Chapter 5

FORCE AND MOTION I

Newtonian Mechanics

- In this chapter we explore the relation between force and acceleration, or Newtonian mechanics.
- Newtonian mechanics describe very well almost all dynamical systems encountered in our daily life.

Newton's First Law

- Before Newton, it was believed that a "force" is needed to keep a body moving at a constant velocity. Without the force, the body will approach its "natural state" of rest.
- We know that over a **frictionless surface**, an object in motion hardly slows. The more frictionless the surface, the longer it takes the object to slow down.

<u>Newton's First Law</u>: If no forces act on a body, the body's velocity cannot change (it does not accelerate.)

- An object at rest stays at rest. An object in motion stays in motion with the same velocity (magnitude and direction.)

Force

- Simply, a force is a pull or push.
- The unit of force is Newton (N). A force of 1 Newton accelerates a mass of 1 kg by $1\ \mathrm{m}/s^2$.
- Forces, are vector quantities: they have magnitudes and directions, and combine according to the vector rules. ($\vec{F}$ is used for force)
- Forces acting on an object are added vectorially to find the **net force**, or **resultant force**.
- The net force has the same effect as that of all individual forces. (The **principle of superposition for forces**.)

Force

Newton's First Law: If no force acts on a body ($\vec{F}_{net} = 0$), the body's velocity cannot change (it does not accelerate.)

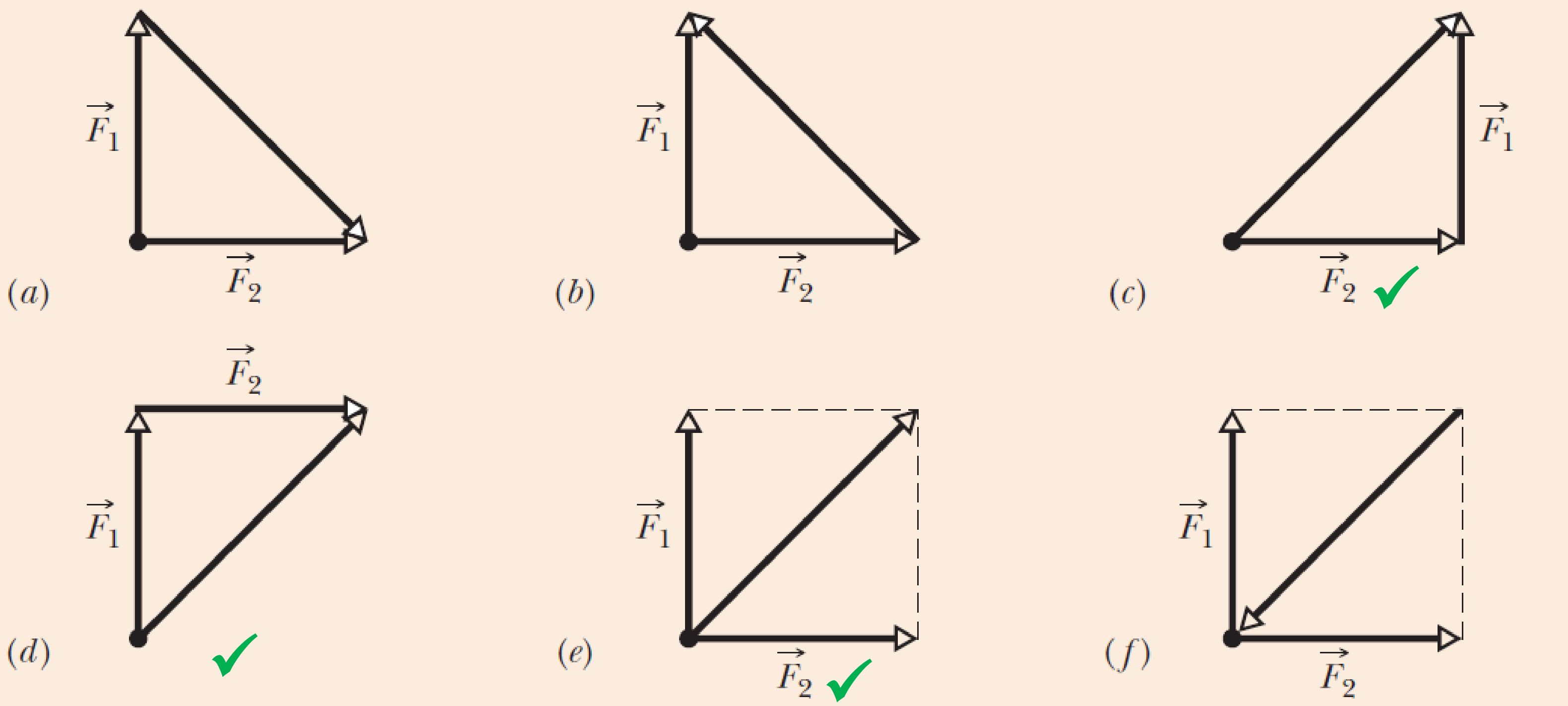
- **Inertial Reference Frames**:

  A reference frame (in which measurements are made) must be nonaccelerating with respect to an object for Newton's first law to hold. Such a reference frame is called an **inertial reference frame**.

Force

CHECKPOINT 1

Which of the figure's six arrangements correctly show the vector addition of forces $\vec{F}_1$ and $\vec{F}_2$ to yield the third vector, which is meant to represent their net force $\vec{F}_{net}$?



Mass

- The same force causes two objects of different masses to accelerate differently.
- The acceleration is inversely proportional to the mass. For instance, the acceleration is halved when the mass is doubled.
- We can measure a mass by measuring its acceleration when a standard force, say, 1.0 N is applied to it.
- The mass of an object is an intrinsic characteristic of it.
- Mass is a scalar quantity.
- In a physical sense, the mass of a body is the characteristic that relates a force on a body to the resulting acceleration.

Newton's Second Law

- Newton's Second Law: The net force on a body is equal to the product of the body's mass and its acceleration

$$\vec{F}_{net} = m\vec{a}.$$

  - Along the axes of an xyz coordinate system

$$F_{net,x} = ma_x; F_{net,y} = ma_y; F_{net,z} = ma_z.$$

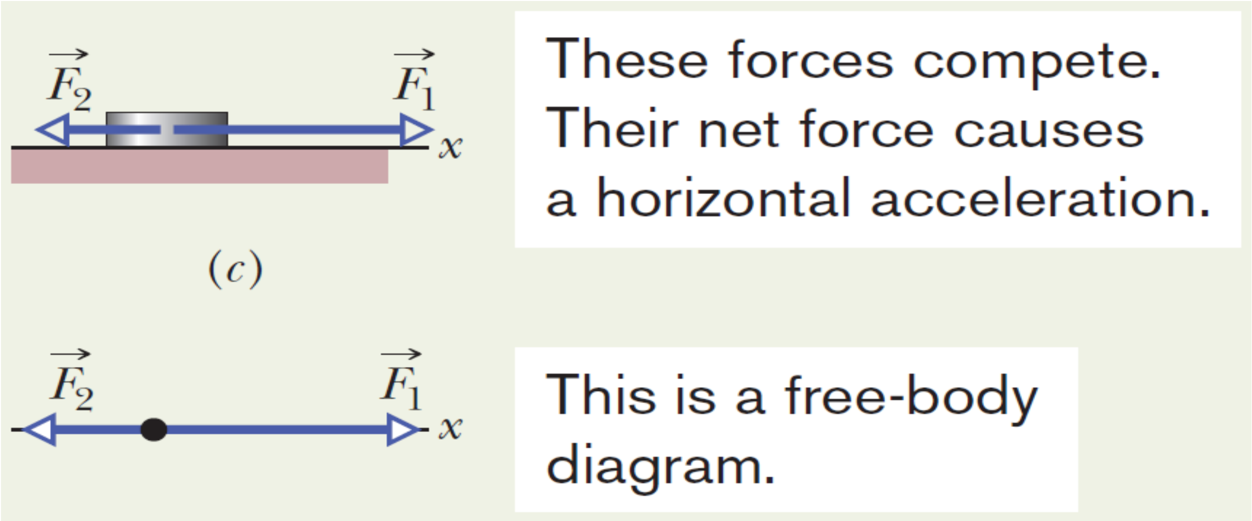
    The acceleration component along a given axis is caused only by the sum of the force components along the same axis.
  - If $\vec{F}_{net} = 0$ for a body then $\vec{a} = 0$. The forces on the body balance (or cancel) one another. The body is in **equilibrium**.

Newton's Second Law

- In SI units

$$1\text{N} = (1\text{kg})(1\text{m/s}^2) = 1\text{kg} \cdot \frac{\text{m}}{\text{s}^2}.$$

- Free-Body Diagram: A body is drawn along with all forces (arrows.) In our book the body is drawn as a dot. Sometimes the acceleration is drawn as well.



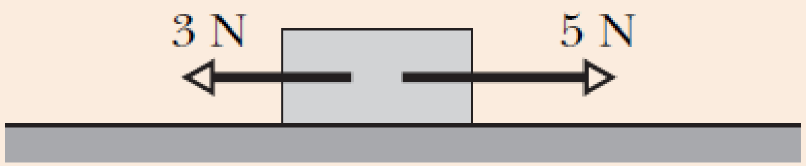
Newton’s Second Law

- A **system** consists of one or more bodies. A force on a body in the system from an external body is called and **external force**. If the bodies making up the system are rigidly connected we can treat the system as one body. $\vec{F}_{net}$ is the vector sum of all external forces. Internal forces between bodies inside the system do not accelerate the system.

