Chapter 4

Newton's Laws of Motion

PowerPoint® Lectures for
University Physics, Thirteenth Edition
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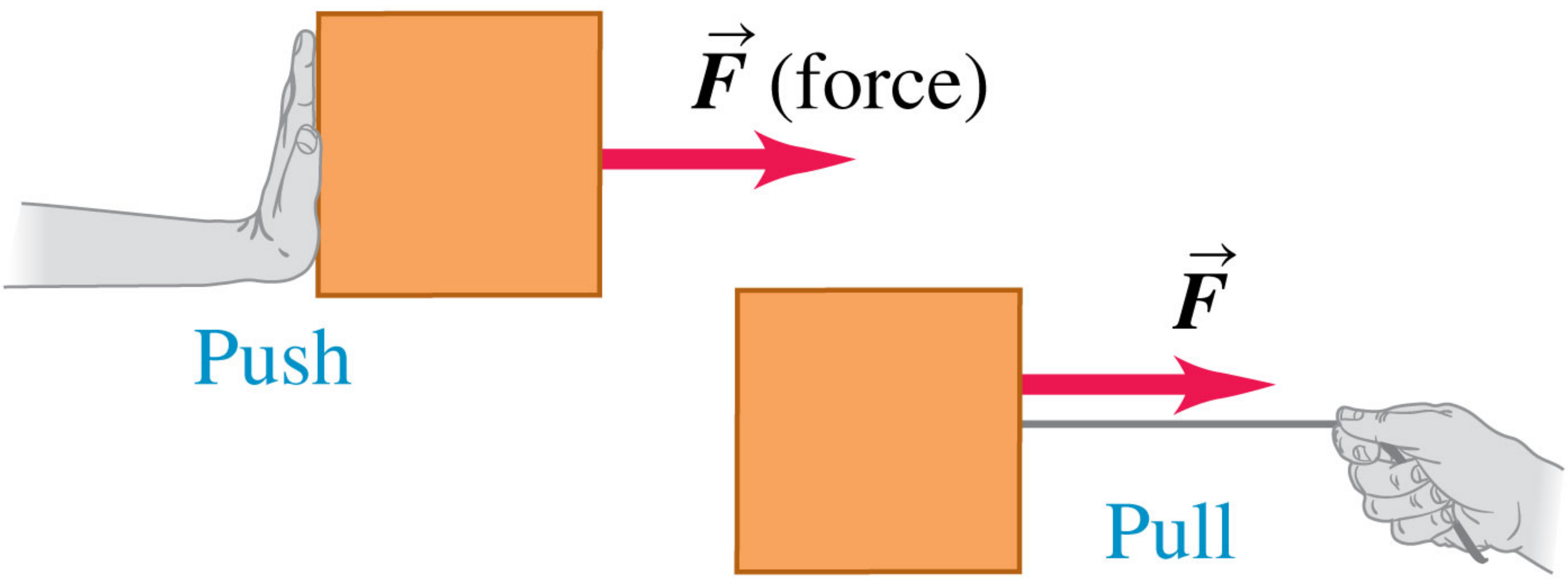
Introduction

- We've seen that acceleration changes an object's velocity and thus position, but haven't discussed the source of acceleration.
- Sir Isaac Newton recognized that *forces* cause acceleration and formulated three laws of motion concerning the forces that act on objects.
- We will present these laws in this chapter and learn to apply them in the next chapter.

What is a force?

- A force is a push or a pull.
- A force is an interaction between two objects or between an object and its environment.
- A force is a vector quantity, with magnitude and direction.

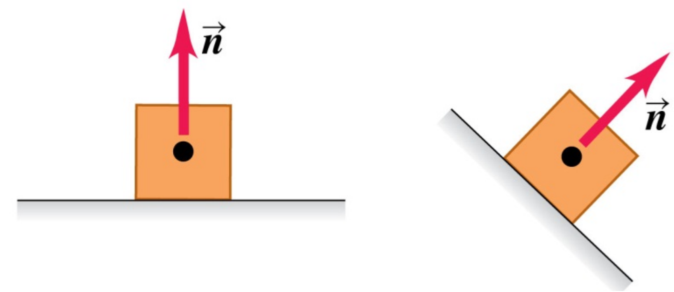


Four common forces

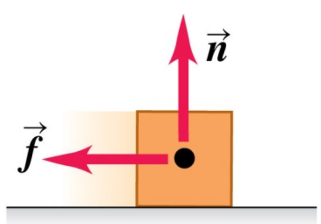
1. *Normal force*: a perpendicular push between two surfaces. Normal forces oppose gravity, preventing an object from falling through a surface on which it rests.

2. *Friction force*: a force that resists the sliding of an object along a surface. Friction either opposes an applied force for an object at rest or is opposite to an object's velocity once it is in motion.

(a) **Normal force $\vec{n}$:** When an object rests or pushes on a surface, the surface exerts a push on it that is directed perpendicular to the surface.



(b) **Friction force $\vec{f}$:** In addition to the normal force, a surface may exert a frictional force on an object, directed parallel to the surface.

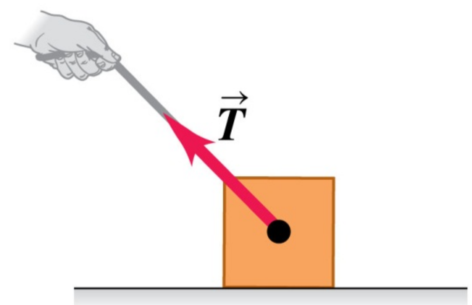


There are four common types of forces II

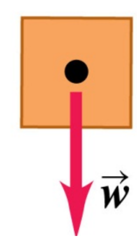
3. *Tension force*: A pulling force exerted on an object by a rope or cord.

4. *Weight*: The pull of gravity on an object. This is a long-range force between massive objects (usually an object and the Earth).

(c) Tension force $\vec{T}$: A pulling force exerted on an object by a rope, cord, etc.



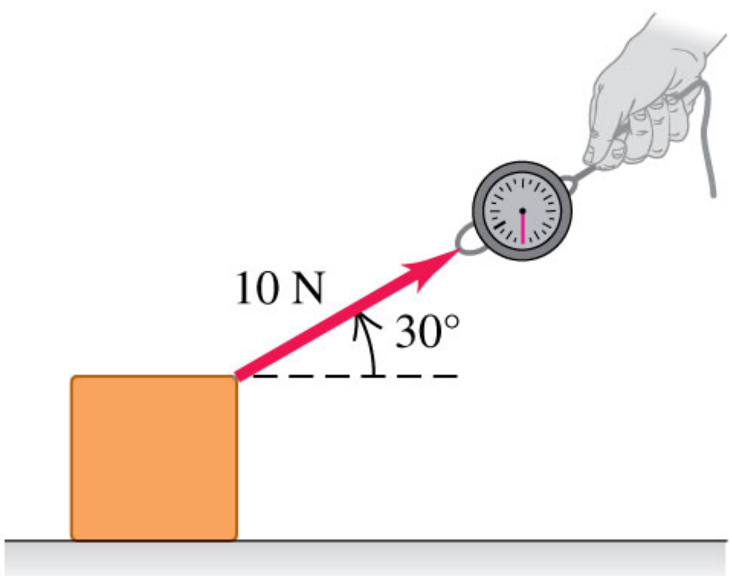
(d) Weight $\vec{w}$: The pull of gravity on an object is a long-range force (a force that acts over a distance).



