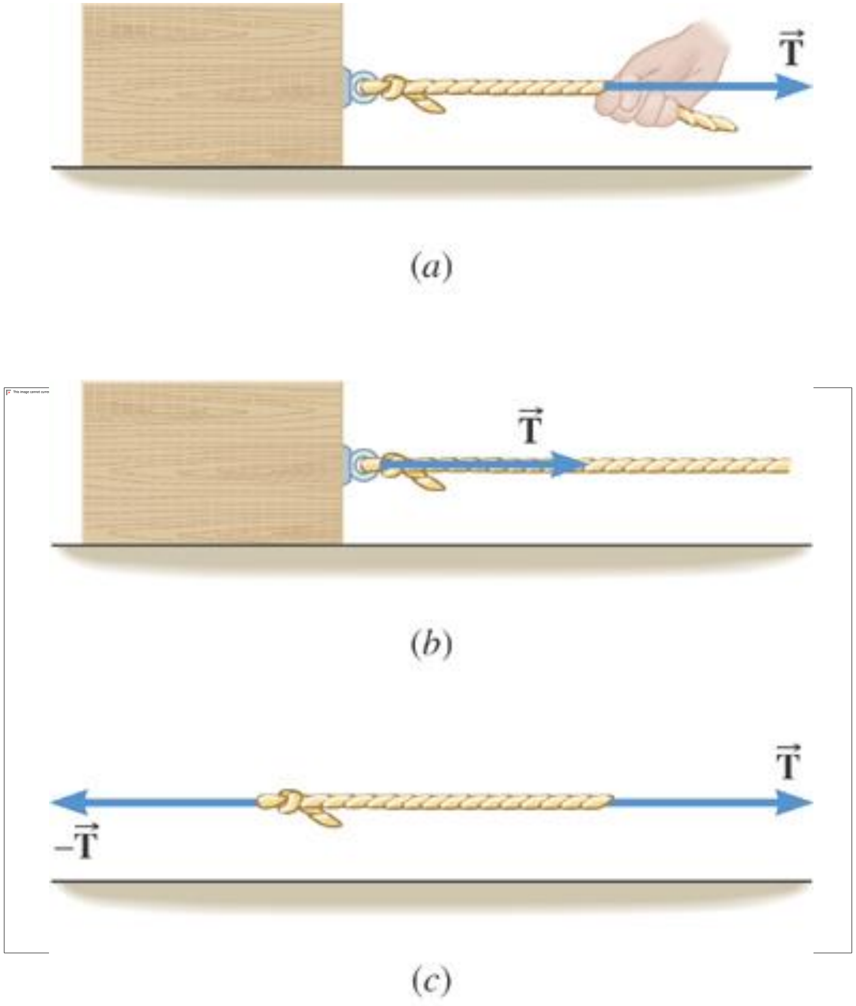
Suppose the coefficient of kinetic friction is 0.05 and the total mass is 40kg. What is the kinetic frictional force?