Newton’s Second Law

CHECKPOINT 2

The figure here shows two horizontal forces acting on a block on a frictionless floor. If a third horizontal force $\vec{F}_3$ also acts on the block, what are the magnitude and direction of $\vec{F}_3$ when the block is (a) stationary and (b) moving to the left with a constant speed of 5 m/s?

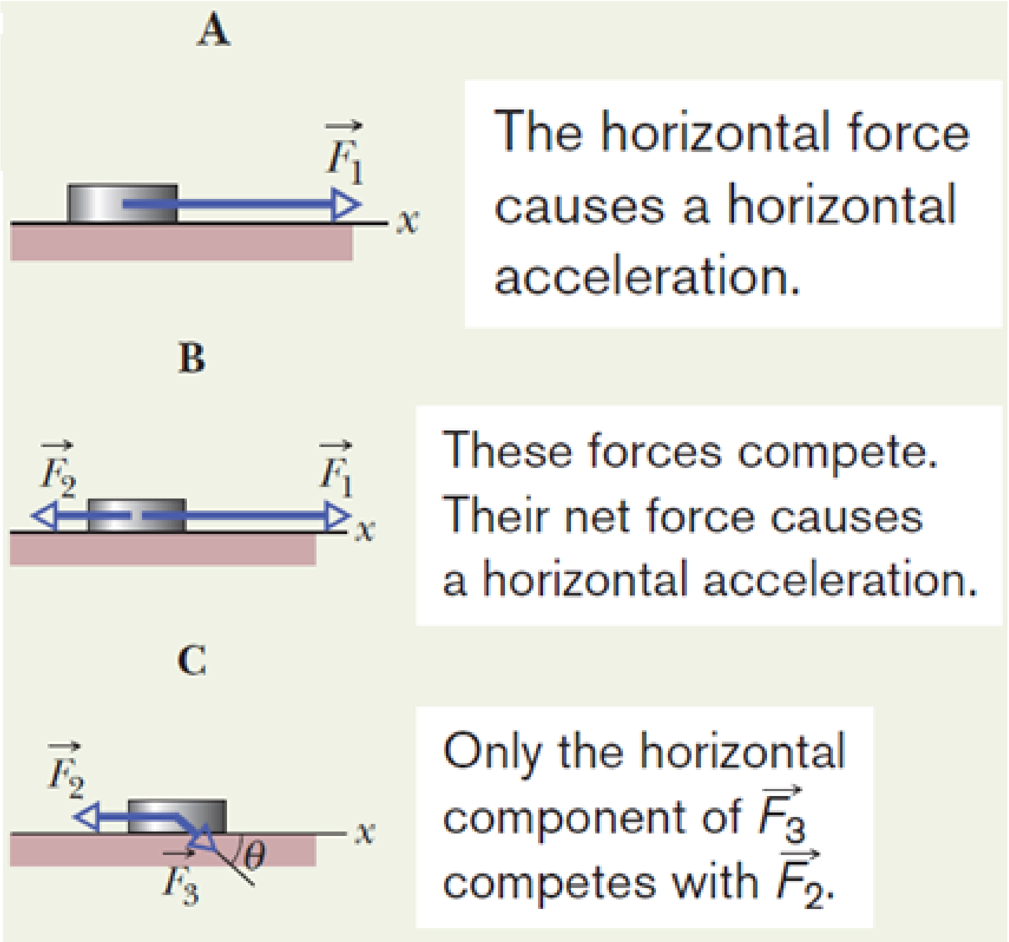


a) $\vec{a} = 0$ or $\vec{F}_{net} = 0$. Hence $\vec{F}_3 = 2$ N leftward.

b) $\vec{a} = 0$ or $\vec{F}_{net} = 0$. Hence $\vec{F}_3 = 2$ N leftward.

Newton's Second Law

Example 1: The forces on a $0.20\ \mathrm{kg}$ puck are shown in three different situations. $\vec{F}_1$ and $\vec{F}_2$ are directed along the axis and have magnitudes $F_1 = 4.0\ \mathrm{N}$ and $F_2 = 2.0\ \mathrm{N}$. Force $\vec{F}_3$ is directed at angle $\theta = 30°$ and has magnitude $F_3 = 1.0\ \mathrm{N}$. In each situation, what is the acceleration of the puck?



Newton's Second Law

The motion is along the x axis in the three cases. Newton's 2nd for the x components is

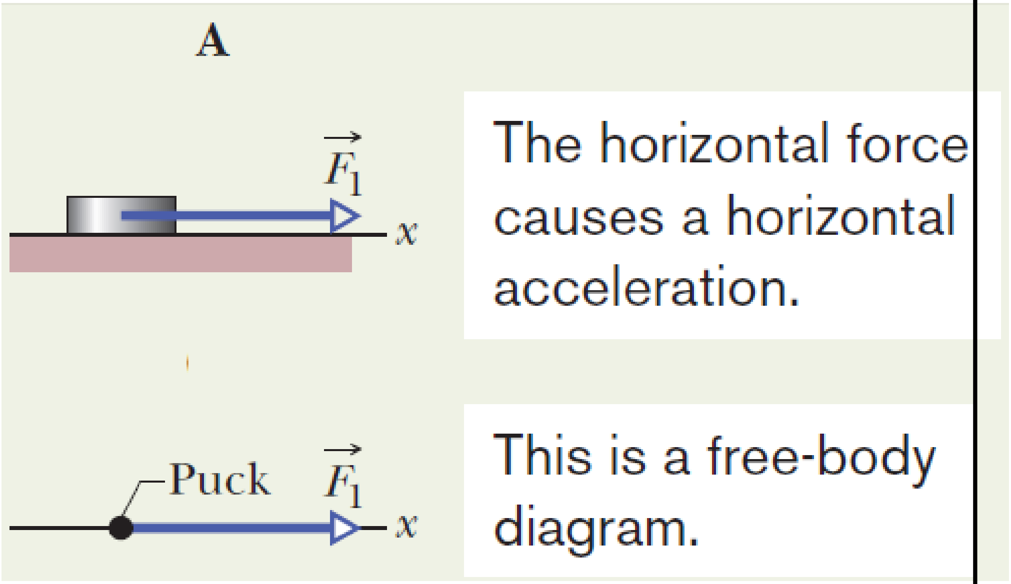
$$F_{net,x} = ma_x.$$

A) In this case $F_{net,x} = F_1$. Therefore,

$$F_1 = ma_x,$$

or

$$a_x = \frac{F_1}{m} = \frac{4.0\ \mathrm{N}}{0.20\ \mathrm{kg}} = 20\ \frac{\mathrm{m}}{\mathrm{s}^2}.$$



Newton's Second Law

B) In this case $F_{net,x} = F_1 - F_2$. Therefore,

$$F_1 - F_2 = ma_x.$$

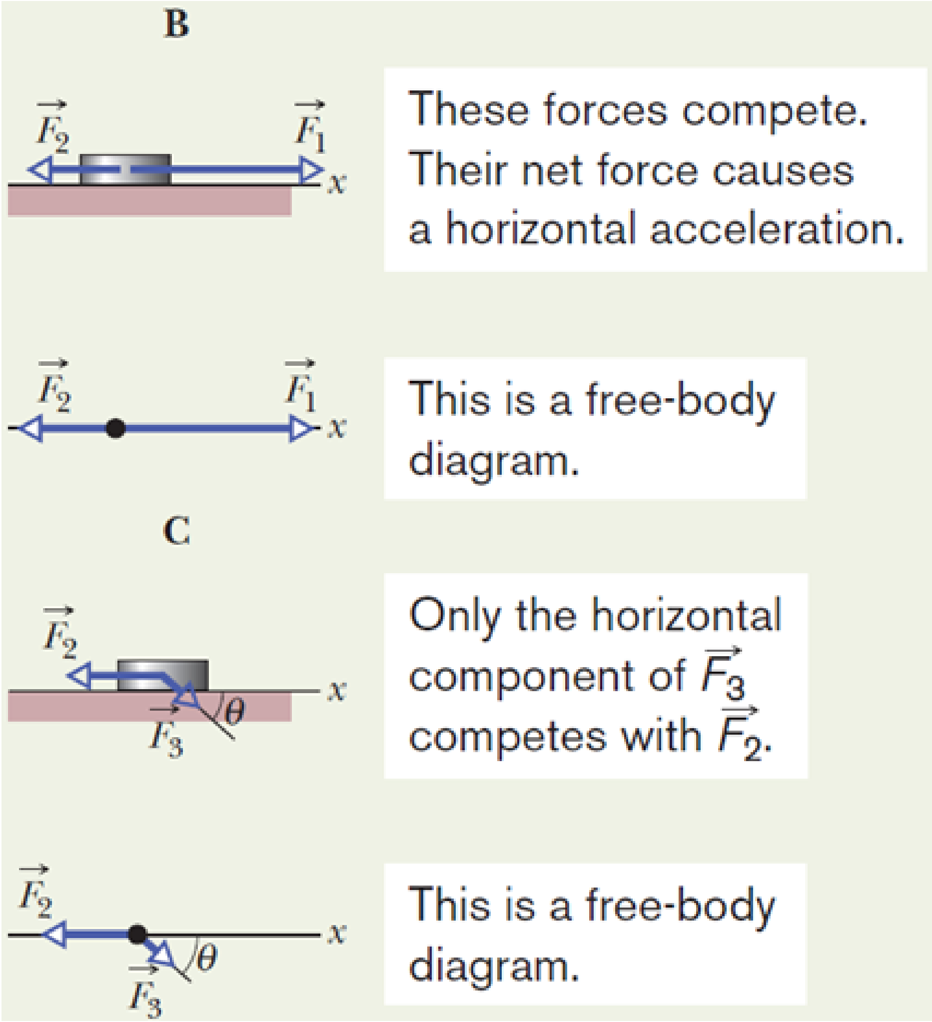
$$a_x = \frac{F_1 - F_2}{m} = \frac{4.0\text{ N} - 2.0\text{ N}}{0.20\text{ kg}} = 10\ \frac{\text{m}}{\text{s}^2}.$$