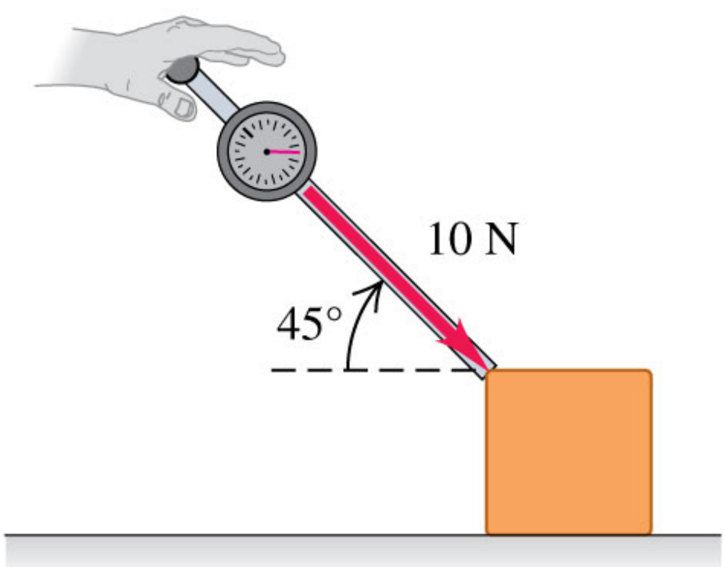
Drawing force vectors

- Force is a vector: use an arrow to indicate its magnitude and direction.

(a) A 10-N pull directed 30° above the horizontal

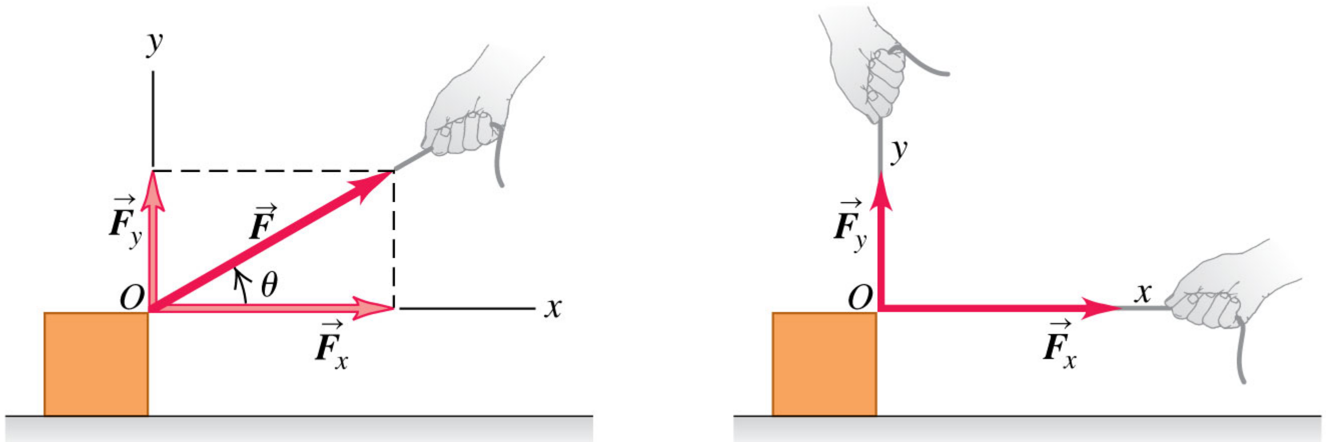


(b) A 10-N push directed 45° below the horizontal



Decomposing a force into its component vectors

- The force $\boldsymbol{F}$ can be decomposed into components like other vectors we have seen.
- Choose perpendicular x and y axes. It is often convenient to choose an axis perpendicular to a surface so that motion is restricted to two or fewer dimensions.
- F_x and F_y are the components of a force along the axes below.



(a) Component vectors: $\vec{F}_x$ and $\vec{F}_y$
Components: $F_x = F\cos\theta$ and $F_y = F\sin\theta$

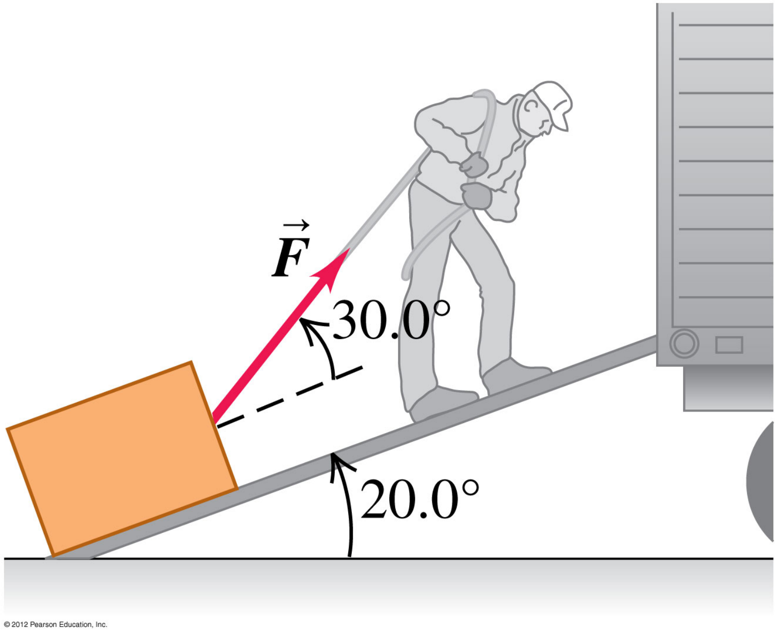
(b) Component vectors $\vec{F}_x$ and $\vec{F}_y$ together have the same effect as original force $\vec{F}$.

Example #1

A man is dragging a trunk up the loading ramp of a mover's truck. The ramp has a slope angle of 20.0° and the man pulls upwards with a force ***F*** whose direction makes an angle of 30.0° with the ramp.

a. How large a force ***F*** is necessary for the component parallel to the ramp to be 90.0 N (a Newton is the SI unit of force)?

b. What will be component of ***F*** perpendicular to the ramp?