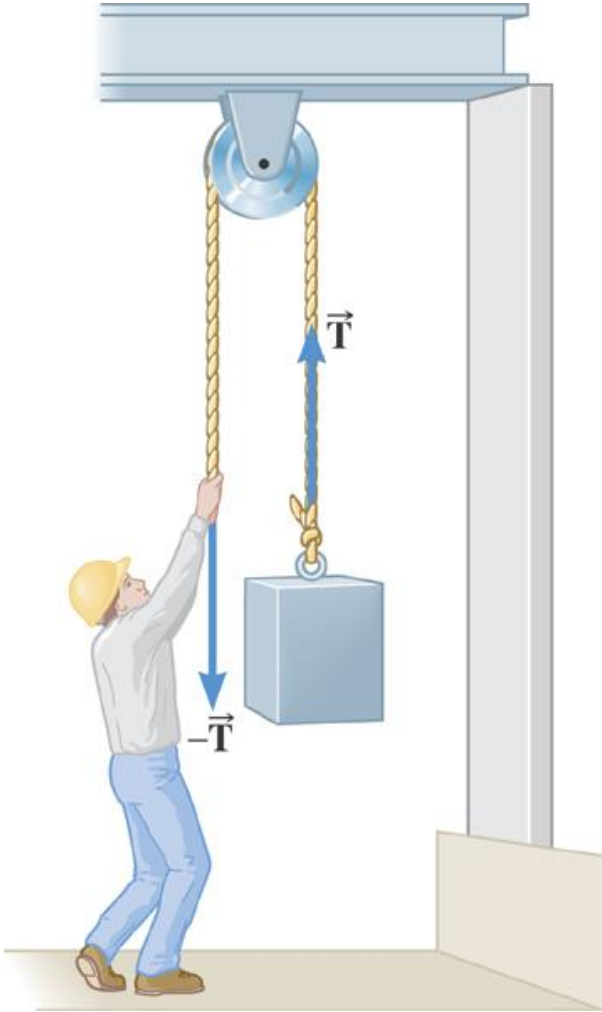
$$f_k = \mu_k F_N = \mu_k mg =$$

$$0.05(40\,\text{kg})(9.80\,\text{m/s}^2) = 20\,\text{N}$$

4.10 The Tension Force

Cables and ropes transmit forces through ***tension***.





A massless rope will transmit tension undiminished from one end to the other.

If the rope passes around a massless, frictionless pulley, the tension will be transmitted to the other end of the rope undiminished.

4.11 Equilibrium Application of Newton's Laws of Motion

Definition of Equilibrium

An object is in equilibrium when it has zero acceleration.

$$\sum F_x = 0$$

$$\sum F_y = 0$$

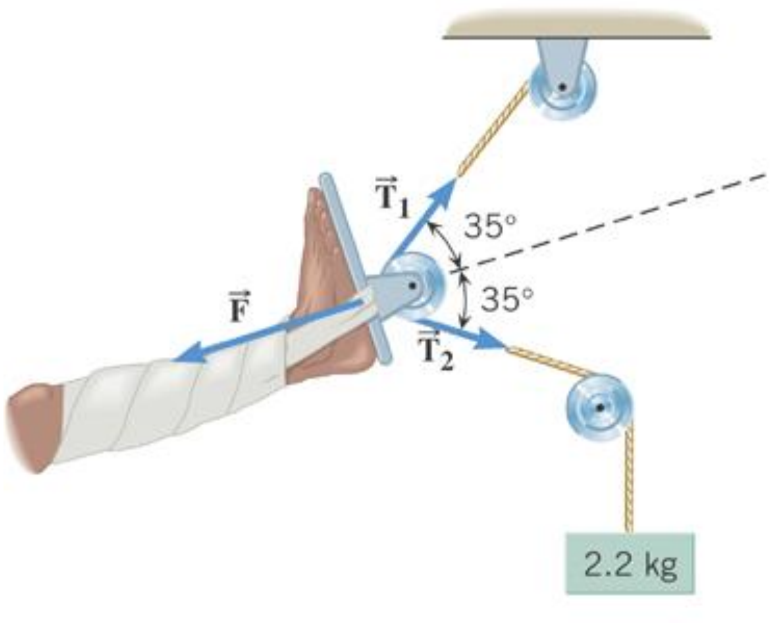
Reasoning Strategy

- Select an object(s) to which the equations of equilibrium are to be applied.