C) In this case $F_{net,x} = F_{3,x} - F_2$. Therefore,

$$F_3 \cos\theta - F_2 = ma_x.$$

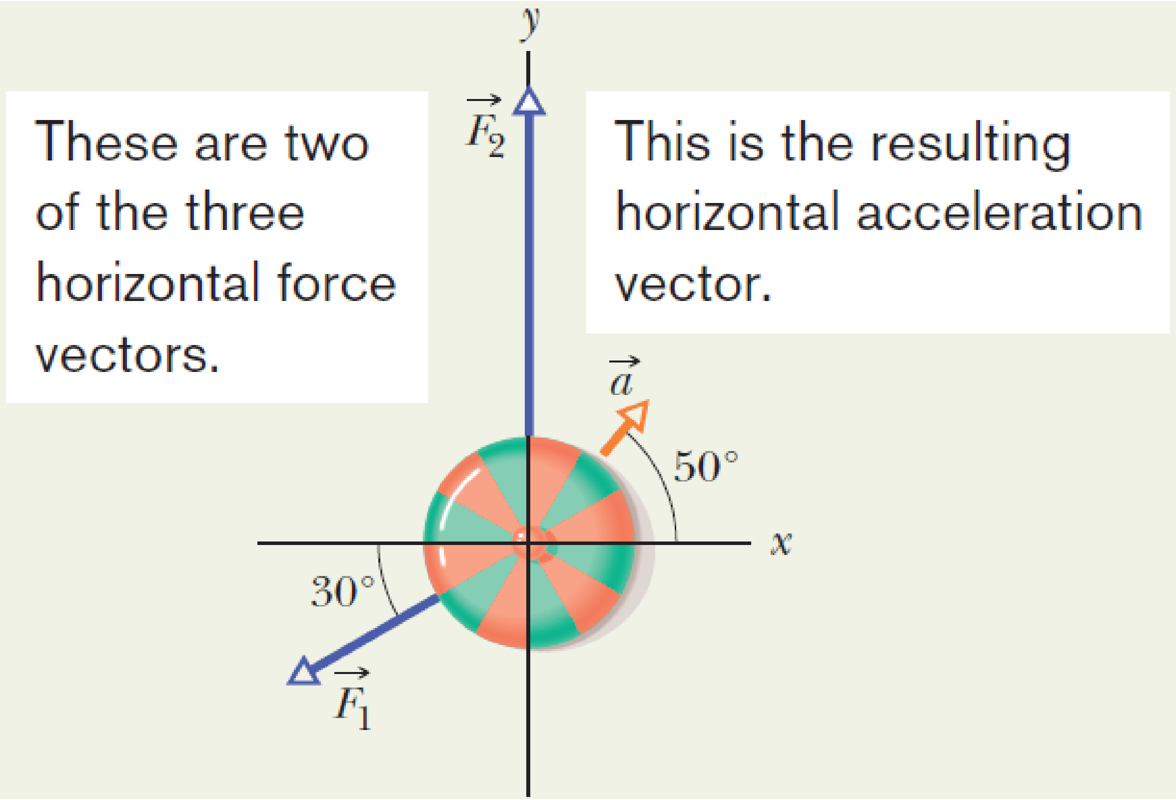
$$a_x = \frac{F_3 \cos\theta - F_2}{m} = \frac{(1.0\text{ N})(\cos -30°) - 2.0\text{ N}}{0.20\text{ kg}}$$

$$= -5.7\ \frac{\text{m}}{\text{s}^2}.$$



Newton's Second Law

Example 2: a $2.0\ \text{kg}$ cookie tin is accelerated at $3.0\ \text{m/s}^2$ in the direction shown by $\vec{a}$, over a frictionless horizontal surface. The acceleration is caused by three horizontal forces, only two of which are shown: $\vec{F}_1$ of magnitude $10\ \text{N}$ and $\vec{F}_2$ of magnitude $20\ \text{N}$. What is the third force $\vec{F}_3$ in unit-vector notation and in magnitude angle notation?



Newton's Second Law

Applying Newton's 2nd law $\vec{F}_{net} = m\vec{a}$, we have

$$\vec{F}_1 + \vec{F}_2 + \vec{F}_3 = m\vec{a},$$

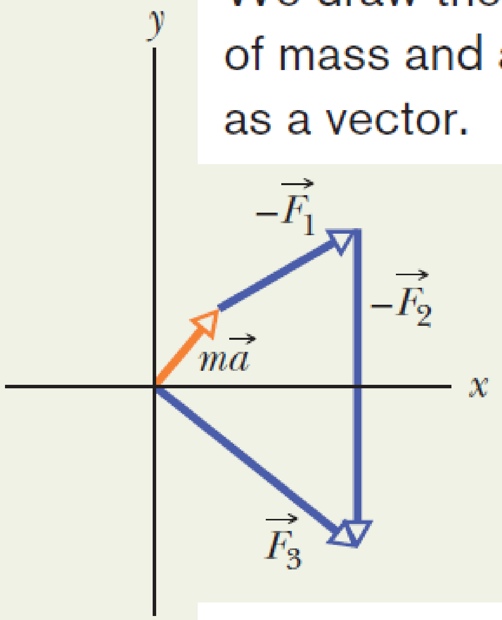
which gives

$$\vec{F}_3 = m\vec{a} - \vec{F}_1 - \vec{F}_2.$$

Along the x axis,

$$\begin{aligned} F_{3,x} &= m\,a_x - F_{1,x} - F_{2,x} \\ &= m\,(a\cos 50°) - F_1\cos 210° - F_2\cos 90° \\ &= (2.0\text{ kg})(3.0\text{ m/s}^2)\cos 50° - (10\text{ N})\cos 210° \\ &= 12.5\text{ N}. \end{aligned}$$

We draw the product of mass and acceleration as a vector.



Then we can add the three vectors to find the missing third force vector.

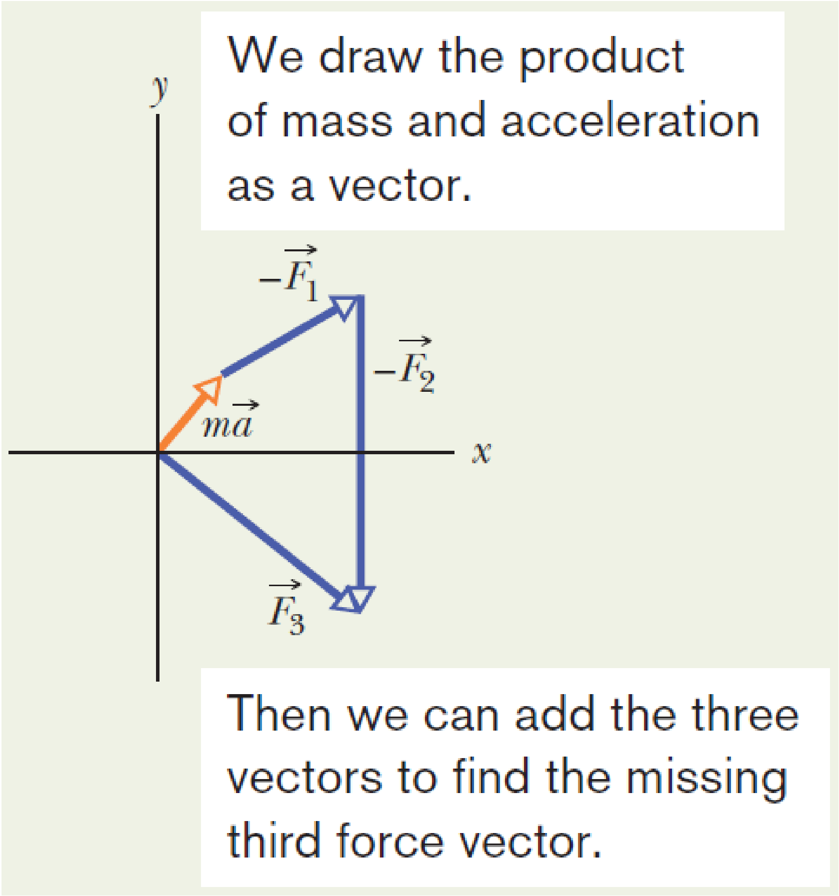
Newton's Second Law

Along the y axis,

$$F_{3,y} = m\,a_y - F_{1,y} - F_{2,y}$$
$$= m\,(a \sin 50°) - F_1 \sin 210° - F_2 \sin 90°$$
$$= (2.0\text{ kg})(3.0\text{ m/s}^2) \sin 50° - (10\text{ N}) \sin 210°$$
$$-(20\text{ N}) \sin 90°$$
$$= -10.4\text{ N}.$$