Solution #1

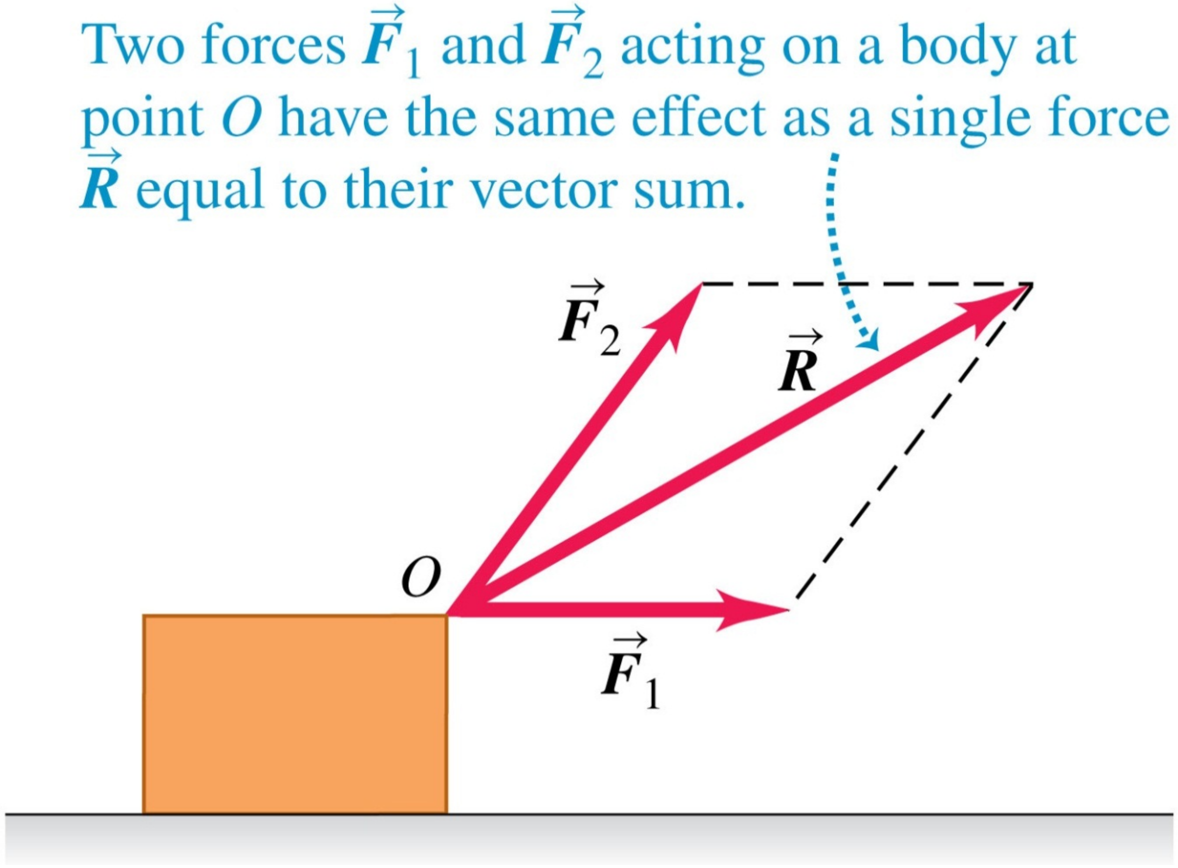
We choose the y axis perpendicular to the ramp so that motion is in the x direction (y doesn't have to be vertical!). Then:

a. $F_x = F \cos 30.0° = 90.0\text{ N} \Longrightarrow F = (90.0\text{ N})/(\tfrac{1}{2}\sqrt{3}) = 104\text{ N}$

b. $F_y = F \sin 30.0° = 52.0\text{ N}$

Superposition of forces

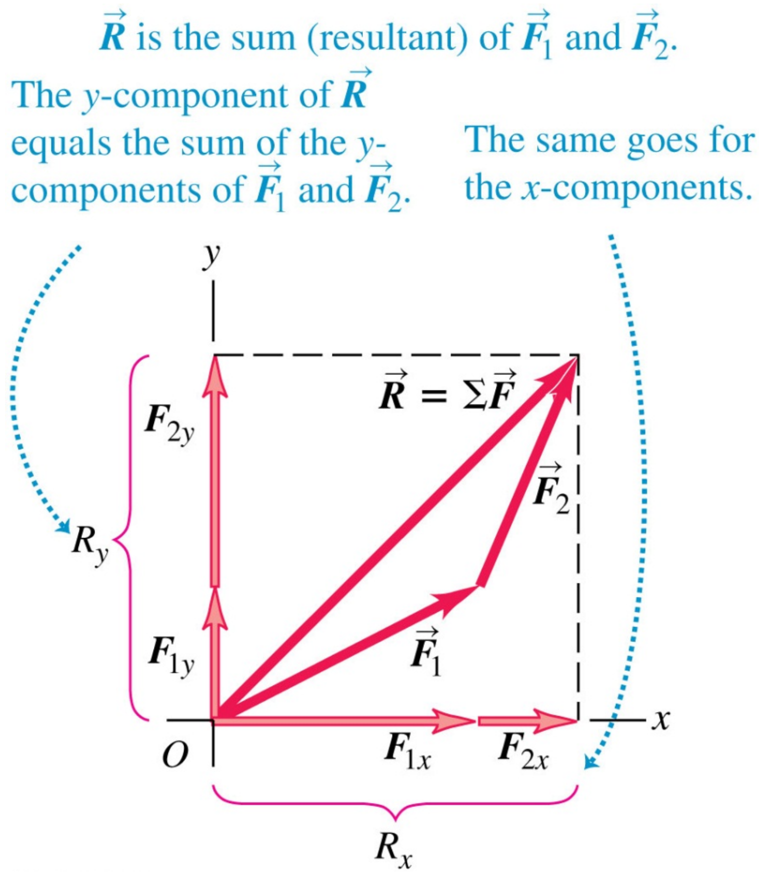
- Several forces acting on an object have the same effect as their vector sum.



Notation for the vector sum

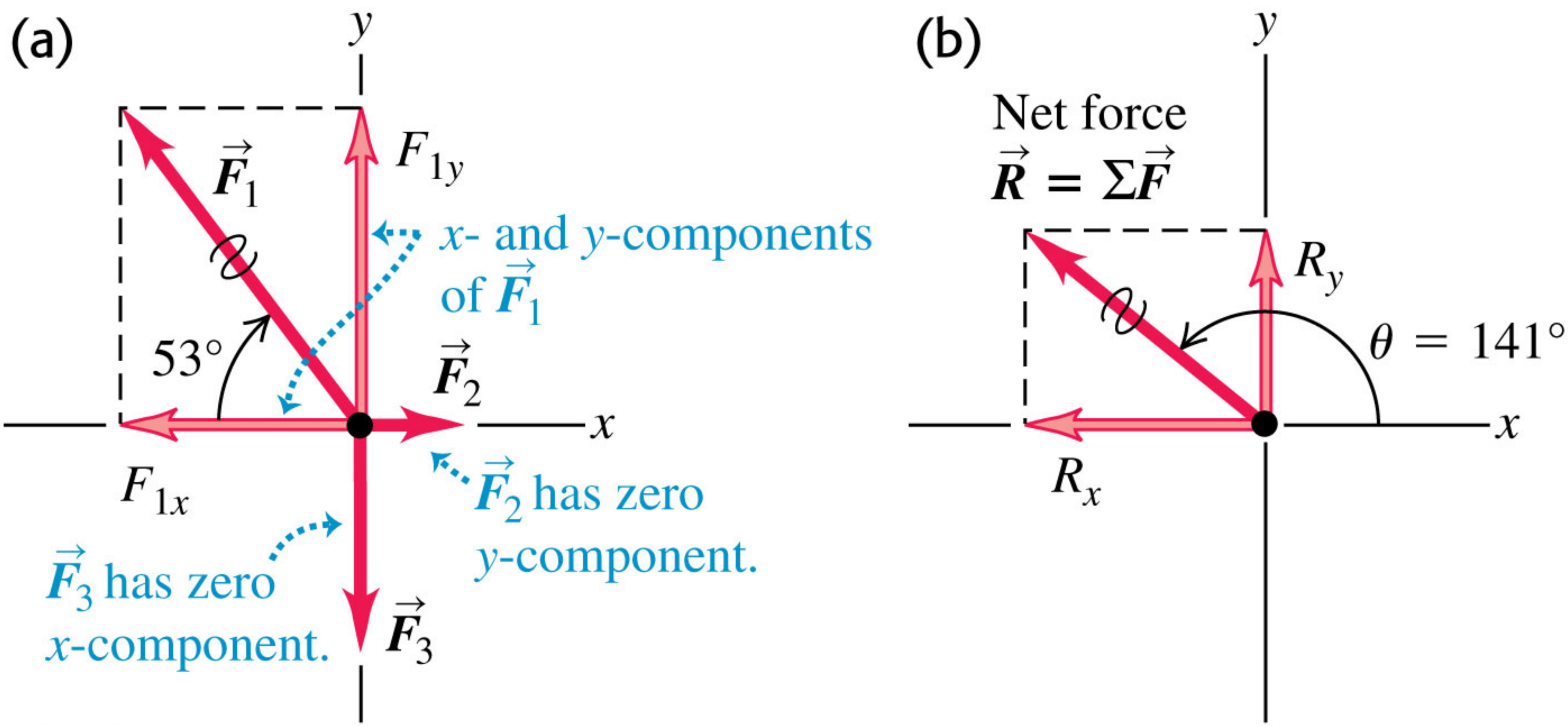
- The vector sum of all the forces on an object is called the *resultant* or *net force*.