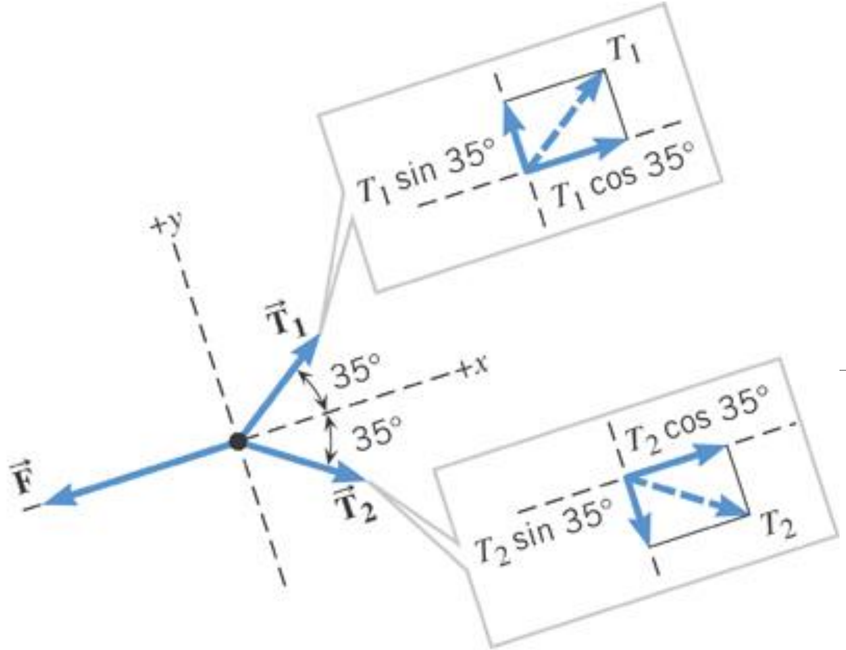
- Draw a free-body diagram for each object chosen above. Include only forces acting on the object, not forces the object exerts on its environment.

- Choose a set of *x*, *y* axes for each object and resolve all forces in the free-body diagram into components that point along these axes.

- Apply the equations and solve for the unknown quantities.



(a)