Therefore,

$$\vec{F}_3 \approx (13\text{ N})\hat{\imath} + (-10\text{ N})\hat{\jmath}.$$



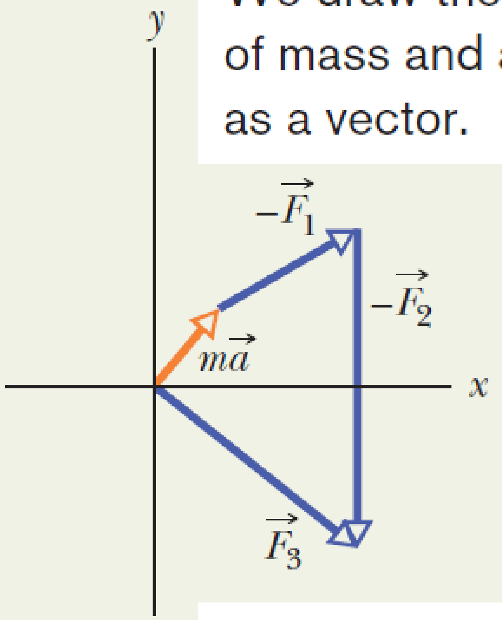
Newton's Second Law

The magnitude and angle of $\vec{F}_3$ are:

$$F_3 = \sqrt{(12.5\ \mathrm{N})^2 + (-10.4\ \mathrm{N})^2} = 16\ \mathrm{N},$$

$$\theta = \tan^{-1}\frac{-10.4\ \mathrm{N}}{12.5\ \mathrm{N}} = -40°.$$

We draw the product of mass and acceleration as a vector.



Then we can add the three vectors to find the missing third force vector.

5-2 Some Particular Forces

- The Gravitational Force

The gravitational force $\vec{F}_g$ on a body is a certain type of pull directed toward a second body (usually Earth.)

A body of mass m in free fall has a downward acceleration of magnitude g. Using Newton's 2nd along the y axis ($F_y = ma_y$)

$$-F_g = m(-g),$$

or

$$F_g = mg.$$

F_g is still the same if the body in not in free fall or at rest.

5-2 Some Particular Forces

- <u>Weight</u>

  The weight W of a body is the magnitude of the net force required to prevent the body from falling, relative to someone on the ground.

  Consider an object that has an acceleration $\vec{a} = 0$ relative to the ground. There are two forces acting on the object: (1) $\vec{F}_g$ directed downward and (2) an upward balancing force of magnitude W. Using $F_{net,y} = ma_y$

$$W - F_g = m(0).$$

  Then

$$W = F_g = mg.$$

  The weight of a body is equal to the magnitude of the gravitational force F_g.

5-2 Some Particular Forces

- Weight

  One way of weighing an object is to use an equal-arm balance from which we get the object's mass. We then multiply the mass by the value of g at the place of the balance to find the weight.

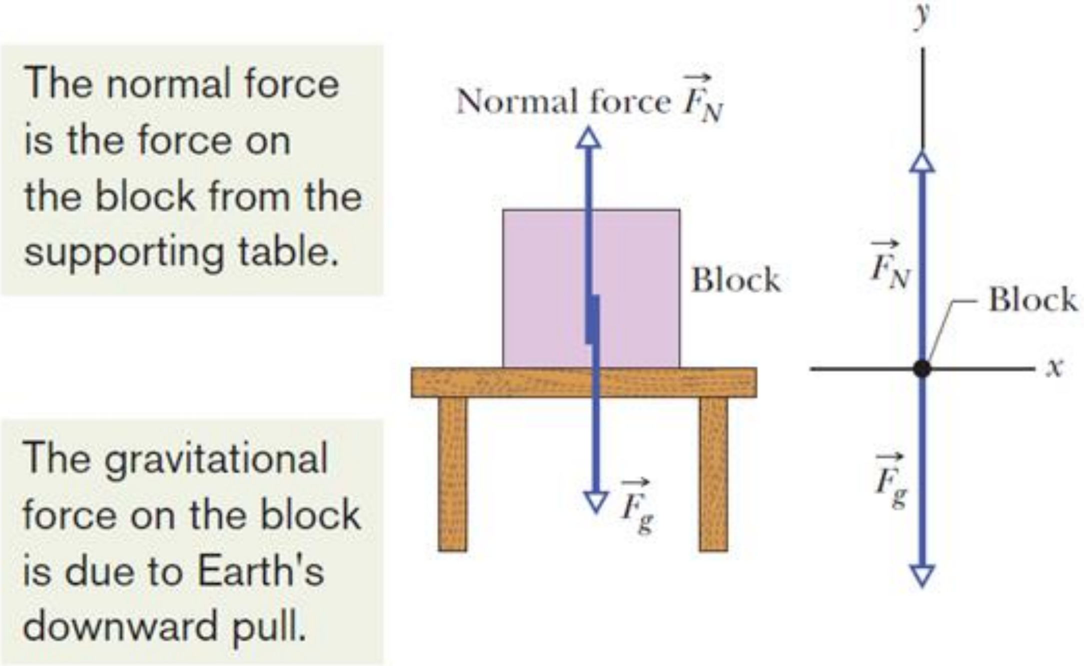
  We can also use a spring scale to weigh the object. However, if the scale is marked in mass units, the measurement will vary if the value of g differs from the value at which the scale was calibrated.

  The weight of a body must be measured when the object is not accelerating vertically. The weight measured in a falling elevator is different from that measured on the ground. The former measurement gives the *apparent weight*.

5-2 Some Particular Forces

- <u>The Normal Force</u>

  When an object presses against a surface, the surface deforms and pushes on the object with a force $\vec{F}_N$ that is normal (perpendicular) to the surface.



5-2 Some Particular Forces

- <u>The Normal Force</u>

  Consider a block on a table. Using $F_{net,y} = ma_y$ we write

$$F_N - F_g = ma_y.$$

  Using $F_g = mg$,

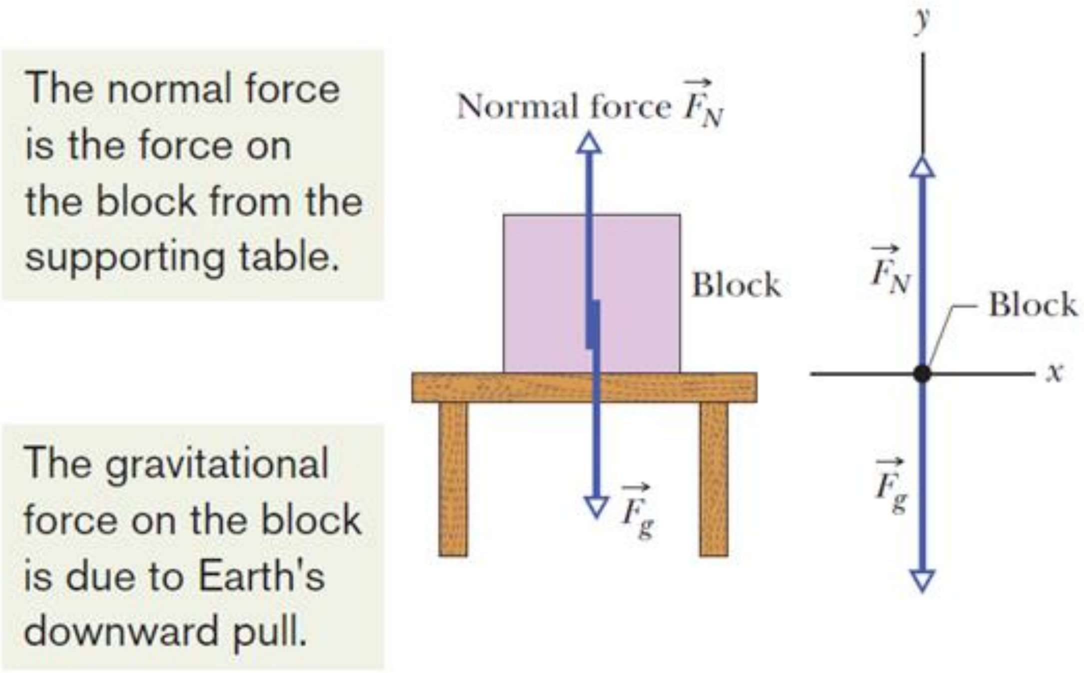
$$F_N - mg = ma_y$$

  or

$$F_N = m(g + a_y).$$

  If the table is not accelerating,

$$F_N = mg.$$



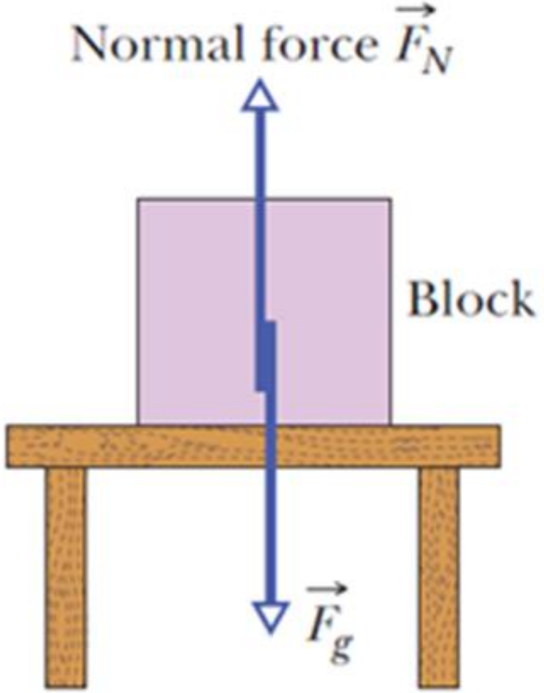
5-2 Some Particular Forces

CHECKPOINT 3

In Fig. 5-7, is the magnitude of the normal force $\vec{F}_N$ greater than, less than, or equal to mg if the block and table are in an elevator moving upward (a) at constant speed and (b) at increasing speed?