$$\vec{R} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots = \sum \vec{F}$$



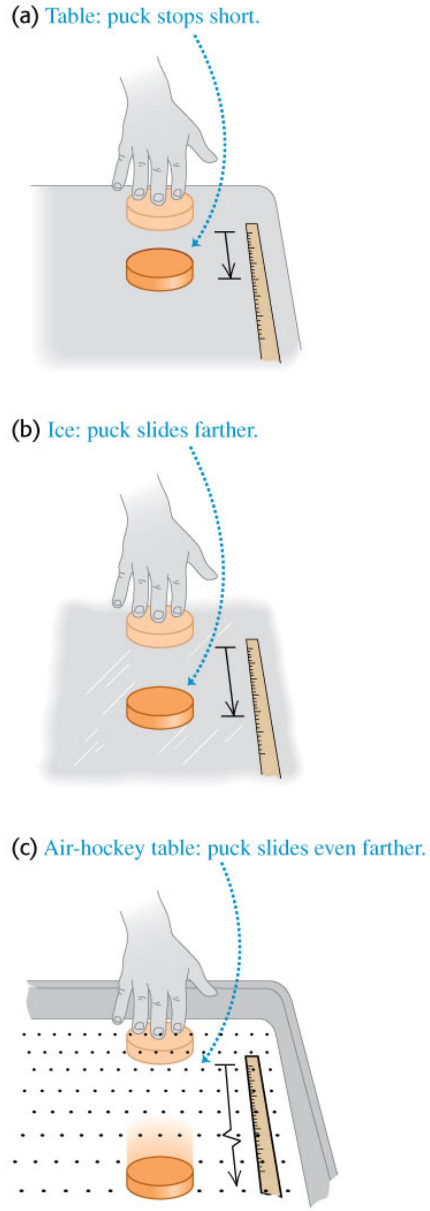
Superposition of forces

- Forces are most easily added component by component like other vectors: $R_x = F_{1x} + F_{2x} + F_{3x} + \ldots$, $R_y = F_{1y} + F_{2y} + F_{3y} + \ldots$



Newton's First Law

- As friction is removed (normal table → ice → air-hockey table), the puck's velocity $\boldsymbol{v}$ approaches a constant.
- We conclude: an object at rest tends to stay at rest, an object in motion tends to stay in uniform motion, unless acted upon by a force.
- More succinctly: A body acted on by zero net force moves with constant velocity (zero acceleration).



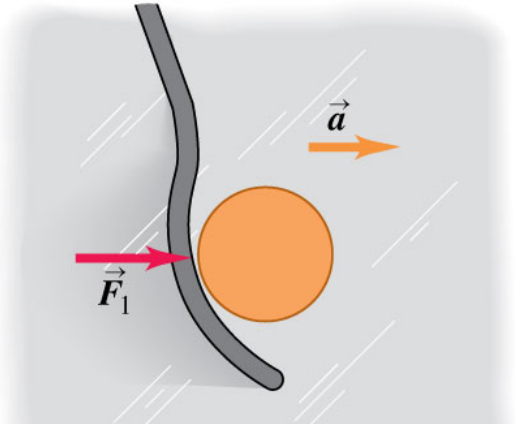
Newton's First Law in practice

- A single hockey force exerts a force $\boldsymbol{F}_1$ on the puck causing an acceleration $\boldsymbol{a}$.
- If a second hockey stick exerts a second force $\boldsymbol{F}_2$ equal in magnitude to $\boldsymbol{F}_1$ but opposite in direction, the net force:

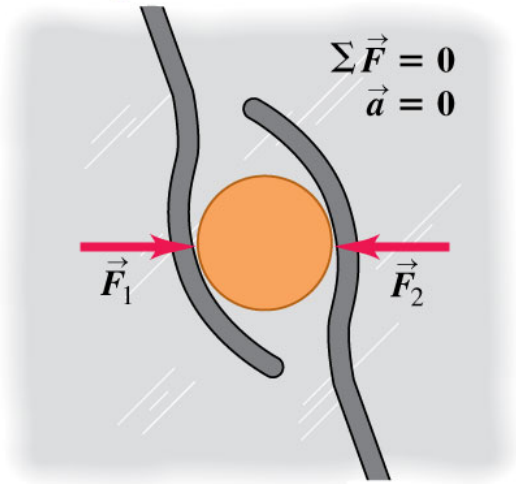
$$\boldsymbol{F} = \boldsymbol{F}_1 + \boldsymbol{F}_2 = 0$$

and the puck remains at rest.

(a) A puck on a frictionless surface accelerates when acted on by a single horizontal force.