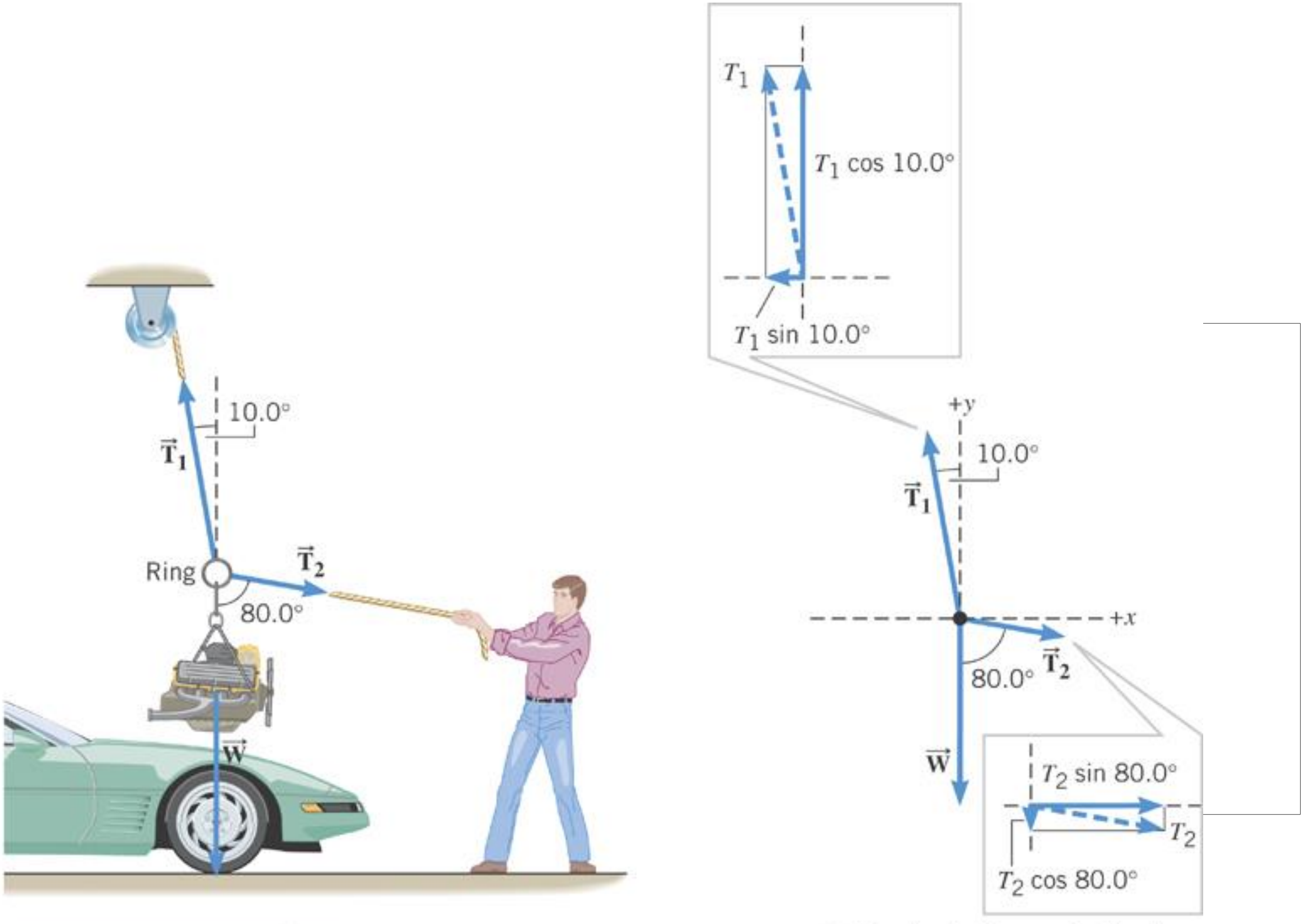


(b) Free-body diagram for the foot pulley

$$+T_1 \sin 35^\circ - T_2 \sin 35^\circ = 0$$

$$+T_1 \cos 35^\circ + T_2 \cos 35^\circ - F = 0$$

4.11 Equilibrium Application of Newton's Laws of Motion



(a)

(b) Free-body diagram for the ring

4.11 Equilibrium Application of Newton's Laws of Motion

Force	*x component*	*y* component
$\vec{\mathbf{T}}_1$	$-T_1 \sin 10.0^\circ$	$+T_1 \cos 10.0^\circ$
$\vec{\mathbf{T}}_2$	$+T_2 \sin 80.0^\circ$	$-T_2 \cos 80.0^\circ$
$\vec{\mathbf{W}}$	0	$-W$

$$W = 3150\ \text{N}$$

4.11 Equilibrium Application of Newton’s Laws of Motion

$$\sum F_x = -T_1 \sin 10.0^\circ + T_2 \sin 80.0^\circ = 0$$

$$\sum F_y = +T_1 \cos 10.0^\circ - T_2 \cos 80.0^\circ - W = 0$$

The first equation gives $T_1 = \left(\dfrac{\sin 80.0^\circ}{\sin 10.0^\circ} \right) T_2$

Substitution into the second gives

$$\left(\frac{\sin 80.0^\circ}{\sin 10.0^\circ} \right) T_2 \cos 10.0^\circ - T_2 \cos 80.0^\circ - W = 0$$

4.11 Equilibrium Application of Newton's Laws of Motion

$$T_2 = \frac{W}{\left(\dfrac{\sin 80.0^\circ}{\sin 10.0^\circ}\right)\cos 10.0^\circ - \cos 80.0^\circ}$$