(a) $a_y = 0$, thus $F_N = mg$.

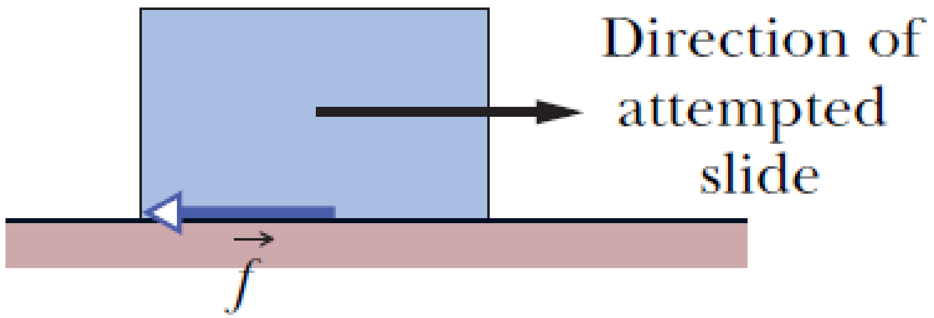
(b) $a_y > 0$, thus $F_N > mg$.



5-2 Some Particular Forces

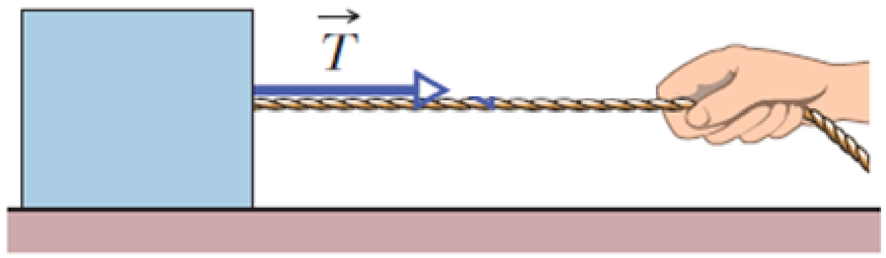
- Friction

  When an object slides or attempts to slide over a surface, the object's motion is resisted by the **frictional force** or **friction** $\vec{f}$.



- Tension

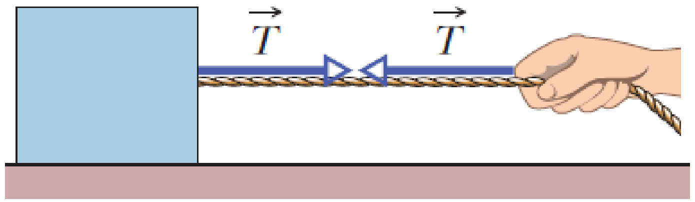
  When a cord that is attached to a body is pulled taut, the cord pulls on the body with a force $\vec{T}$ along the cord, directed away from the body. $\vec{T}$ is called the force of tension.

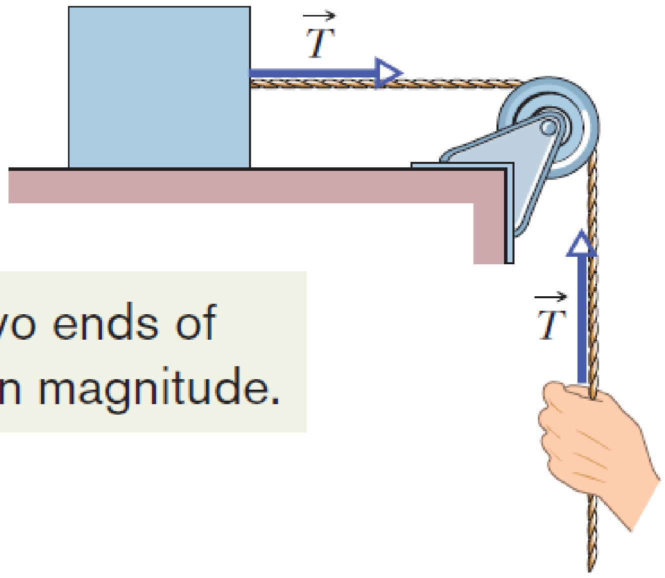


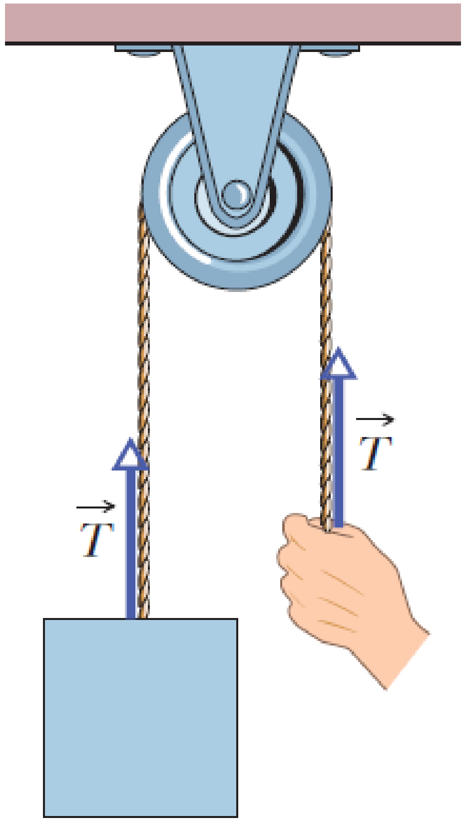
5-2 Some Particular Forces

- <u>Tension</u>

  The cord is said to be under tension. The pulls at both ends of the cord have the same magnitude T if the cord is massless, even if the cord runs around a *massless, frictionless pulley.*







The forces at the two ends of the cord are equal in magnitude.

5-2 Some Particular Forces

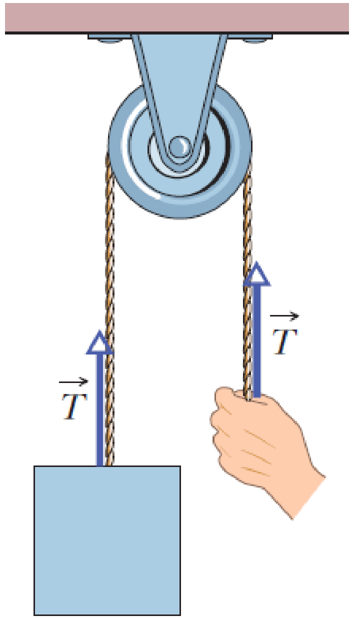
CHECKPOINT 4

The suspended body in Fig. 5-9*c* weighs 75 N. Is T equal to, greater than, or less than 75 N when the body is moving upward (a) at constant speed, (b) at increasing speed, and (c) at decreasing speed?

(a) $a_y = 0$, thus $T = 75$ N.

(b) $a_y > 0$, thus $T > 75$ N.

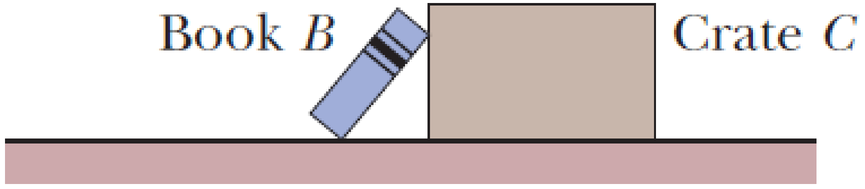
(c) $a_y < 0$, thus $T < 75$ N.



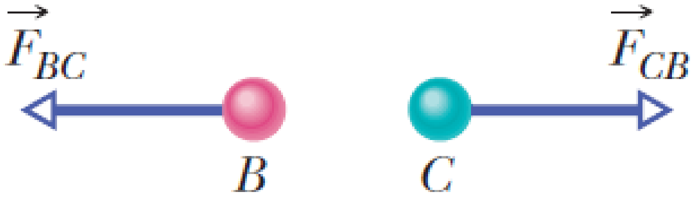
5-3 Newton's Third Law

- Two bodies are said to interact when they push on each other.

Newton's Third Law: When two bodies interact, the forces on the bodies from each other are equal in magnitude and opposite in direction.