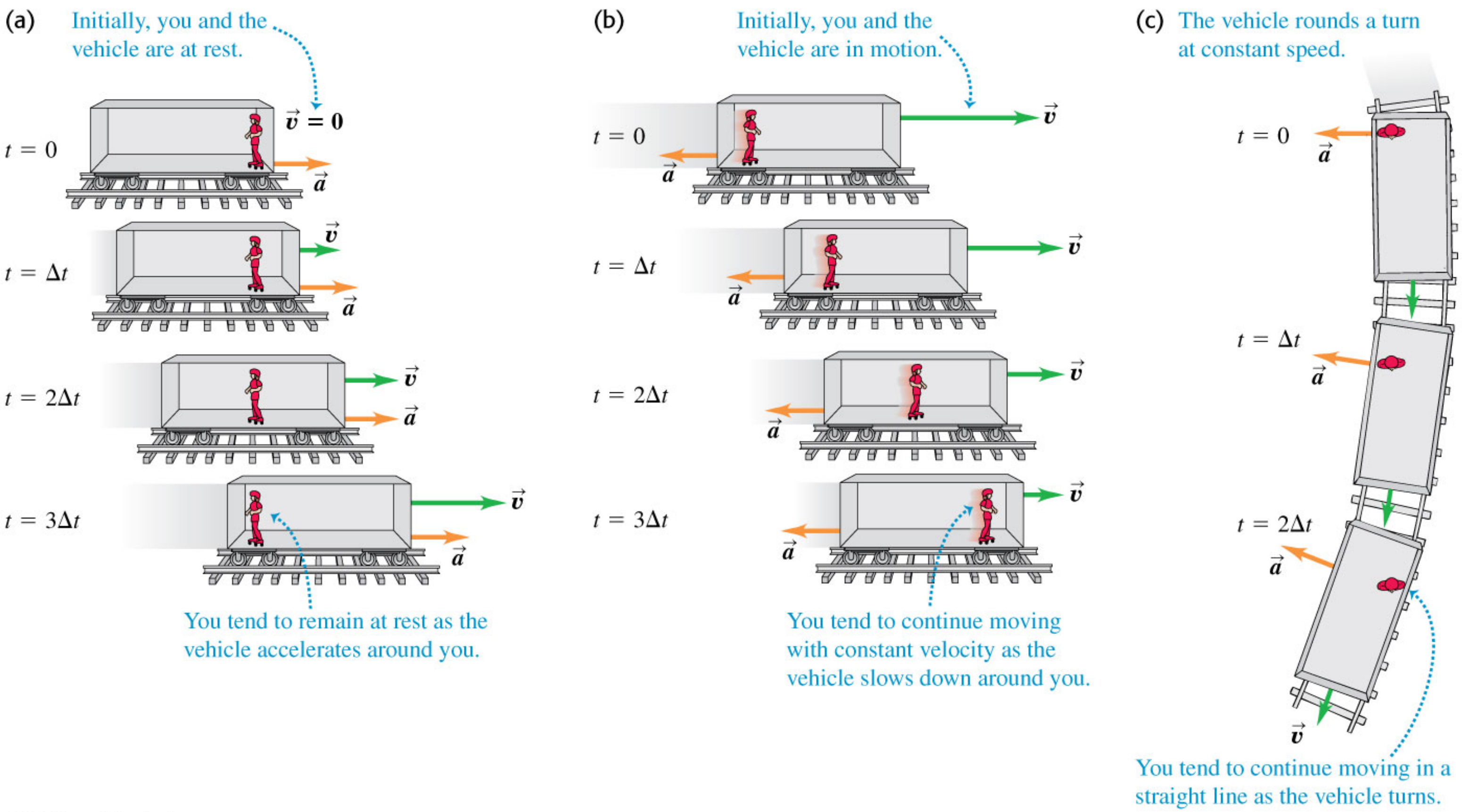


(b) An object acted on by forces whose vector sum is zero behaves as though no forces act on it.



Newton's laws are only valid in inertial frames

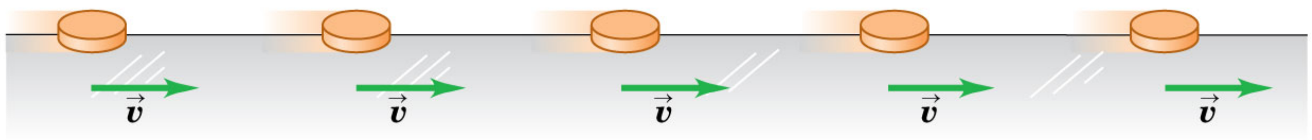
- If no net force acts on the rider, his velocity *with respect to the Earth* will remain constant.
- The rider will appear to be pushed opposite to the acceleration of the *non-inertial* frame of the accelerating vehicle.



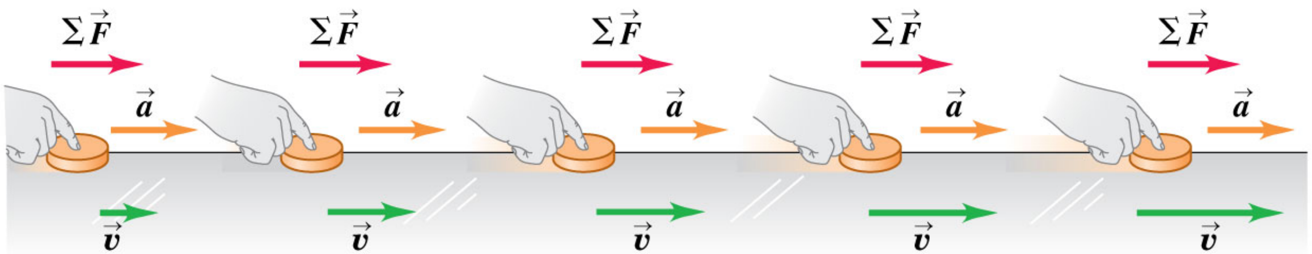
Newton's Second Law

- An object to accelerates parallel to the direction of the net force ΣF.

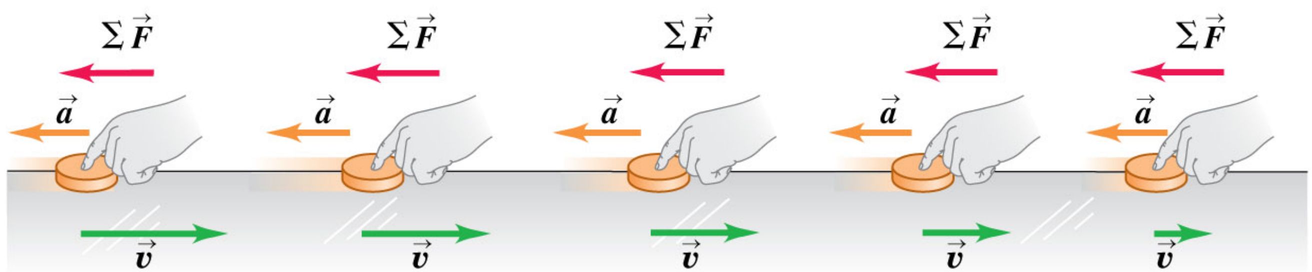
(a) A puck moving with constant velocity (in equilibrium): $\Sigma \vec{F} = 0$, $\vec{a} = 0$



(b) A constant net force in the direction of motion causes a constant acceleration in the same direction as the net force.

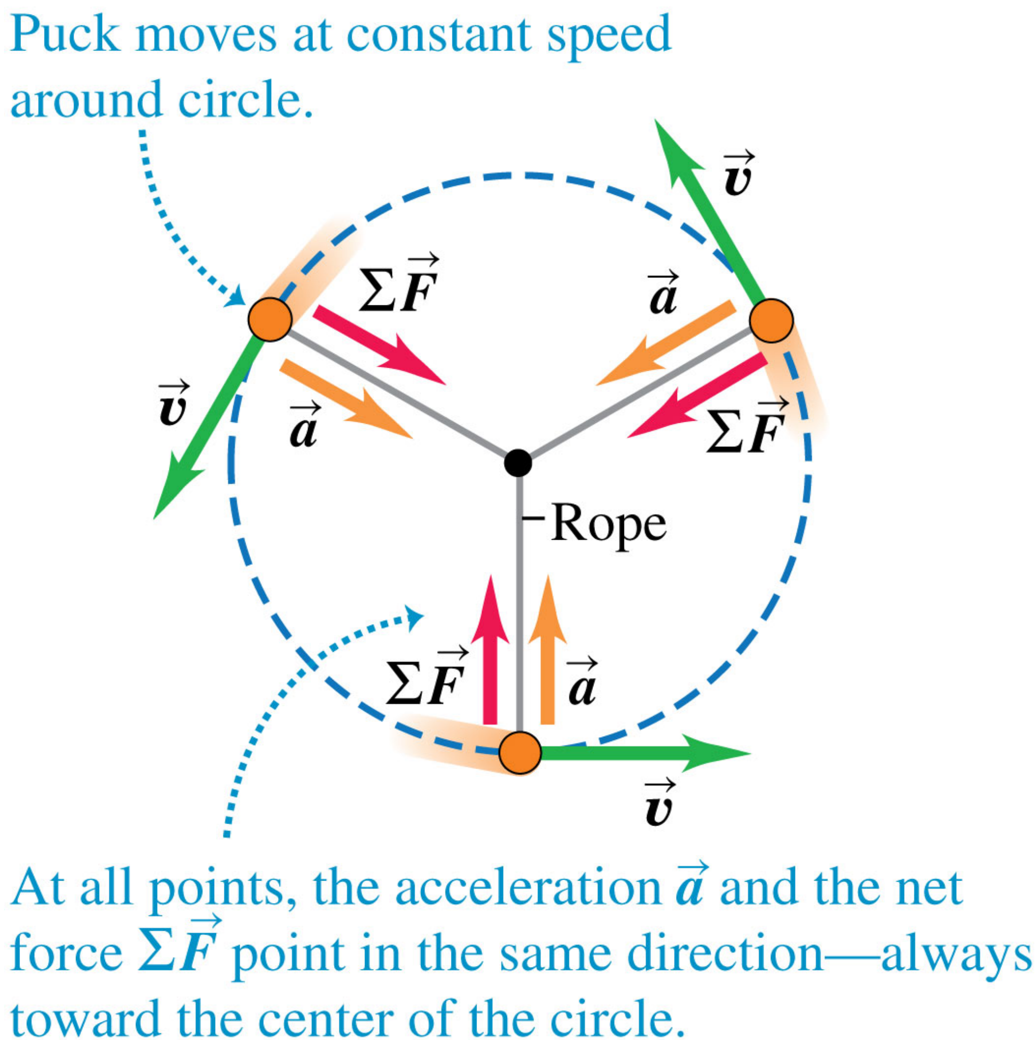


(c) A constant net force opposite the direction of motion causes a constant acceleration in the same direction as the net force.