$$T_2 = 582\ \text{N}$$

$$T_1 = 3.30 \times 10^3\ \text{N}$$

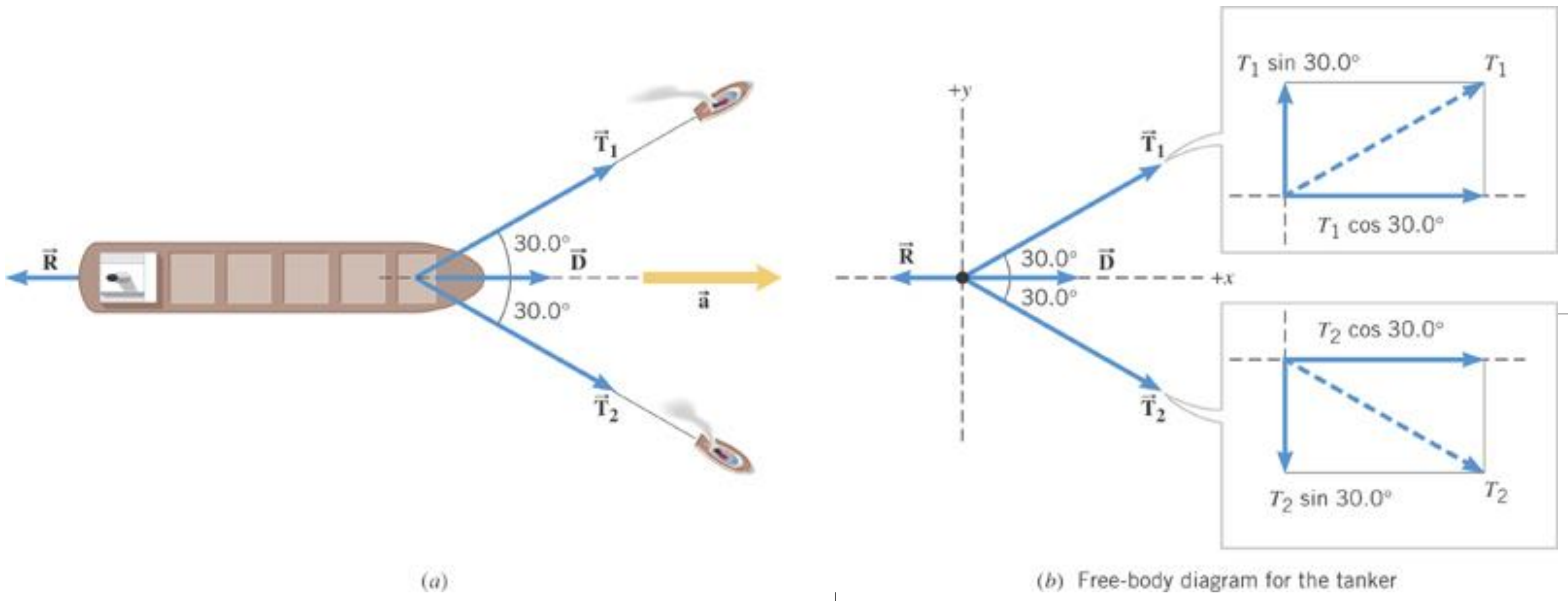
4.12 Nonequilibrium Application of Newton's Laws of Motion

When an object is accelerating, it is not in equilibrium.

$$\sum F_x = ma_x$$

$$\sum F_y = ma_y$$

4.12 Nonequilibrium Application of Newton's Laws of Motion



The acceleration is along the *x* axis so $a_y = 0$

4.12 Nonequilibrium Application of Newton's Laws of Motion

Force	*x* component	*y* component
$\vec{\mathbf{T}}_1$	$+T_1 \cos 30.0^\circ$	$+T_1 \sin 30.0^\circ$
$\vec{\mathbf{T}}_2$	$+T_2 \cos 30.0^\circ$	$-T_2 \sin 30.0^\circ$
$\vec{\mathbf{D}}$	$+D$	0
$\vec{\mathbf{R}}$	$-R$	0

4.12 Nonequilibrium Application of Newton's Laws of Motion

$$\sum F_y = +T_1 \sin 30.0^\circ - T_2 \sin 30.0 = 0$$

$$\Rightarrow T_1 = T_2$$

$$\sum F_x = +T_1 \cos 30.0^\circ + T_2 \cos 30.0 + D - R$$

$$= ma_x$$

$$(mass = 1.50x10^8\, kg)$$

4.12 Nonequilibrium Application of Newton's Laws of Motion

$$T_1 = T_2 = T$$

$$T = \frac{ma_x + R - D}{2\cos 30.0^\circ} = 1.53\times 10^5\ \mathrm{N}$$