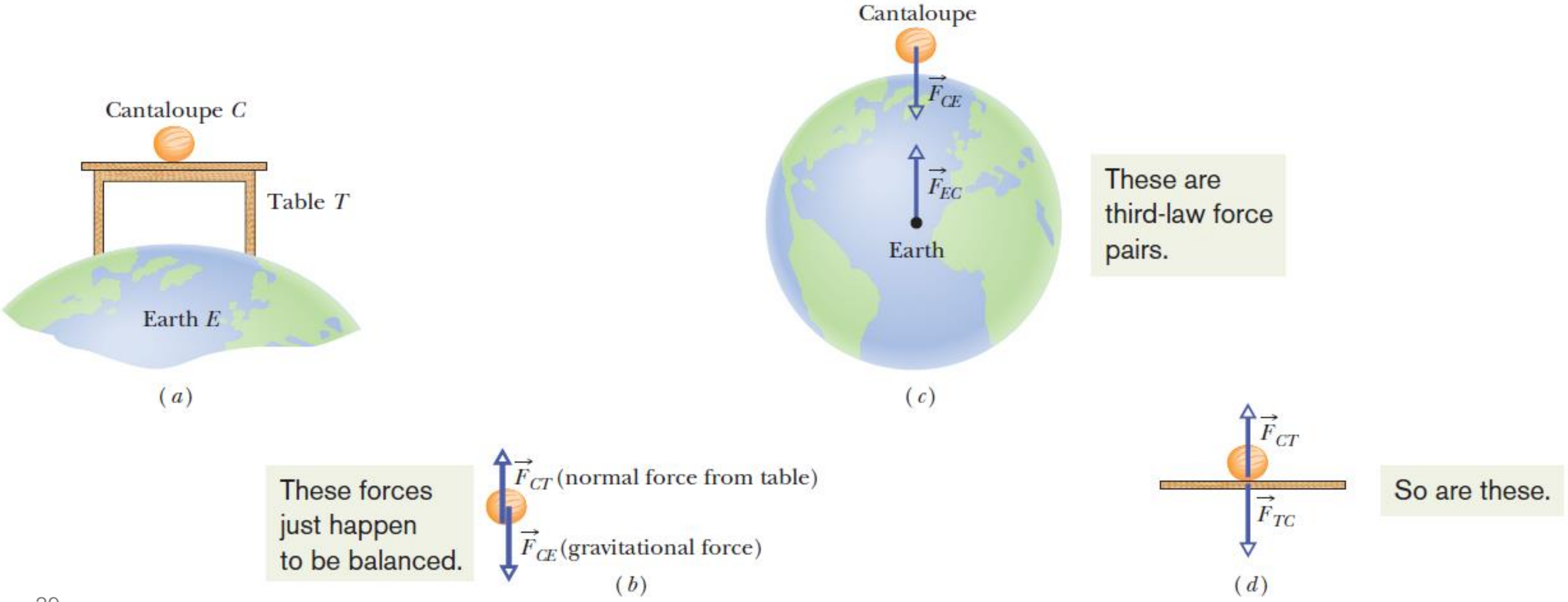
(a)



$$F_{BC} = F_{CB}$$
$$\vec{F}_{BC} = -\vec{F}_{CB}$$

5-3 Newton’s Third Law

- The forces between two interacting bodies are called a **third-law forces pair**.



5-3 Applying Newton's Laws

CHECKPOINT 5

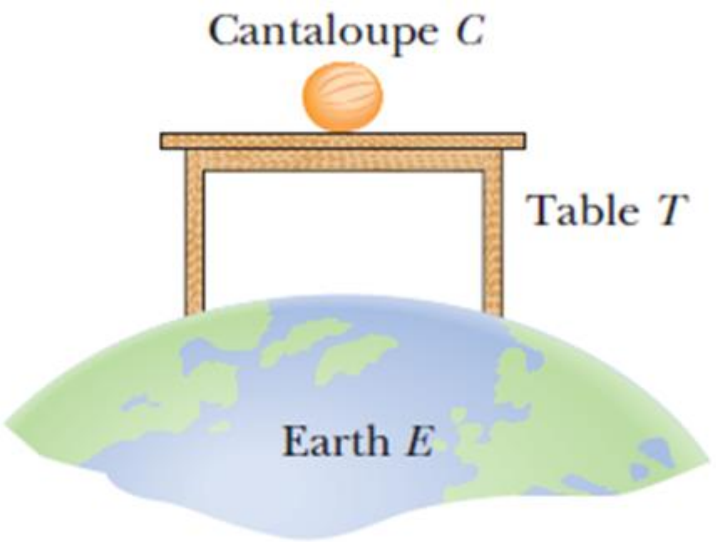
Suppose that the cantaloupe and table of Fig. 5-11 are in an elevator cab that begins to accelerate upward. (a) Do the magnitudes of $\vec{F}_{TC}$ and $\vec{F}_{CT}$ increase, decrease, or stay the same? (b) Are those two forces still equal in magnitude and opposite in direction? (c) Do the magnitudes of $\vec{F}_{CE}$ and $\vec{F}_{EC}$ increase, decrease, or stay the same? (d) Are those two forces still equal in magnitude and opposite in direction?

(a) Increase.

(b) Yes.

(c) Stay the same.

(d) Yes.



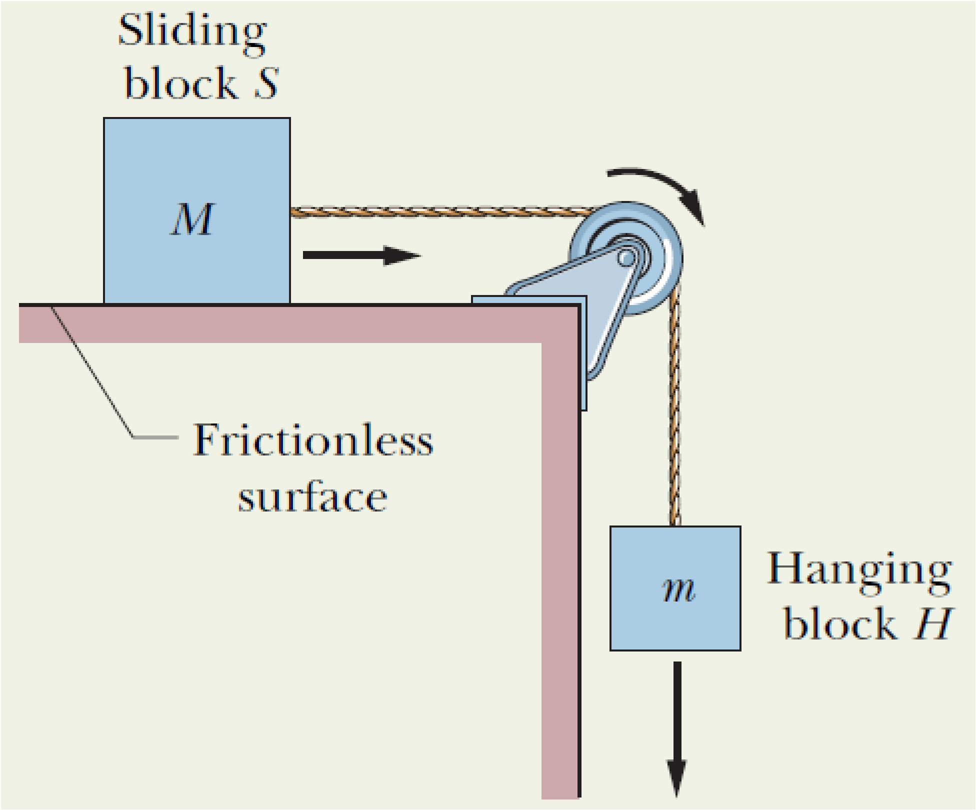
5-3 Applying Newton’s Laws

Example 3: In the configuration shown, $M = 3.3\ \mathrm{kg}$ and $m = 2.1\ \mathrm{kg}$. The pulley is massless and frictionless. The cord’s mass is negligible compared to these of the blocks. Block H falls as Block S accelerates to the right.

(a) What is the acceleration of block S?

(b) What is the acceleration of block H?

(c) What is the tension in the cord?



5-3 Applying Newton's Laws

The accelerations of the two blocks are equal in magnitude. We apply Newton's 2nd law to the two blocks.

For block S:

$$F_{net,y} = Ma_y,$$

or

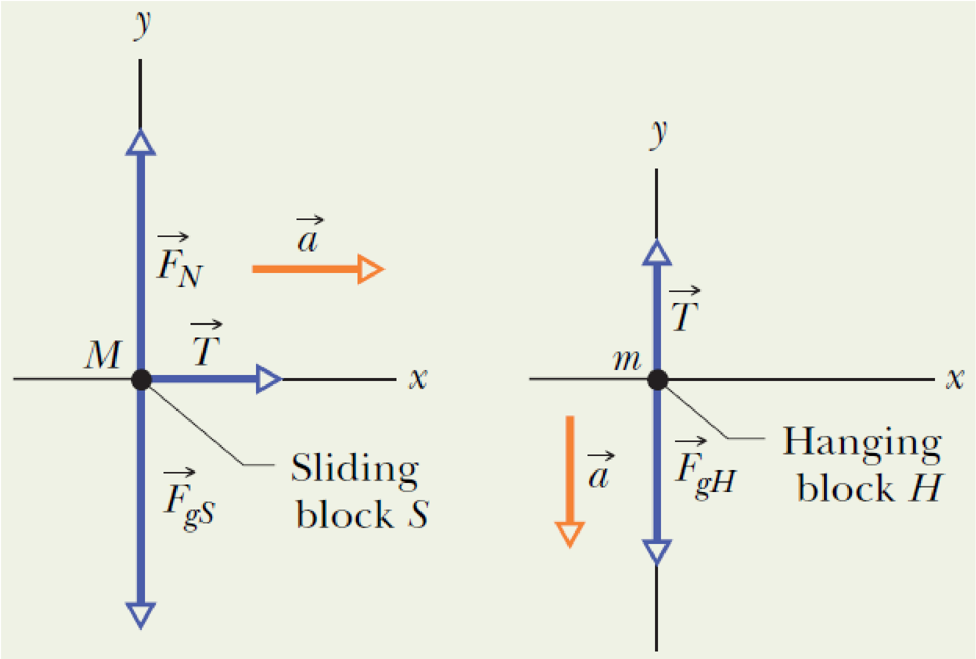
$$F_N - F_{gS} = F_N - Mg = 0.$$

Also,

$$F_{net,x} = Ma_x,$$

or

$$T = Ma_x = Ma. \qquad (1)$$



5-3 Applying Newton's Laws

For block H:

$$F_{net,y} = ma_y,$$

or

$$T - F_{gH} = ma_y = -ma.$$

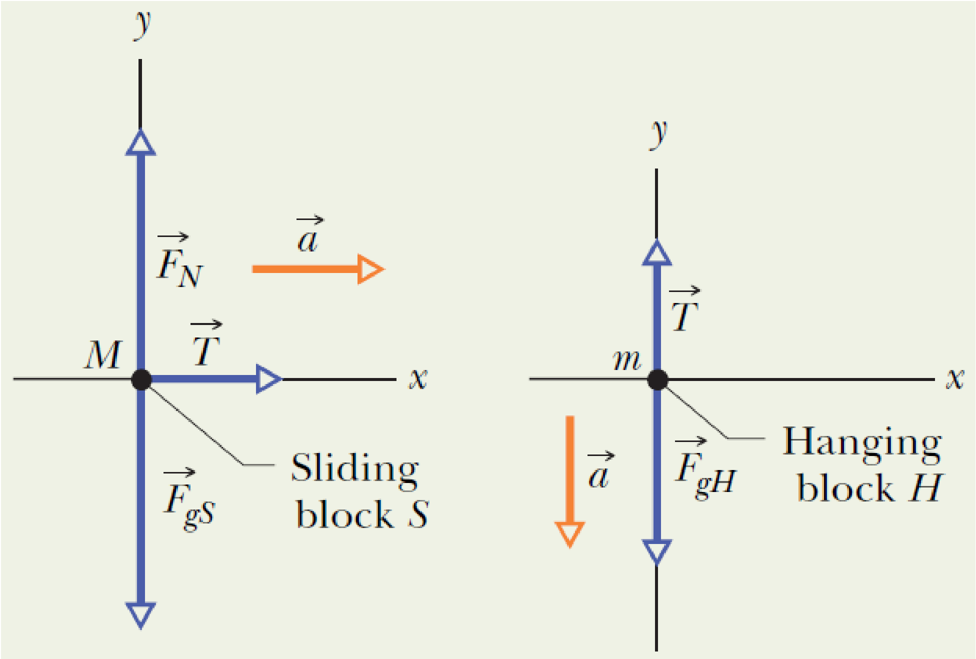
or

$$T - mg = -ma. \qquad (2).$$

Solving (1) and (2) for a and T yields

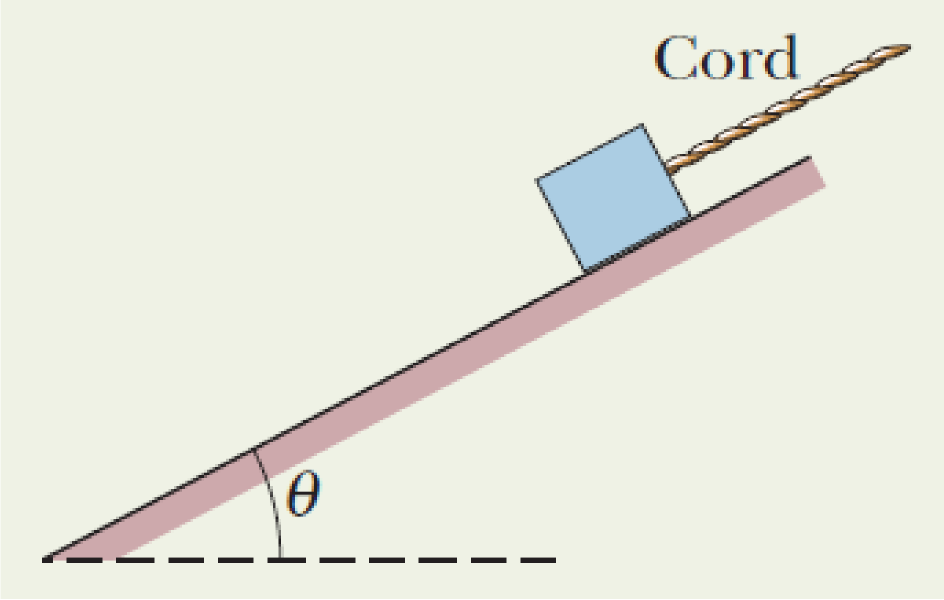
$$a = \frac{m}{M+m}g = \frac{2.1\text{ kg}}{3.3\text{ kg} + 2.1\text{ kg}}\left(9.8\ \frac{\text{m}}{\text{s}^2}\right) = 3.8\ \frac{\text{m}}{\text{s}^2},$$

$$T = \frac{Mm}{M+m}g = \frac{(2.1\text{ kg})(3.3\text{ kg})}{3.3\text{ kg} + 2.1\text{ kg}}\left(9.8\ \frac{\text{m}}{\text{s}^2}\right) = 13\text{ N}.$$



5-3 Applying Newton’s Laws

Example 4: A cord pulls on a box up along a frictionless plane inclined at $\theta = 30°$. The box has mass $m = 5.00\,\text{kg}$, and the force from the cord has magnitude $T = 25.5\,\text{N}$. What is the box’s acceleration component a along the inclined plane?



The acceleration of the box along the plane is determined by the net force along it. We will take the positive direction of the x axis to be up the plane.

5-3 Applying Newton's Laws

The gravitational force $\vec{F}_g$ is downward and has magnitude $F_g = mg$. Its component along the x axis is $-F_g \sin\theta$. Newton's second law for the motion along the x axis is

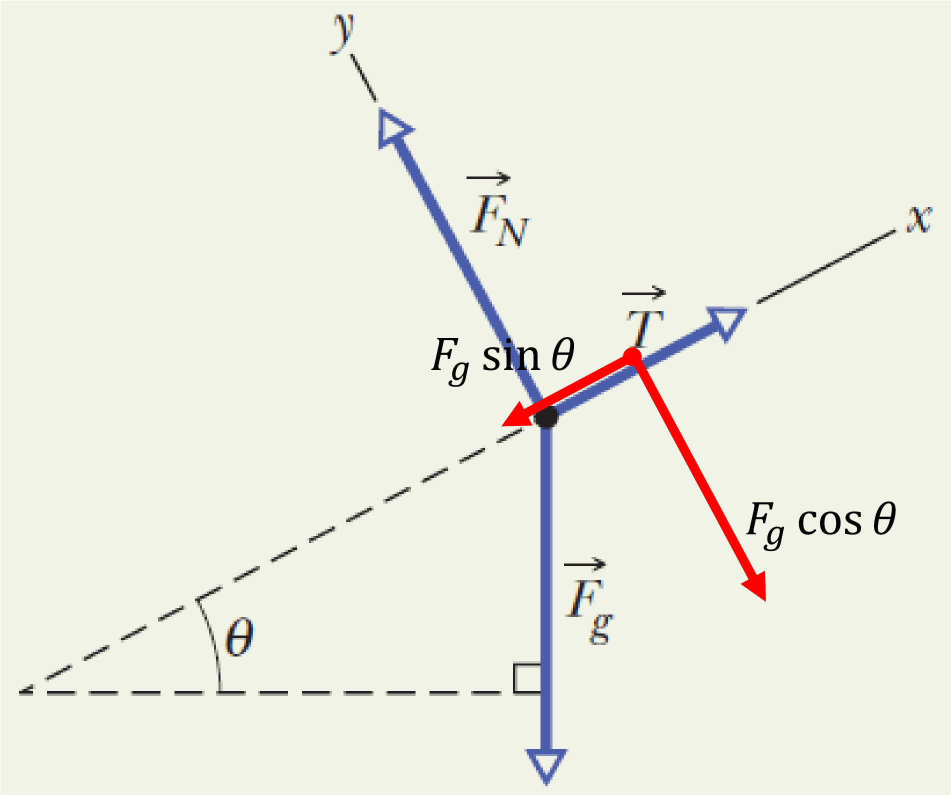
$$F_{net,x} = ma_x,$$

or

$$T - mg\sin\theta = ma_x = ma.$$

Solving for a and substituting we get

$$a = \frac{T}{m} - g\sin\theta = 0.100\ \frac{\mathrm{m}}{\mathrm{s}^2}.$$

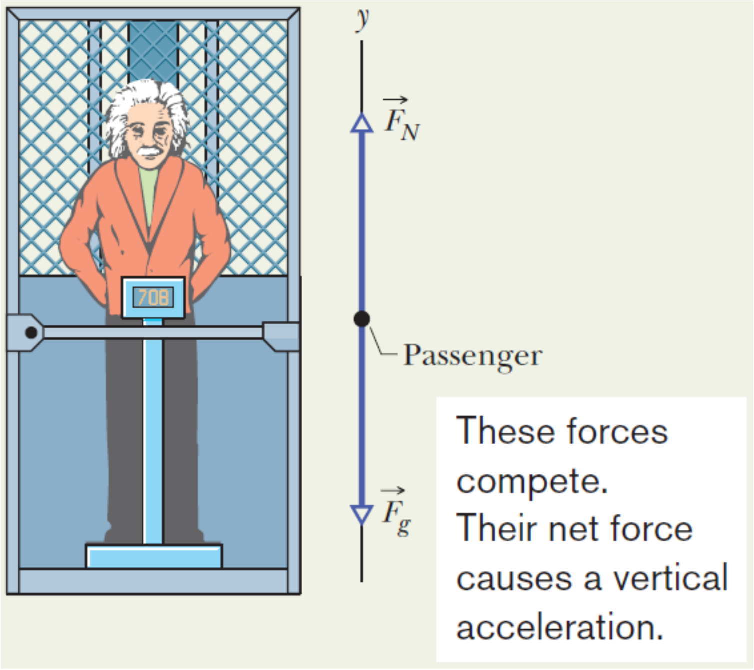


See page 110 in the textbook for more explanation.