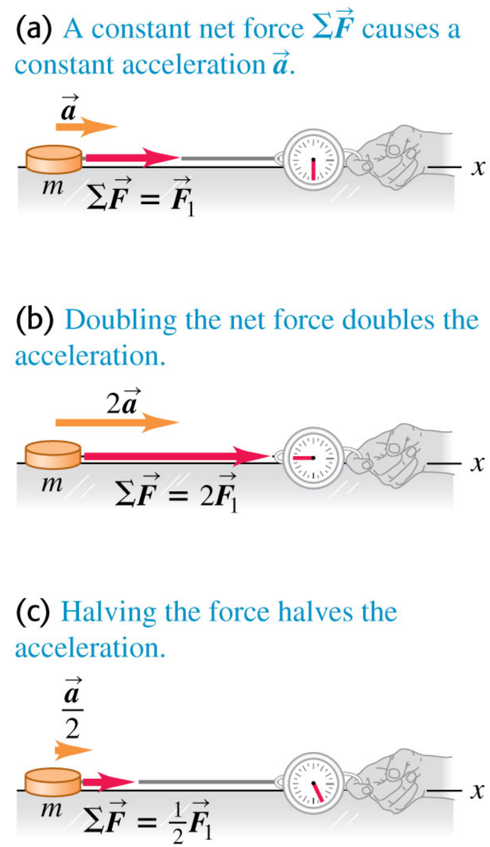
An object undergoing uniform circular motion

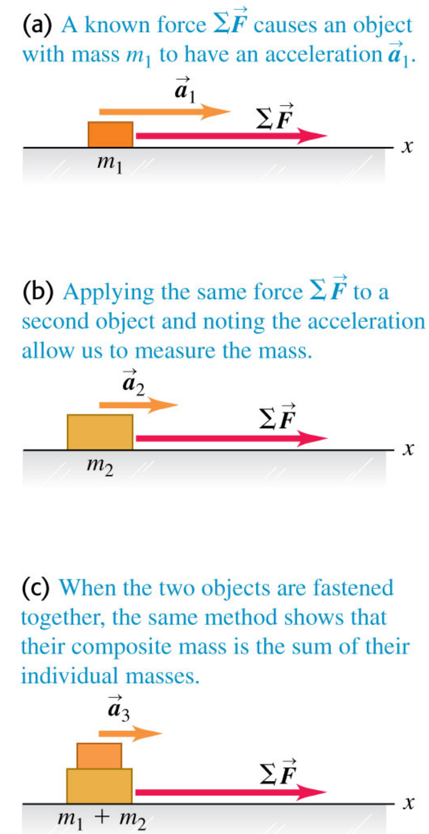
A net force ΣF directed to the center of the circle is needed to provide the centripetal acceleration a for uniform circular motion.



Newton's second law

- The acceleration $\boldsymbol{a}$ is linearly proportional to the net force $\Sigma \boldsymbol{F}$ and inversely proportional to the mass m.
- This implies Newton's 2nd law: $\Sigma \boldsymbol{F} = m\boldsymbol{a}$.
- The SI unit of force is the Newton (N) = kg × m/s^2.





Example #2

A .22-caliber rifle bullet travelling at 350 m/s strikes a large tree and penetrates it to a depth of 13.0 cm. The mass of the bullet is 1.80 g. Assume a constant retarding force. What force does the tree exert on the bullet?

Solution #2

One of the equations of motion for constant acceleration is:

$v_x^2 = v_{0x}^2 + 2ad \Longrightarrow$

$a = -½v_{0x}^2/d = -½(350\text{ m/s})^2/(0.130\text{ m}) = -4.71 \times 10^5\text{ m/s}^2$

$F_x = ma = (0.0018\text{ kg})(-4.71 \times 10^5\text{ m/s}^2) = 848\text{ N}$

Systems of units

- We will use the SI system.
- In the British system, force is measured in *pounds,* distance in feet, and mass in *slugs*.
- In the cgs system (used by astronomers), mass is in grams, distance in centimeters, and force in *dynes*.

Table 4.2 Units of Force, Mass, and Acceleration

System of Units	Force	Mass	Acceleration
SI	newton (N)	kilogram (kg)	m/s^2
cgs	dyne (dyn)	gram (g)	cm/s^2
British	pound (lb)	slug	ft/s^2

Mass and weight

- The *weight* of an object is the gravitational force that the Earth exerts on it.

- The weight W of an object of mass m is

$$W = mg$$

- The value of g depends on altitude (as the inverse square of the distance from the Earth's center) and is 9.8 m/s^2 near the Earth's surface.

- On other planets, g will have an entirely different value since they have different masses and radii. On the Sun's surface:

$a = (M_{\odot}/M_{\oplus})(R_{\odot}/R_{\oplus})^{-2}g = 27.9\ g$ (it's hot there too!)

Example #3

- You walk into an elevator and step onto a scale. Your weight is 625 N.

a. Draw a free body diagram illustrating the forces acting on you.

b. You press the "up" button and accelerated upwards at 2.50 m/s^2. Do any of the forces in part (a) change? What does the scale read now?

c. If you hold a 3.85 kg package by a light vertical string, what is its tension as the elevator accelerates in part (b)?

Solution #3

a. With the elevator at rest, your acceleration is zero implying that the net force is as well. The downward force of gravity is balanced by an upwards normal force from the scale.

b. Elevators don't change gravity, so the normal force must increase to provide a net upwards force to produce the acceleration:

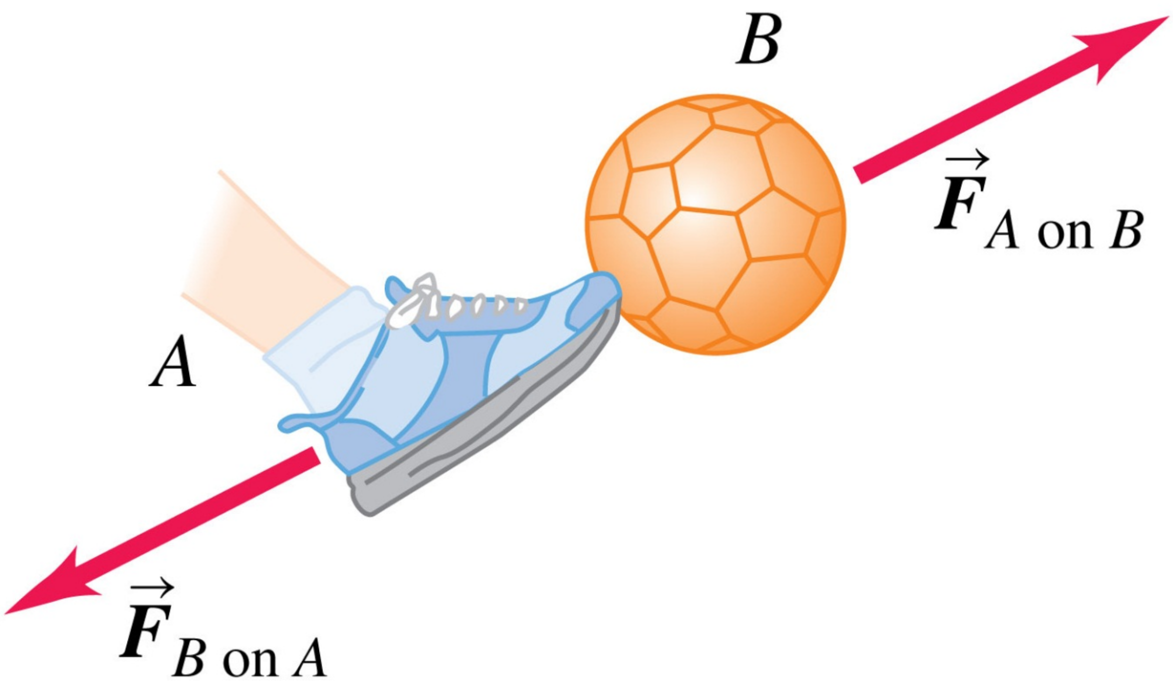
$\boldsymbol{n} - m\boldsymbol{g} = m\boldsymbol{a} \Longrightarrow n = mg(1 + a/g) = (625\text{ N})(1 + 2.50/9.8) = 784\text{ N}$

c. The tension in the string is similarly:

$T = mg(1 + a/g) = (3.85\text{ kg})(9.8\text{ m/s}^2)(1 + 2.50/9.8) = 47.4\text{ N}$

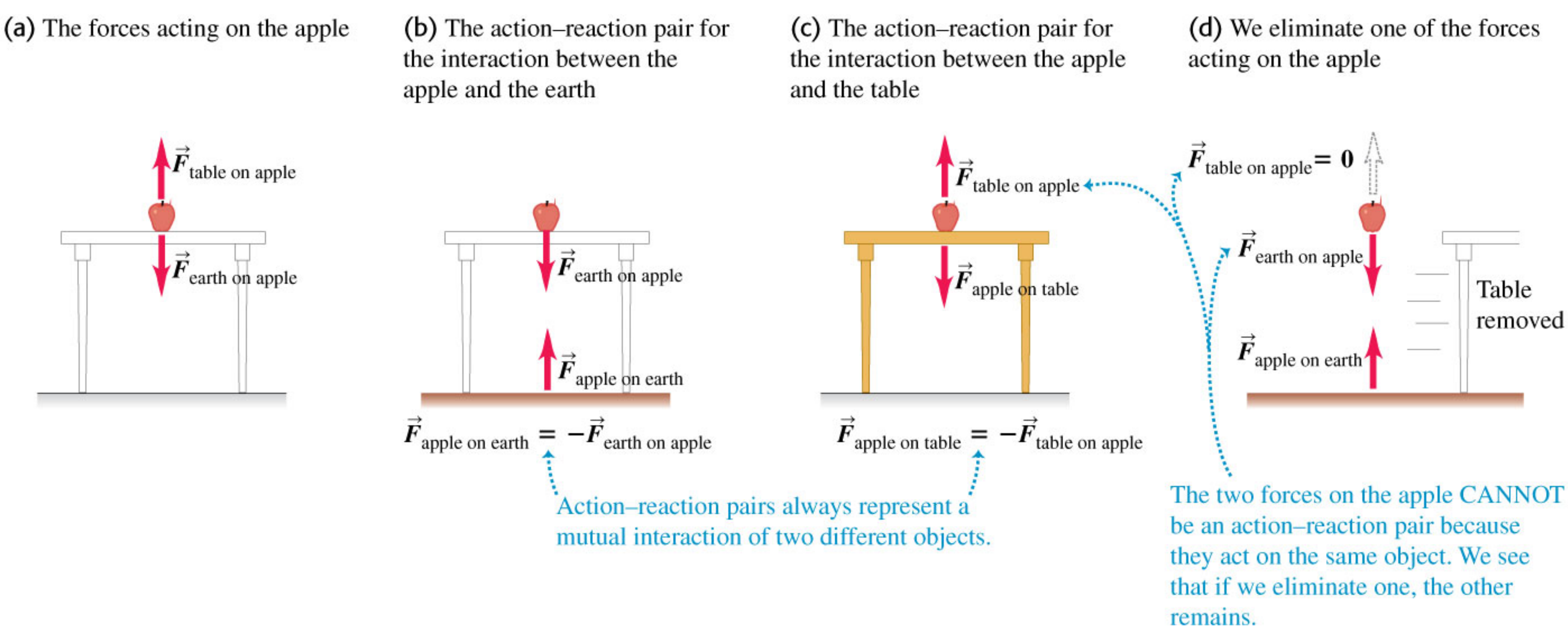
Newton's Third Law

- If you exert a force on a body (an "action"), the body always exerts a force (the "reaction") back upon you.
- A force and its reaction force have the same magnitude *but opposite directions*. These forces act on *different bodies* (the soccer ball and foot in this case.)



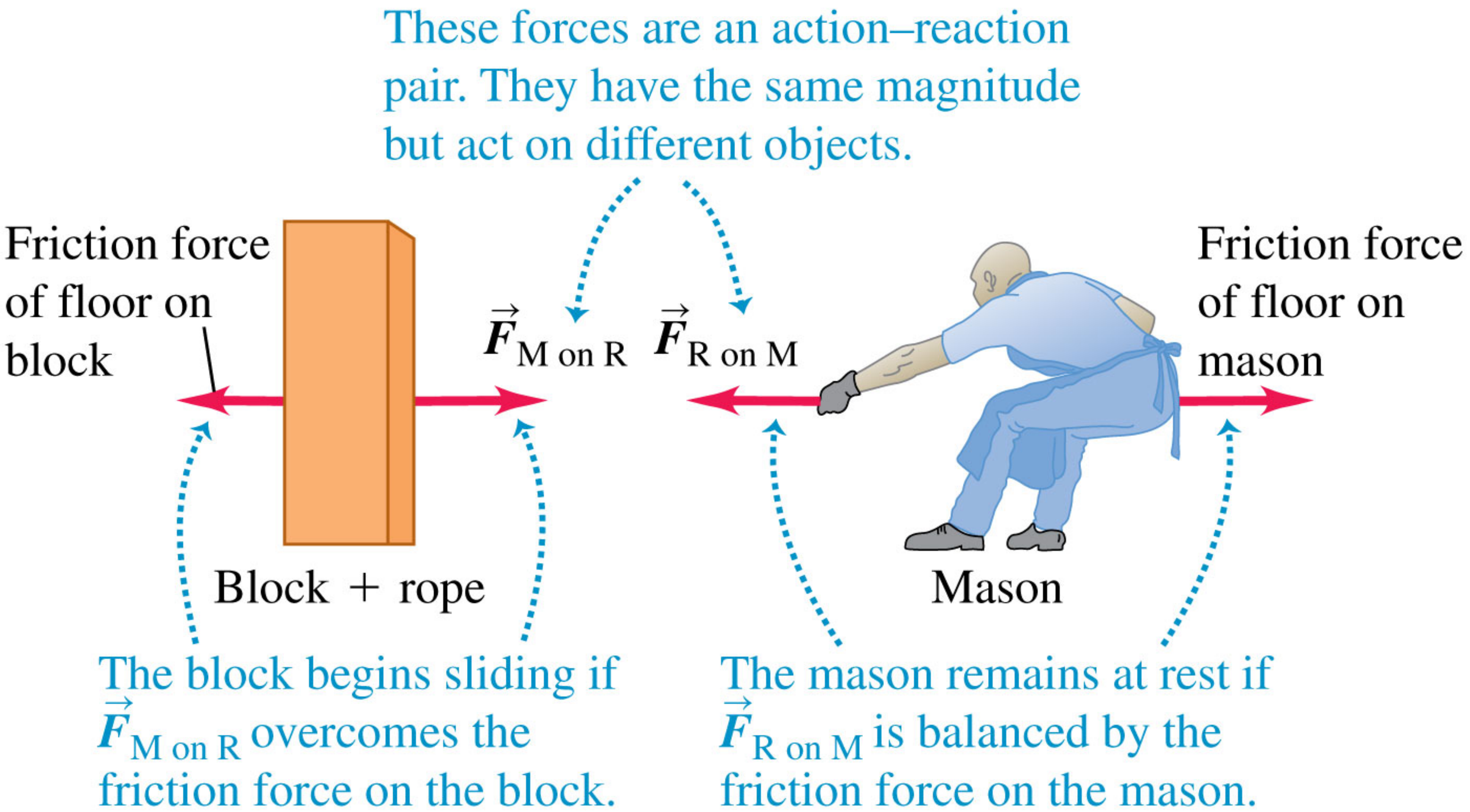
Applying Newton's Third Law: Objects at rest