5-3 Applying Newton's Laws

Example 5: a passenger of mass $m = 72.2$ kg stands on a platform scale in an elevator cab. We are concerned with the scale readings when the cab is stationary and when it is moving up or down.

(a) Find a general solution for the scale reading, whatever the vertical motion of the cab.



The scale reading is equal to the magnitude of the normal force F_N. Newton's 2nd law written for the y components gives

$$F_N - F_g = ma_y,$$

or

$$F_N = ma_y + mg = m(g + a_y).$$

5-3 Applying Newton's Laws

(b) What does the scale read if the cab is stationary or moving upward at a constant $0.500\ \mathrm{m/s}$?

In both cases $a_y = 0$;

$$F_N = (72.2\ \mathrm{kg})(9.81\ \mathrm{m/s^2} + 0) \\ = 708\ \mathrm{N}.$$

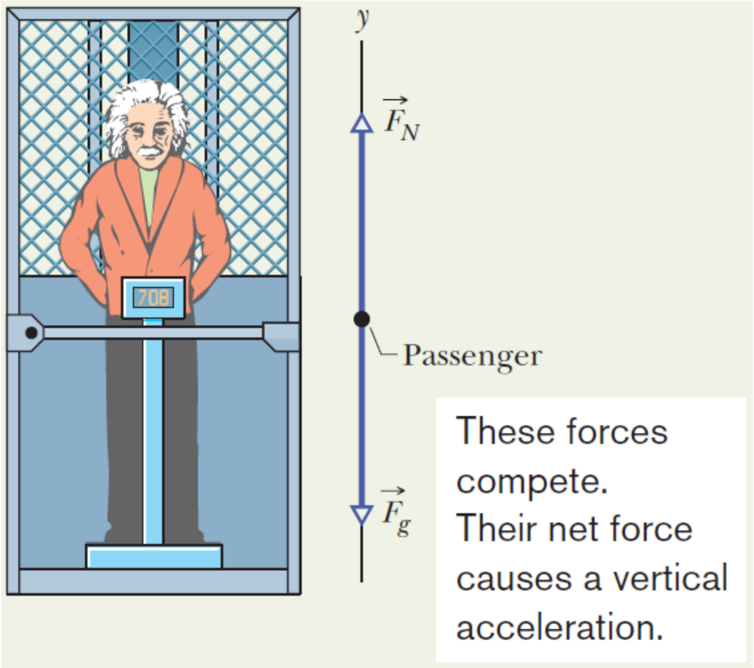
(c) What does the scale read if the cab accelerates upward at $3.20\ \mathrm{m/s^2}$ and downward at $3.20\ \mathrm{m/s^2}$?

For $a_y = 3.20\ \mathrm{m/s^2}$,

$$F_N = (72.2\ \mathrm{kg})(9.81\ \mathrm{m/s^2} + 3.20\ \mathrm{m/s^2}) = 939\ \mathrm{N}.$$

For $a_y = -3.20\ \mathrm{m/s^2}$,

$$F_N = (72.2\ \mathrm{kg})(9.81\ \mathrm{m/s^2} - 3.20\ \mathrm{m/s^2}) = 477\ \mathrm{N}.$$

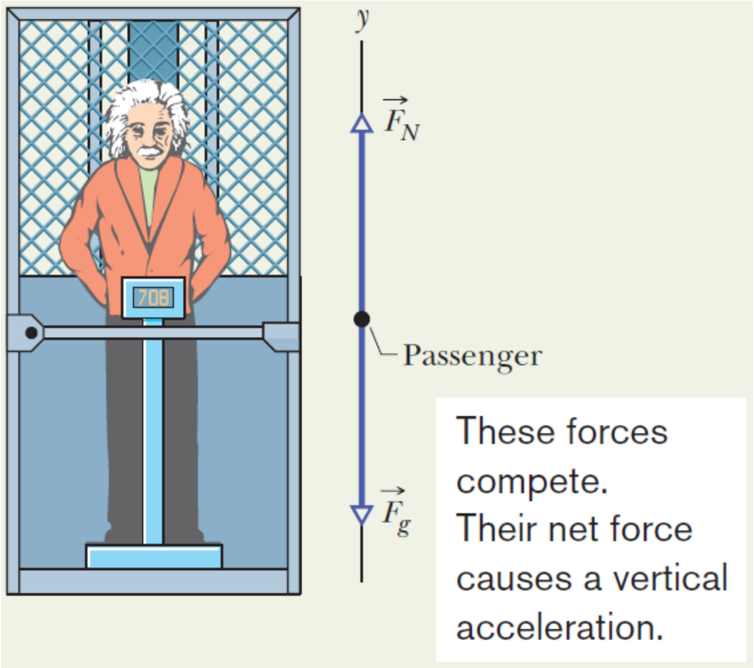


5-3 Applying Newton's Laws

(d) During the upward acceleration in part (c), what is the magnitude F_{net} of the net force on the passenger, and what is the magnitude of his acceleration as measured in the frame of the cab $a_{p,cab}$? Does $\vec{F}_{net} = m\vec{a}_{p,cab}$?

$$F_{net} = F_N - F_g = 939\text{ N} - 708\text{ N} = 231\text{ N}.$$

The passenger acceleration relative to the cab $a_{p,cab}$ is zero. $\vec{F}_{net} \neq m\vec{a}_{p,cab}$, since the cab is a non-inertial frame.



5-3 Applying Newton's Laws

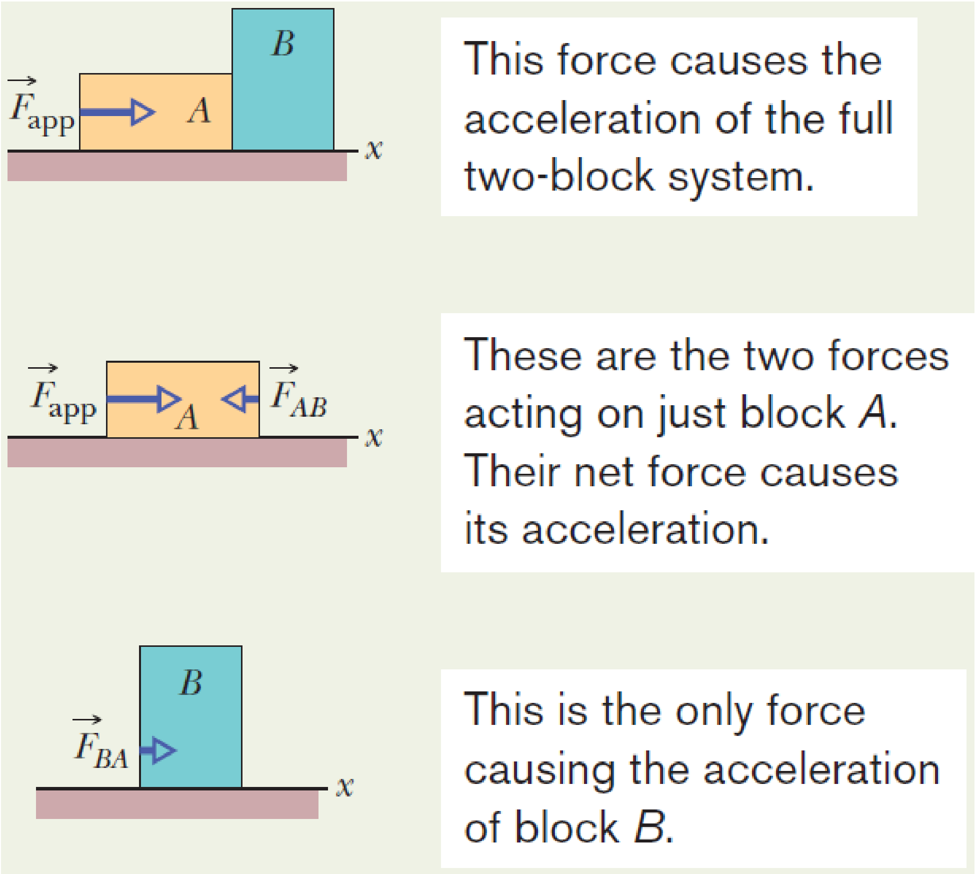
Example 6: A constant horizontal force of magnitude $20\ \mathrm{N}$ is applied to block A of mass $m_A = 4.0\ \mathrm{kg}$, which pushes against block B of mass $m_B = 6.0\ \mathrm{kg}$. The blocks slide over a frictionless surface, along an x axis.

(a) What is the acceleration of the blocks?

The two blocks move together as a single object. Therefore,

$$F_{app} = (m_A + m_B)a,$$

which gives $a = 2.0\ \mathrm{m/s^2}$.



5-3 Applying Newton's Laws

(b) What is the (horizontal) force on block B from block A?

Newton's 2nd law along the x axis for block B is

$$F_{BA} = m_B a = (6.0\ \mathrm{kg})(2.0\ \mathrm{m/s^2}) = 12\ N.$$