- An apple rests on a table. What forces that act on it?
- What are their reaction pairs?
- How does the situation change of the table is removed?



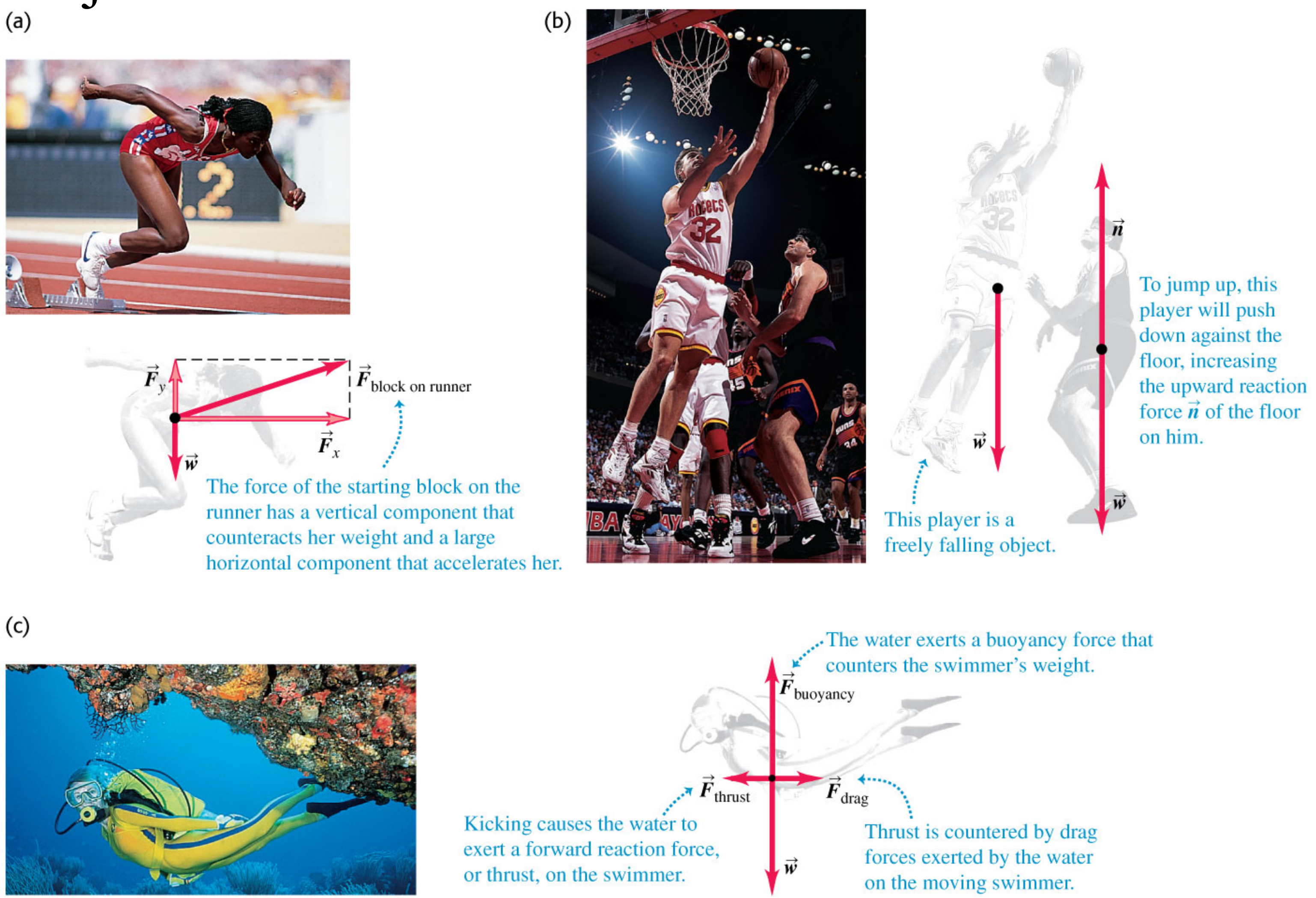
A paradox?

- If an object pulls back on you just as hard as you pull on it, how can it ever accelerate?



Free-body diagrams

- A *free-body diagram* is a sketch showing all the forces acting on an object.

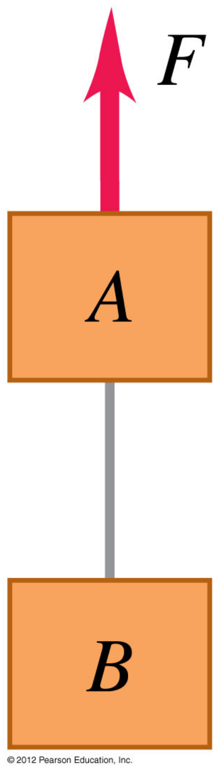


Example #4

Boxes *A* and *B* are connected to each end of a light vertical rope. A constant upwards force *F* = 80.0 N is applied to box *A*. Starting from rest, box *B* descends 12.0 m in 4.00 s. The tension in the rope connecting the two boxes is 36.0 N.

a. What is the mass of box *B*?

b. What is the mass of box *A*?



Solution #4

If box B descends 12.0 m in 4.00 s, its acceleration is:

$y = \frac{1}{2}at^2 \Longrightarrow a = 2y/t^2 = 2(-12.0\text{ m})/(4.00\text{ s})^2 = -1.50\text{ m/s}^2$

The forces acting on it are the upwards tension T and gravity:

$T - m_B g = m_B a \Longrightarrow$

$m_B = T/(g + a) = (36.0\text{ N})/(9.80\text{ m/s}^2 - 1.50\text{ m/s}^2) = 4.34\text{ kg}$

The forces acting on box A are the upwards F, downwards T, and gravity. It experiences the same acceleration as box B:

$F - T - m_A g = m_A a \Longrightarrow$

$m_A = (F - T)/(g + a) = (80.0\text{ N} - 36.0\text{ N})/(9.80\text{ m/s}^2 - 1.5\text{ m/s}^2)$

$= 5.30\text{ kg}$